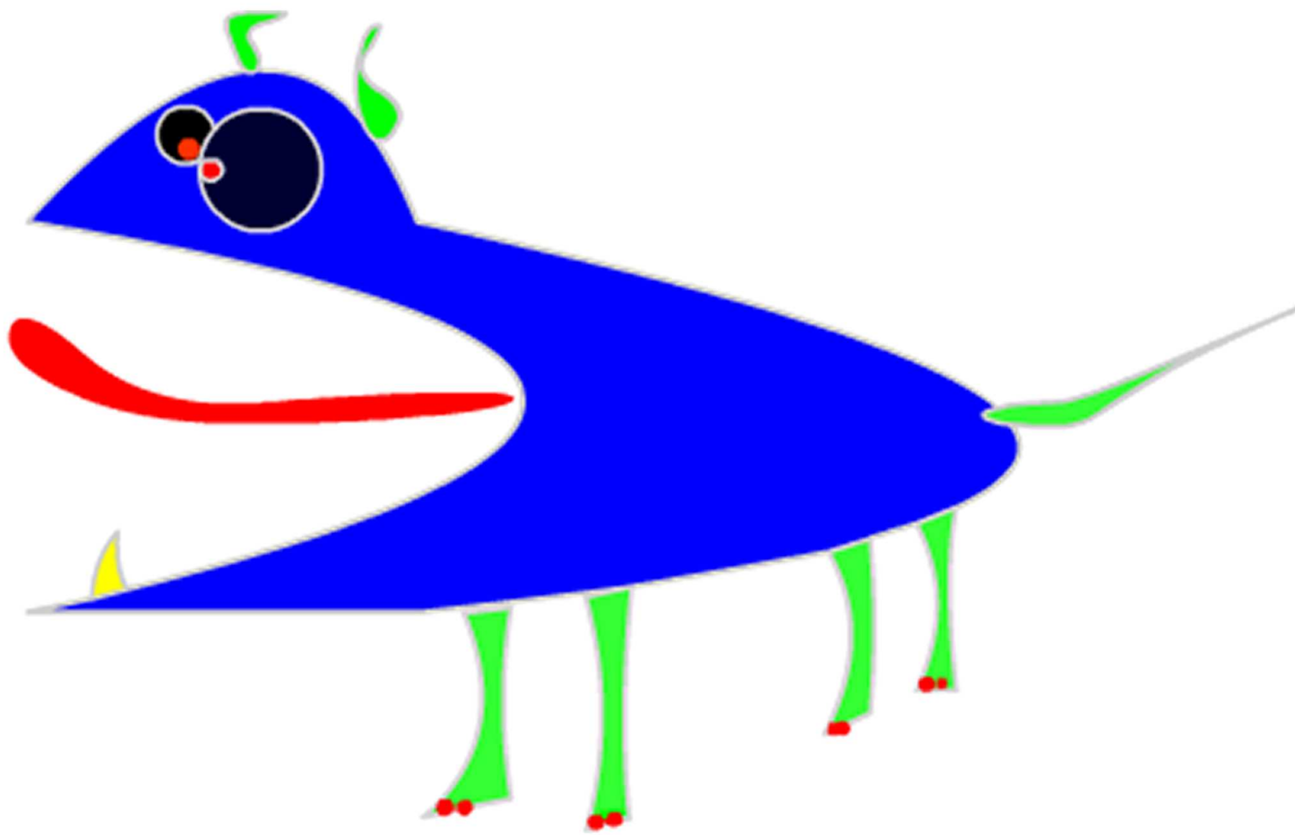
NMSU ASTRONOMY
ASTR 110G: SECTIONS 01, 02, & 03
LABORATORY NOTEBOOK

with Professor Nicole Vogt



Fall 2010

ASTR110G Laboratory Notebook Contents

Name:

Lab 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, as is true for 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 very basic concepts necessary to enable you to successfully complete the various laboratory exercises you will encounter later this semester. When necessary, 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 inches 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. The units you will encounter most in the Astronomy 110 labs are 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 encounter in this class are listed in Table 1.

Table 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 hundreth)
milli	m	0.001 (one thousandth)
micro	μ	0.0000001 (one millionth)
nano	n	0.0000000001 (one billionth)

In the metric system 3,600 meters is equal to 3.6 kilometers; 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 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. Using AU instead of meters or kilometers makes it 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 terms parsec, kiloparsec (1 thousand pc), and 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.

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 the next figure is a map of the state of New Mexico. Down at the bottom left hand corner is a scale in miles and kilometers.

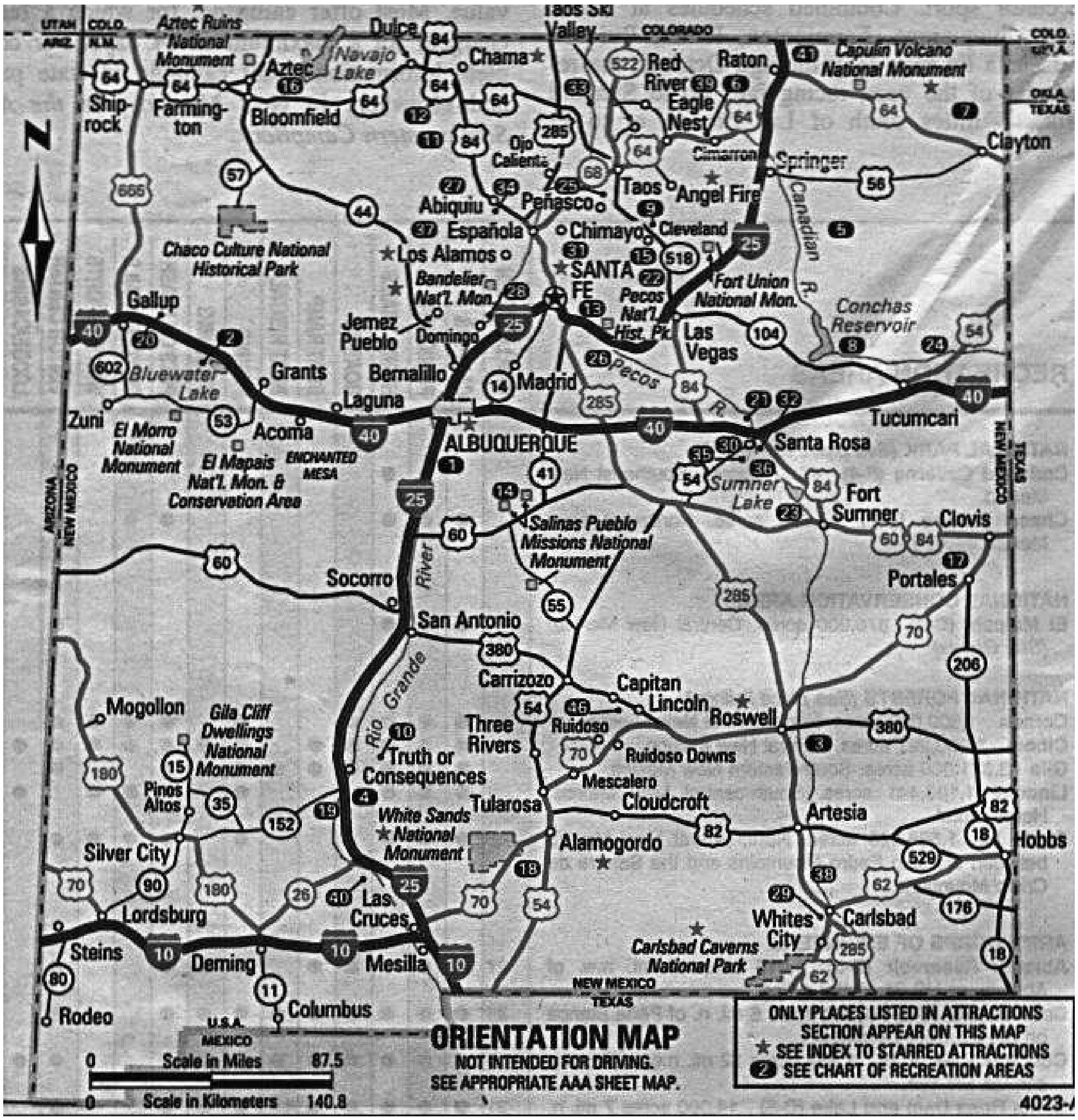


Figure 1.1: A map of New Mexico

Map Exercises: Using a ruler, determine the following values.

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?

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

1.3 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 ($\sqrt{17} = 17^{1/2}$) $= 4.123$

1.4 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 shorthand 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, let's 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 ensure 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.

1.5 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 $y = 13$ ($y = 3{\times}2 + 7 = 13$). 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: $q = 3\times5 + 9 = 15 + 9 = 24$

$y = 5x^2 + 3$, if $x=2$, what is y? Answer: $y = 5\times(2^2) + 3 = 5\times4 + 3 = 20 + 3 = 23$

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.

1.6 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 (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.

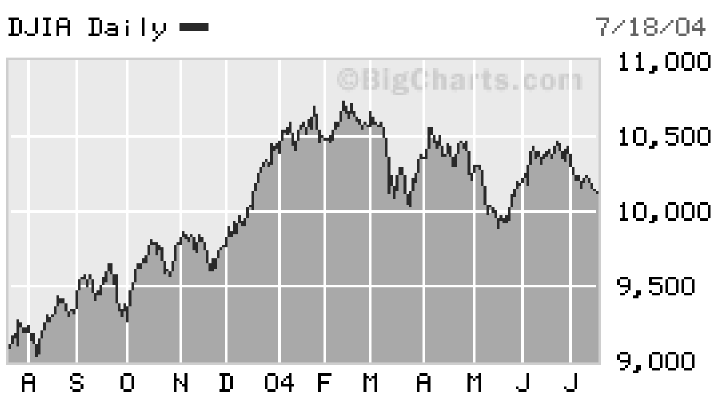


Figure 1.2: The change in the Dow Jones stock index over one year (from April 2003 to July 2004).

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

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

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 $y = -3.57\times10^{-3}x + 59.0$. Why is the 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 ontop 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

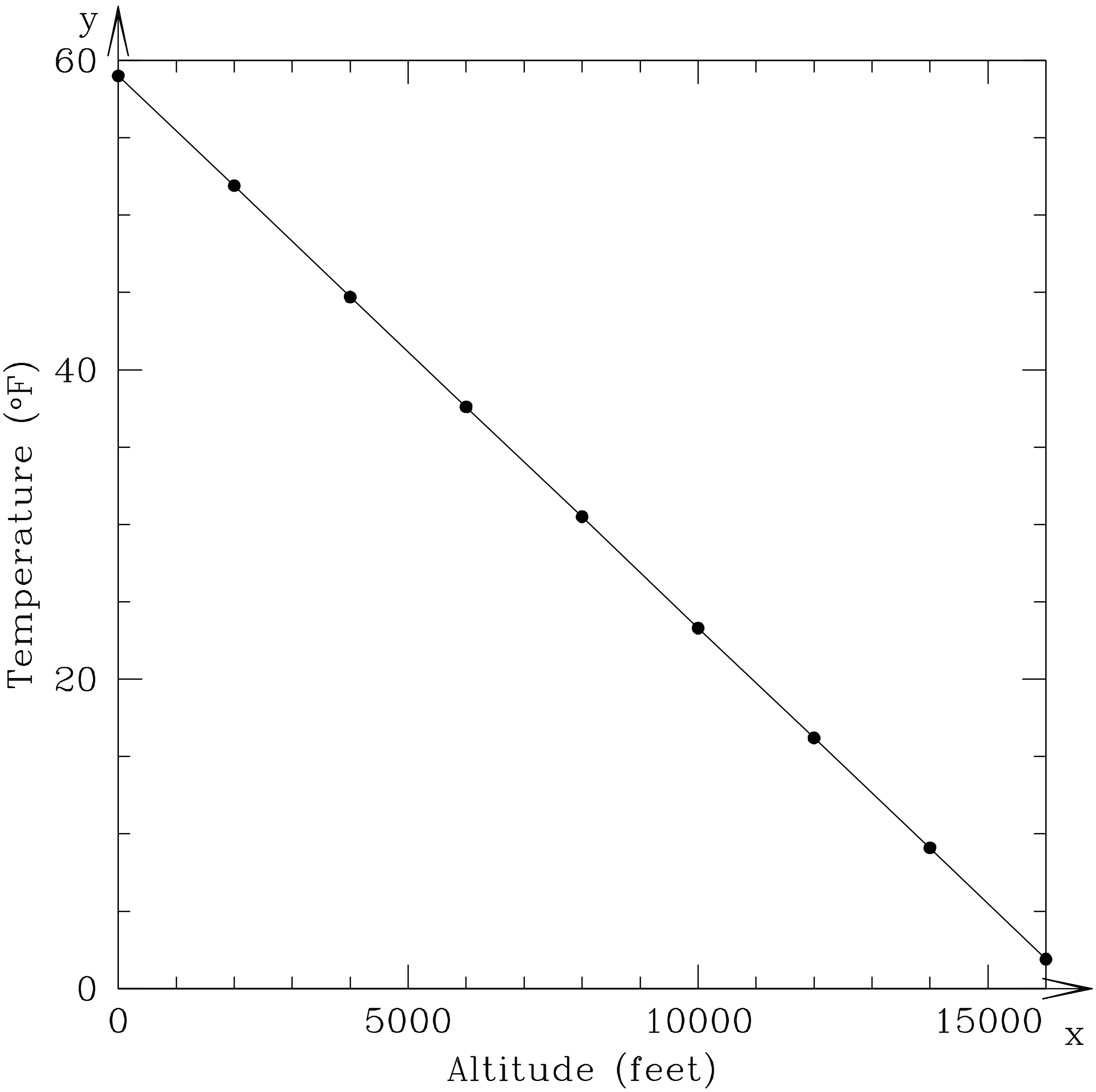


Figure 1.3: The change in temperature as you climb in altitude with the data from the preceeding table. At sea level (0 ft altitude) the surface temperature is 59°F. As you go higher in altitude, the temperature goes down.

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).

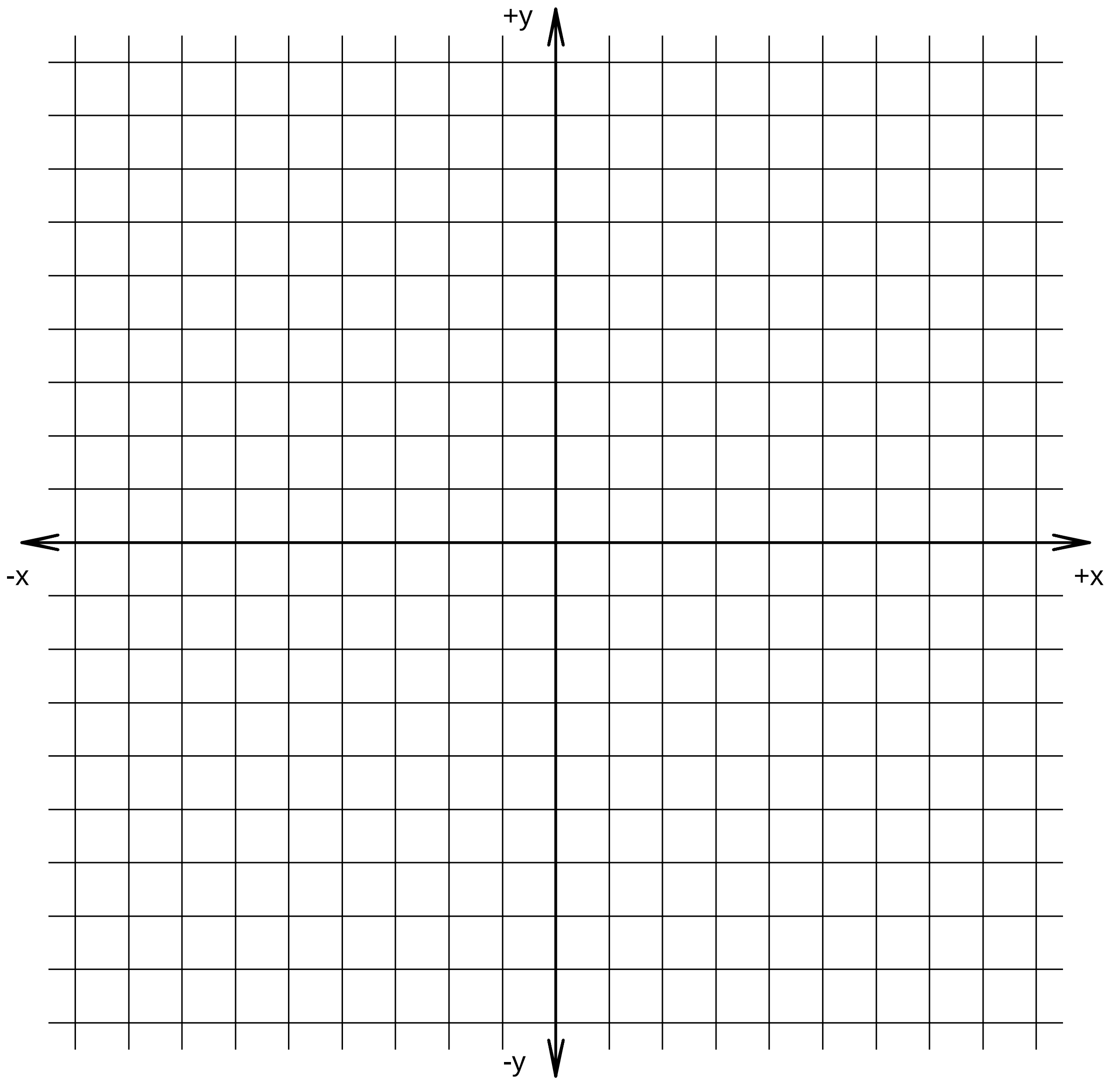


Figure 1.4: Graph paper for plotting the equation y = 2x + 2.

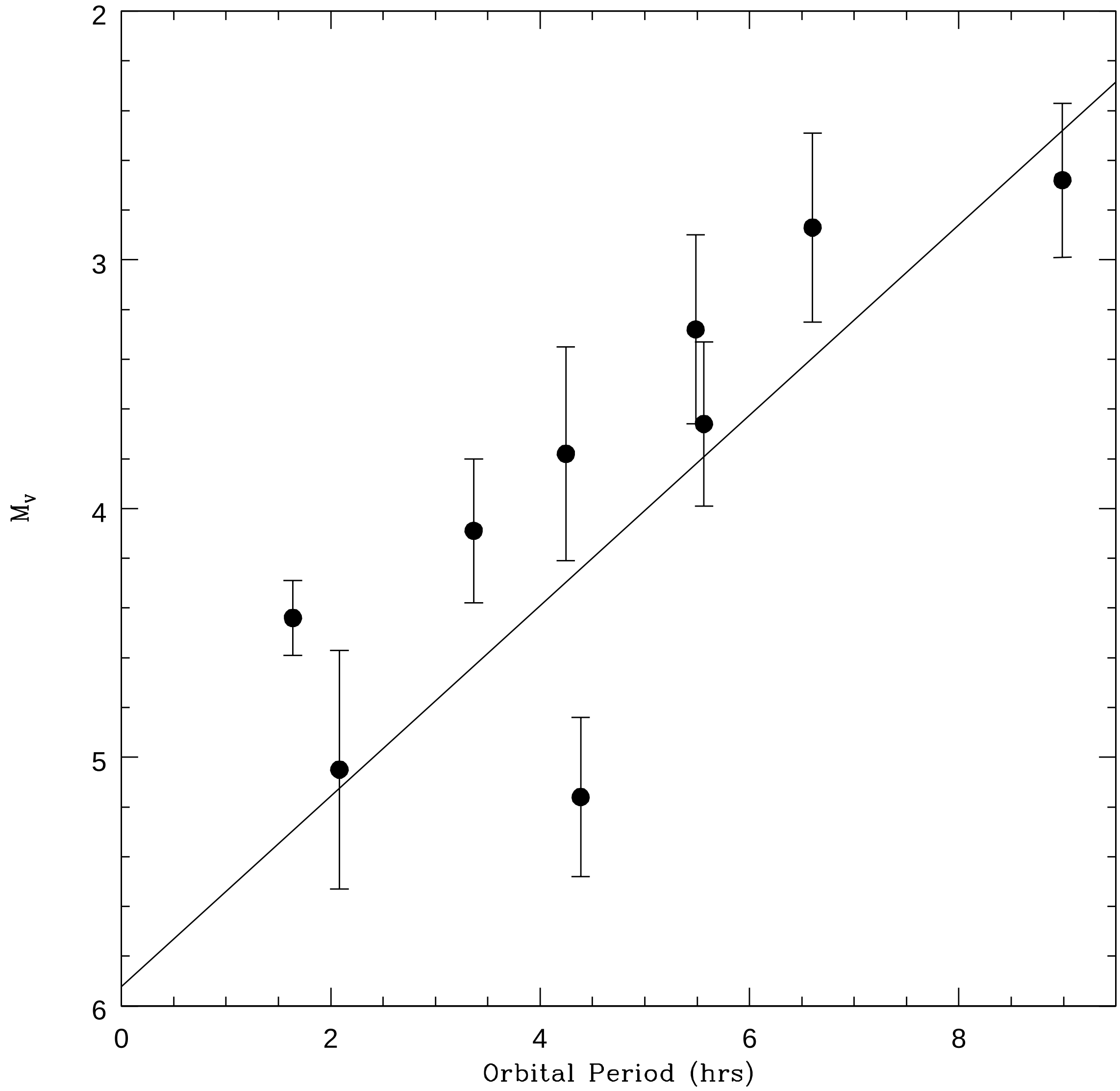


Figure 1.5: The relationship between absolute visual magnitude (M_V) and Orbital Period for catclysmic variable binary stars.

Name:

Lab 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 styrofoam 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.

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

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

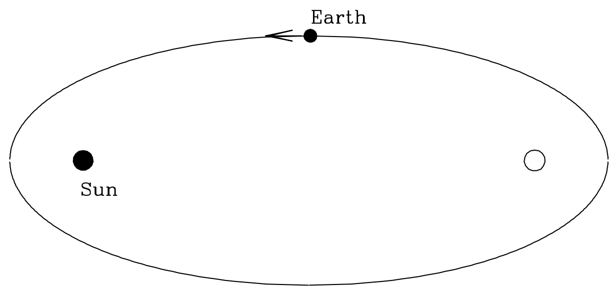


Figure 2.1: An ellipse with the two "foci" identified. The Sun sits at one focus, while the other focus is empty. The Earth follows an elliptical orbit around the Sun, but not nearly as exaggerated as that shown here!

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. (3pts)

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

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 = ____________. (1pt)

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

5) So, if an object appears bigger when we get closer to it, when is the Earth closest to the Sun? (2pts)

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"? (4pts)

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 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 ? (1pt)

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. (1pt)

9) In January, there are more daylight hours in ______________________. (1pt)

10) In July, there are more daylight hours in ______________________. (1pt)

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

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

13) In January, there are more daylight hours in ______________________. (1pt)

14) In July, there are more daylight hours in ______________________. (1pt)

15) **Summarizing:** During the Wintertime (January) in both Las Cruces and Fairbanks there are fewer daylight hours, *and* it is colder. During July, it is warmer in both Fairbanks and Las Cruces, *and* there are more daylight hours. Is this also true for Sydney?: ____________. (1pt)

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

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

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

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

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

2.3 The Spinning, Revolving Earth

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

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 styrofoam globe, a piece of string, a ruler, and the halogen desklamp. **Warning: while the globe used here is made of fairly inexpensive parts, it is very time consuming to make. Please be careful with your globe, as the styrofoam 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 styrofoam 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^o.

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 (there is a dim, and a bright setting). Note these lamps get very hot, so be careful. For this lab, we will define the top of the globe as the Northern hemisphere, and the bottom as the Southern hemisphere.

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

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

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 (and it is probably best to do this more than once!). Fill in the following table (4pts):

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 pts):

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

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.

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? (3pts)

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. Near the North Pole, there is a black line on the globe that allows you to precisely orient the globe: just make sure the shadow of the wooden axis falls on this line segment. With this alignment, the Earth's axis should point exactly away from the Sun (you can spin the globe slightly for better alignment). Fill in the following two tables (4 pts):

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 pts)

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 pts)

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^o 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 pts):

Table 2.6: Position #3: Solstice Data Table

Latitude	**Length of Daylight Arc**	**Length of Nightime Arc**
Equator		
45^{o}N		
Arctic Circle		
Antarctic Circle		

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

Latitude	**Daylight Hours**	**Nighttime Hours**
Equator		
45^{o}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^o degree latitude with that for Minneapolis. What season does this appear to be? (2 pts)

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 pts)

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 pts)

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$^{\rm st}$) there are more daylight hours, at the start of the Autumn ($\sim$ Sept. 20$^{\rm th}$) and Spring ($\sim$ Mar. 21$^{\rm st}$) the days are equal to the nights. In the Winter (approximately Dec. 21$^{\rm st}$) 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.

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.

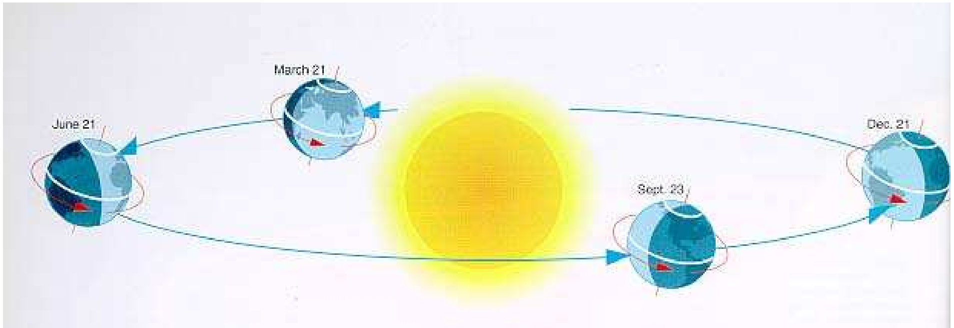


Figure 2.4: The Earth's spin axis always points to one spot in the sky, *and* it is tilted by 23.5° to its orbit. Thus, as the Earth orbits the Sun, the illumination changes with latitude: sometimes the North Pole is bathed in 24 hours of daylight, and sometimes in 24 hours of night. The exact opposite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

2.4 Elevation Angle and the Concentration of Sunlight

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

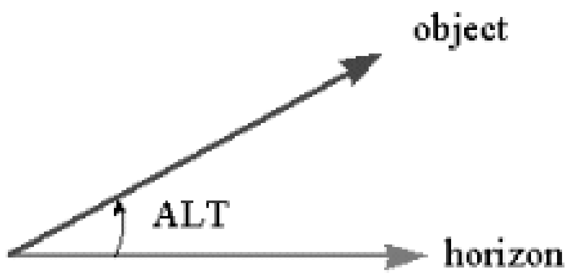


Figure 2.5: Altitude ("Alt") is simply the angle between the horizon, and an object in the sky. The smallest this angle can be is 0°, and the maximum altitude angle is 90°. Altitude is interchangebly known as elevation.

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

Exercise #4: Using the elevation angle apparatus, we now want to measure what happens when the Sun is at a higher or lower elevation angle. We mimic this by a flashlight mounted on an arm that allows you to move it to just about any elevation angle. It is difficult to exactly model the Sun using a flashlight, as the light source is not perfectly uniform. But here we do as well as we can. Play around with the device. 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 white paper and tape it to the base so we have a more reflective surface. Now arrange the apparatus so the elevation angle is 90°. The illuminated spot should look circular. Measure the diameter of this circle using a ruler.

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 pt)

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

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

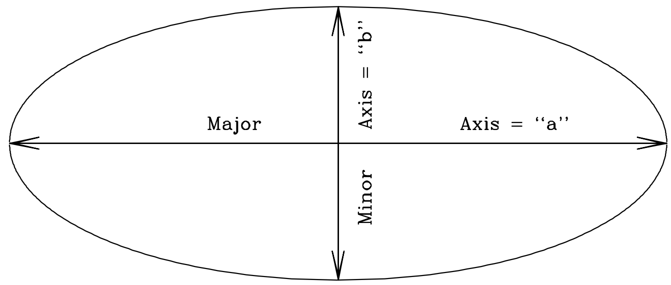


Figure 2.6: An ellipse with the major and minor axes defined.

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 pt).

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 pt).

At 45°, the amount of light per centimeter is 100 divided by the Area of the ellipse

$=$ __________________ units of light per cm^2 (1 pt).

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 pts)

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.

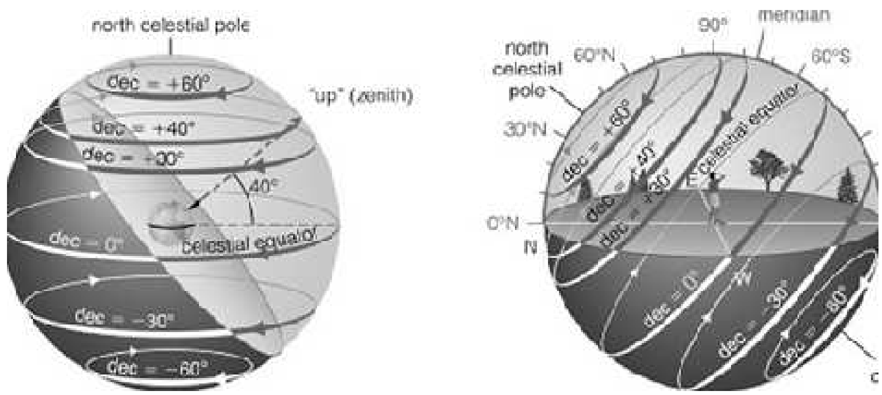


Figure 2.7: The Celestial Equator is the circle in the sky that is straight overhead ("the zenith") of the Earth's equator. In addition, there is a "North Celestial" pole that is the projection of the Earth's North Pole into space (that almost points to Polaris). But the Earth's spin axis is tilted by 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 which it retraces its steps until it reaches the Autumnal Equinox (September 20th), after which it is South of the Celestial Equator. It is lowest in the sky on December 21st. This is simply due to the fact that the Earth's axis is tilted with respect to its orbit, and this tilt does not change. You can see this geometry by going back to the illuminated globe model used in Exercise #3. If you stick a pin at some location on the globe away from the equator, turn on the halogen lamp, and slowly rotate the entire apparatus around (while 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 concepts 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 Extra Credit

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. (5 pts)

2.7 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?

Name:

Lab 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, we had enough scientific 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 we sent the space missions that orbited 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.

On the Moon, there are extensive lava flows, rugged highlands and many impact craters of all 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 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

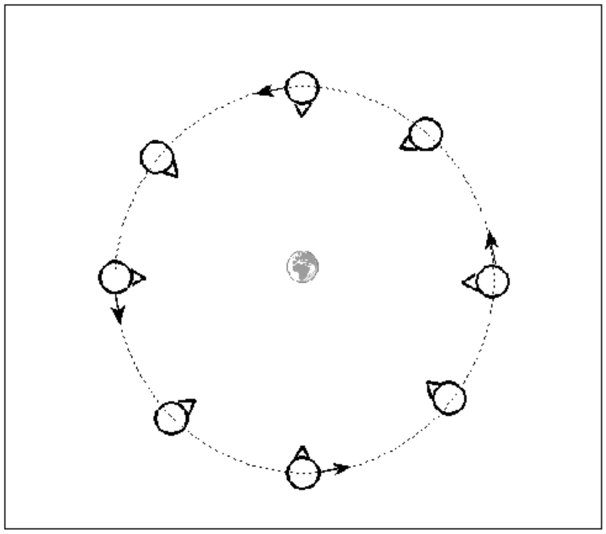


Figure 3.1: The Moon's synchronous orbit.(Not drawn to scale.)

- *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).

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 *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.

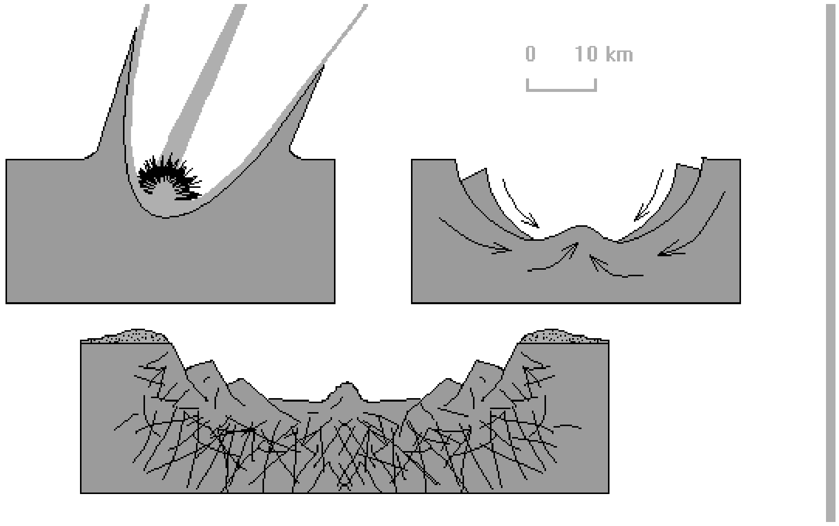


Figure 3.2: Formation of an Impact Crater.

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 *mare* (*mare* is the plural of maria) which have less craters. We also know that if we see a crater on top of a maria, the maria 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 in several "stations". Each station will have different images of the Moon (or Earth) and a few questions about these images. In some sections 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 sections, 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. Be careful and answer all of the questions. In most cases, the questions are numbered. The point values for all of the questions you must answer are specifically listed. **Remember to back up your answers with reasonable explanations.**

3.4.1 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. (*4 Points*)

Images #4 and #5 are close-ups of small sections 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. (*4 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 Organs (by estimating their coverage). 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?] (*6 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 telesope (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 section 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 maria 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 Antartica 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)*

3.4.2 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 mare suggest? [Hint: do you remember how maria are formed?] (*5 points*)

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

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%

(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.

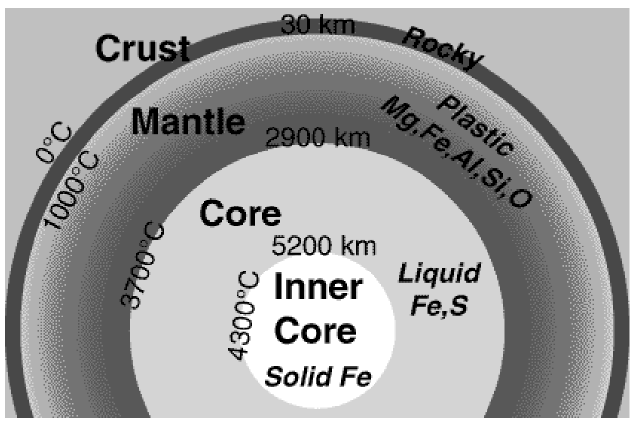


Figure 3.3: The internal structure of the Earth, showing the dimensions of the crust, mantle and core, as well as their composition and temperatures.

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 the Table (3.2) 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*)

3.5 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 maria 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.

3.6 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 synchrounous rotation?
6. How can we determine the relative ages of different lunar surfaces?

Name:

Lab 4

Kepler's Laws and Gravitation

4.1 Introduction

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

4.2 Gravity

Gravity is the fundamental force governing the motions of astronomical objects. No other force is as strong over as great a distance. Gravity influences your everyday life (ever drop a glass?), and keeps the planets, moons, and satellites orbiting smoothly. Gravity affects everything in the Universe including the largest structures like super clusters of galaxies down to the smallest atoms and molecules. Experimenting with gravity is difficult to do. You can't just go around in space making extremely massive objects and throwing them together from great distances. But you can model a variety of interesting systems very easily using a computer. By using a computer to model the interactions of massive objects like planets, stars and galaxies, we can study what would happen in just about any situation. All we have to know are the equations which predict the gravitational interactions of the objects.

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

$$F_{gravity} = \frac{GM_1M_2}{R^2} \tag{4.1}$$

A diagram detailing the quantities in this equation is shown in Fig. 4.1. Here $F_{gravity}$ is the gravitational attractive force between two objects whose masses are M_1 and M_2. The distance between the two objects is "R". The gravitational constant G is just a small number that scales the size of the force. **The most important thing about gravity is that the**

force depends only on the masses of the two objects and the distance between them. This law is called an Inverse Square Law because the distance between the objects is *squared*, and is in the denominator of the fraction. There are several laws like this in physics and astronomy.

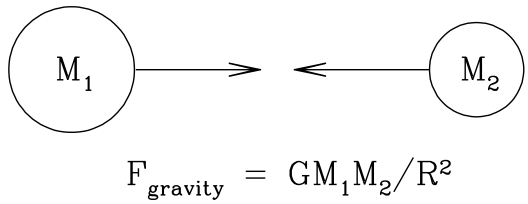


Figure 4.1: The force of gravity depends on the masses of the two objects (M_1, M_2), and the distance between them (R).

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.

- *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

4.3 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. 4.2.

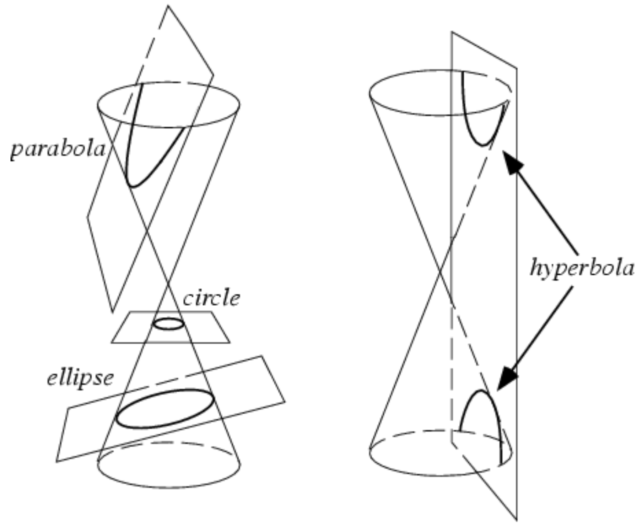


Figure 4.2: Four types of curves can be generated by slicing a cone with a plane: a circle, an ellipse, a parabola, and a hyperbola. Strangely, these four curves are also the allowed shapes of the orbits of planets, asteroids, comets and satellites!

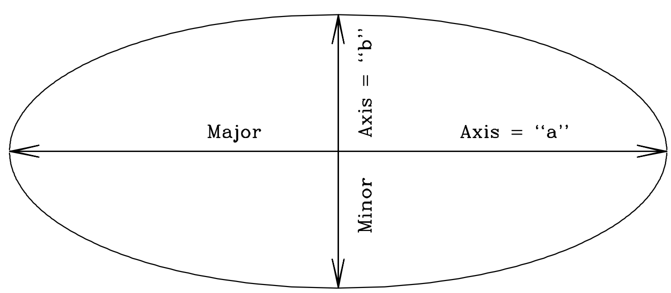


Figure 4.3: An ellipse with the major and minor axes identified.

Before we describe an ellipse, let's examine a circle, as it is a simple form of an ellipse. As you are aware, the circumference of a circle is simply 2πR. The radius, R, is the distance between the center of the circle and any point on the circle itself. In mathematical terms, the center of the circle is called the "focus". An ellipse, as shown in Fig. 4.3, is like a flattened circle, with one large diameter (the "major" axis) and one small diameter (the "minor" axis). A circle is simply an ellipse that has identical major and minor axes. Inside of an ellipse, there are two special locations, called "foci" (foci is the plural of focus, it is pronounced "fo-sigh"). The foci are special in that the sum of the distances between the foci and any points on the ellipse are always equal. Fig. 4.4 is an ellipse with the two foci indentified, "F_1" and "F_2".

Exercise #1: On the ellipse in Fig. 4.4 are two X's. Confirm that that sum of the distances between the two foci to any point on the ellipse is always the same by measuring the distances between the foci, and the two spots identified with X's. Show your work. (2 points)

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

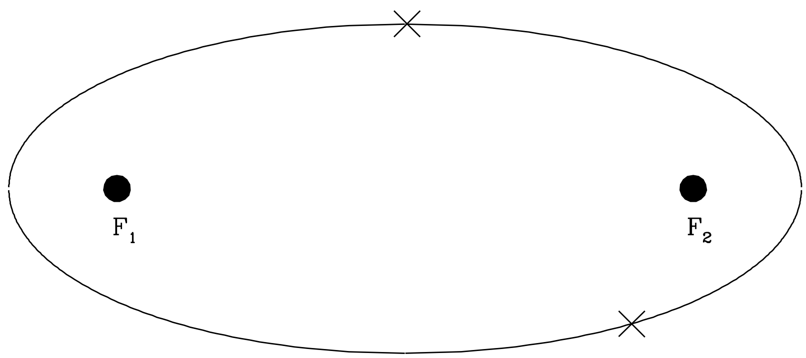


Figure 4.4: An ellipse with the two foci identified.

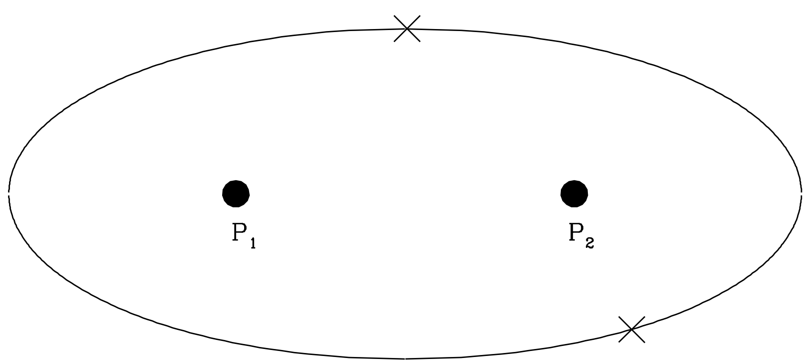


Figure 4.5: An ellipse with two non-foci points identified.

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:

$$V = \sqrt{(G(M_{\text{sun}} + M_{\text{planet}})(2/r - 1/a))} \tag{4.2}$$

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 $G(M_{\text{sun}} + M_{\text{planet}}) = 1$ 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 ($P^2 = C \times a^3$) for an arbitrary planet divided by the Third Law equation for the Earth:

$$\frac{P_P^2}{P_E^2} = \frac{C \times a_P^3}{C \times a_E^3} \tag{4.3}$$

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:

$$\frac{P_P^2}{P_E^2} = \frac{a_P^3}{a_E^3} \tag{4.4}$$

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:

$$\frac{P_P^2}{1} = \frac{a_P^3}{1} \quad or \quad P_P^2 = a_P^3 \tag{4.5}$$

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

Let's use equation (4.5) 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:

$$P_J^2 = a_J^3 = 5^3 = 5 \times 5 \times 5 = 125 \tag{4.6}$$

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:

$$\sqrt{P^2} = P = \sqrt{125} = 11.2 \;\; years \tag{4.7}$$

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 4.1: 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)

4.4 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. 4.6 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.

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

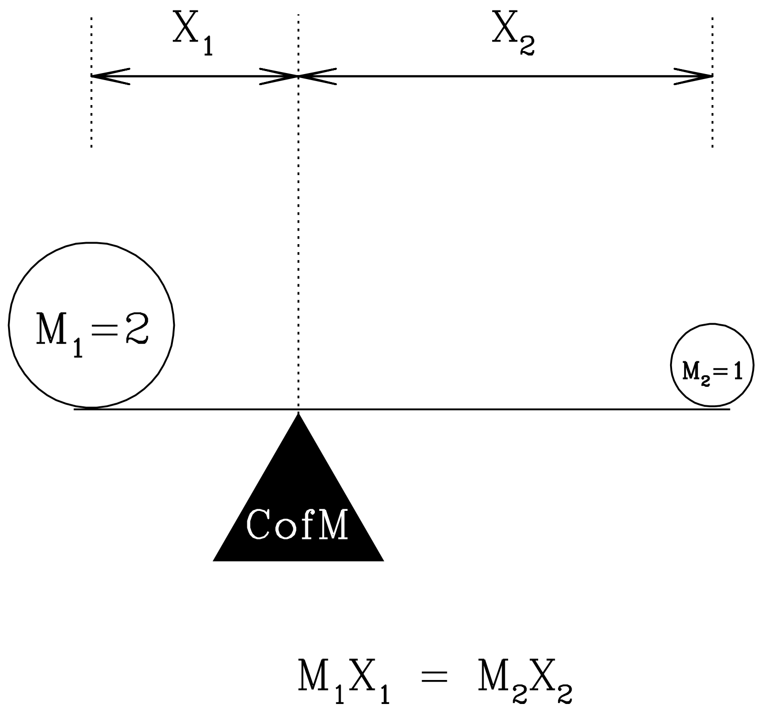


Figure 4.6: A diagram of the definition of the center of mass. Here, object one (M_1) is twice as massive as object two (M_2). Therefore, M_1 is closer to the center of mass than is M_2. In the case shown here, $X_2 = 2X_1$.

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. 4.6.] (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 (see Figure 6.6). 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.)

4.5 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.

4.6 Extra Credit

Derive Kepler's third law ($\mathrm{P}^2 = C \times a^3$) 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 $\mathrm{P}^2 = C \times a^3$? What does the constant "C" have to equal to get Kepler's third law? (5 points)

4.7 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"?

Name:

Lab 5

Parallax Measurements and Determining Distances

5.1 Introduction

How do we know how far away stars and galaxies are from us? Determining the distances to these distant objects is one of the most difficult tasks that astronomers face. Since we cannot simply pull out a very long ruler to make a few measurements, we have to use other methods.

Inside the solar system, astronomers can bounce a radar signal off of a planet, asteroid or comet to directly measure its distance. How does this work? A radar signal is an electromagnetic wave (a beam of light), so it always travels at the same speed, the speed of light. Since we know how fast the signal travels, we just measure how long it takes to go out and to return to determine the object's distance.

Some stars, however, are located hundreds, thousands or even tens of thousands of "light-years" away from Earth. A light-year is the distance that light travels in a single year (about 9.5 trillion kilometers). To bounce a radar signal off of a star that is 100 light-years away, we would have 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 the stars are.

In fact, there is one, and only one, direct method to measure the distance to a star: the "parallax" method. Parallax is the angle by which something *appears* to move across the sky when an observer looking at that object changes 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 develop an appreciation for the small angles that astronomers must measure to determine the distances to stars.

To get the basic idea, 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 and your right eye open. Now close your right eye and open your left one. See how your thumb appeared to move to the right? Keep staring at your thumb, and change eyes several times. You should see your thumb appear to move back and forth, relative to the background. Of course, your thumb is not moving. Your *vantage point* is moving, and so your thumb *appears* to move. That's the parallax effect!

How does this work for stars? Instead of switching from eye to eye, we shift the position of our entire planet! We observe a star once, and then wait six months to observe it again. In six months, the Earth will have revolved half-way around the Sun. This shift of two A.U. (twice the distance between the Earth and the Sun) is equivalent to the distance between your two eyes. Just as your thumb will appear to shift position relative to background objects when viewed from one eye and then the other, over six months a nearby star will appear to shift position in the sky relative to very distant stars.

5.1.1 Goals

The primary goals of this laboratory exercise are to understand the theory and practice of using parallax to find the distances to nearby stars, and to use it to measure the distance to objects for yourself.

5.1.2 Materials

All online lab exercise components can be reached from the GEAS project lab URL, listed below.

http://astronomy.nmsu.edu/geas/labs/labs.html

You will need the following items to perform your parallax experiment:

- a wall-mountable parallax ruler, and a protractor (provided on pages 95–103)
- a pair of scissors, and a roll of strong tape
- a yardstick or a tape measure (35 feet long, if available)
- at least 35 feet of non-stretchy string (not yarn)
- a ruler
- 4 coins (use quarters, or even heavier objects, if windy)
- 2 pencils or pens
- a calculator

- a thin object and a tall object, such as: a toothpick and an 6-inch stack of textbooks, **OR** a thin straw and a filled soft drink can, **OR** a thin chopstick and a soup can
- a friendly assistant

Your assistant could be an adult or an older child, and needs no special knowledge of astronomy. S/he will assist you in marking points on your parallax ruler and measuring their separations, measuring the angle between two lines-of-sight, and measuring the spacing between your two eyes.

Wear clothes which can get slightly dusty, as you will be lying down on the ground while making some of your measurements. You may also want to bring an old towel, to protect your clothing and shield yourself from the temperature of the ground.

You will also need a computer with an internet connection, and a calculator, to analyze the data you collect from your parallax experiment.

5.1.3 Primary Tasks

This lab comprises two activities: 1) a parallax measurement experiment, to be performed in a safe, dry, well-lit space measuring at least 35 feet by eight feet, and 2) an application of the parallax technique to stars, which can be recorded either on paper or directly on a computer. Students will complete these two activities, answer a set of final (post-lab) questions, write a summary of the laboratory exercise, and create a complete lab exercise report via the online Google Documents system (see http://docs.google.com).

The activities within this lab are are a combination of field-work and computer-based ones, so you may either read most of this exercise on a computer screen, typing your answers to questions directly within the lab report template at Google Documents, or you may print out the lab exercise, make notes on the paper, and then transfer them into the template when you are done. We strongly recommend that you print out at least pages 70–87 for use in conducting the parallax experiment in §5.2.

5.1.4 Grading Scheme

There are 100 points available for completing the exercise and submitting the lab report perfectly. They are allotted as shown below, with set numbers of points being awarded for individual questions and tasks within each section. Note that Section 5.6 (§5.6) contains 4 extra credit points.

Table 5.1: Breakdown of Points

Activity	Parallax Experiment	Stellar Parallax	Questions	Summary
Section	§5.2	§5.3	§5.4	§5.5
Page	72	87	90	93
Points	39	7	19	35

5.1.5 Timeline

Week 1: Read §5.1–§5.3, complete activities in §5.2 and §5.3, and begin final (post-lab) questions in §5.4. Identify any issues that are not clear to you, so that you can receive feedback and assistance from your instructors before Week 2. Enter your preliminary results into your lab report template, and make sure that your instructors have been given access to it so that they can read and comment on it.

Week 2: Finish final (post-lab) questions in §5.4, write lab summary, and submit completed lab report.

5.2 The Parallax Experiment

In this experiment, you will develop a better understanding of parallax by measuring the apparent shift in position of an object along a parallax ruler (described below). You will explore the effects of changing the "object distance," the distance between an object and an "observer" (you), and of changing the "vantage point separation" (the distance between your two eyes).

5.2.1 Setting up your experiment

Our first step is to set up the parallax experiment. You will need to find a location with a wall wide enough to hold a six-foot-long ruler and a clear, flat open space (ideally 35 feet long) in front of it, as shown in Figure 5.1. A safe driveway, a fairly flat backyard, a long hallway, or a racquetball court or gymnasium might all be possible places to work. Be sure that your location is safe, well-lit, and not too windy.

Find the four pages of "ruler segment" provided in your lab manual at the end of this chapter (pages 95–101). To create a wall-mounted "parallax ruler," cut out the eight ruler segments, and tape them together. (You can also cut out the protractor on page 103 at this time.) The segments will form a six-foot ruler, with inch and foot divisions clearly marked. Now tape your parallax ruler to the wall, roughly 6 inches above the ground. Make sure that the sheets are securely attached to each other and to the wall, so that your ruler does not fall apart in the middle of the lab. It is also important that the ruler be placed as horizontally as possible, and be attached without sagging at any point.

The next step is to construct a support for the thin object which you will observe. If you are using a toothpick and a stack of textbooks, stack the books on top of each other neatly and tape the toothpick securely to the side of the top book. It should point up straight, like a flagpole, and extend well above the height of the book. If you are using a thin straw and a soft drink, tape the straw securely to the side of the can, pointing straight up, so that the top of the straw lies at least 6 inches above the ground. If you are using a thin chopstick and a soup can, tape the chopstick securely to the side of the can, pointing straight up, so that the top of the chopstick lies at least 6 inches above the ground.

The toothpick is the most ideal thin object of the three, because it is so narrow. If you use a thicker object, such as a straw or chopstick, be very careful to always train your eye along the same side (left or right) of the object when you observe it.

You will be lining up the position of the top of your thin object (the tip of the toothpick, one end of the straw, or the thinner end of the chopstick) with positions along the parallax ruler by eye, so it needs to be held straight, without drooping or falling.

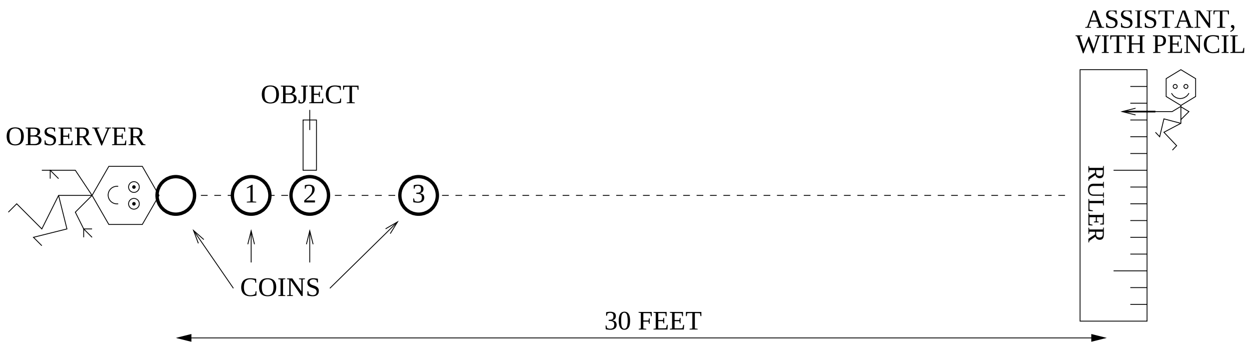


Figure 5.1: Basic layout of the parallax experiment. Lay the coins in a straight line along the string or tape measure, between the observer and the center of the ruler.

5.2.2 Taking parallax measurements

Complete the following, answering questions and filling in the blanks in Tables 5.2–5.5 as requested. (Filling in the four tables correctly is worth 18 points, and the associated questions are worth 19 additional points.)

You will need to have an assistant available for this part of the lab exercise. You will be the "observer," and your assistant will kneel next to the parallax ruler with a pencil and mark positions on it at your command.

Ask your assistant to hold one end of the long piece of string on the ground directly below the **center** of the parallax ruler. (If your tape measure is long enough, you may use it instead of string.) Take the other end of the string and walk 30 feet (12 really large paces) directly away from the center of the parallax ruler. We will refer to this position as the "observation spot." Pull the string taut and set it on the ground. Mark your observation spot on the ground with a coin next to the string, so that you can return to it later.

Measure how far your observation spot lies from the wall, and record your measurement here, to a fraction of an inch: _______________. (1 point)

If your tape measure is less than 30 feet long, you will need to do this in two (or more) stages. Measure to roughly 90% of the length of your tape measure away from the ruler, and carefully place a second coin at this location. Then measure the remaining distance to the observation spot, add the distances, and pick up the second coin.

You will now place three more coins along the string, between one and five feet away from the observation spot. Place the first coin just over a foot in front of the observation spot, the second coin four to six inches further away, and the third coin roughly five feet in front of the observation spot.

Before you continue, you should check that your detailed observations will be possible at the first location. Place the thin object on top of or next to the first coin, trying to position it exactly above either one edge or the center of the coin. (You may place the object just to the side of the string, if you are worried about the coin being moved, but make sure that the thin object lies the same distance from the observation spot as does the coin.) Now lie down flat behind the observation spot and look forward, so that your eyes are resting lightly on your folded hands above the observation spot and you can see both the thin object and the parallax ruler.

Look at the thin object through first one eye and then the other, and make sure that it lines up with the ruler, and does not "spill off" either end. If the thin object lines up with a position less than 0 feet, or more than 6 feet, then shift the first coin and the thin object forward an inch, and check again. Repeat as necessary. (If you need to shift the first coin forward more than an inch, then you may want to shift the second coin forward by a similar amount as well.)

You will now measure two numbers at each of the three object positions marked with coins, repeating each set of measurements three times.

First, use your tape measure to measure the distance along the ground between the coin at the observation point and each of the three coins at object positions (in inches). These are the true distances to the object positions. Record this information under the column labeled Trial 1 for Position 1, Position 2, and Position 3 in Table 5.2. Repeat this process two more times, entering the measurements into the next two columns. **The largest source of error in this measurement will be your ability to place your eyes repeatably directly above the coin at the observation point, so hold your head as carefully as possible when making measurements.**

While it is easy to measure these distances for toothpicks less than 30 feet away from us, it is impossible to measure them directly for stars, as they lie many light-years away from Earth.

Table 5.2: Direct Measurements of Distance

Make all measurements in fractions of inches.			
	Trial 1	Trial 2	Trial 3
Distances from observer to object, in inches.			
Position 1			
Position 2			
Position 3			

(3 points)

We will use these measurements as "controls," and compare our parallax-derived distances to them at the end of the experiment.

Second, place your thin object above or just next to the coin at Position 1. You measured the distance from the observation spot to the center, or one edge, of the coin, so be sure to align the object at precisely the same location.

Now measure the apparent shift of the object against the wall-mounted ruler as you observe it through first one eye and then the other. Lie down behind the observation spot again, so that your eyes are directly above the coin which marks your position. As you did previously (when observing your thumb), you will look at the thin object with first your right eye and then your left eye (you may want to close or cover the other eye as you make the measurements). Your eyes, the thin object, and the parallax ruler should all lie in a line roughly 6 inches above the ground.

You assistant will help you to measure the number of inches on the parallax ruler by which the object appears to move as you switch eyes. Begin by looking through one eye, and have your assistant hold up a pencil vertically in front of the ruler. Direct him or her to shift it to the left or right along the ruler, until it appears to you to lie directly behind the thin object. (You may want to call out "shift four inches to the left," or "shift just a quarter-inch to the right," to help your assistant to move quickly to the correct position. However, if you find that speaking while measuring causes your head to move too much, then use a set of hand signals to indicate "shift left," "shift right," "make smaller shifts (getting close)," and "stop.") When you are happy with the position of the pencil, have your assistant write a small "1" at exactly this position along the ruler. Now switch to your other eye, and have your assistant write a second "1" at the matching position along the ruler.

Your assistant can now measure the distance between the two "1"s on the ruler with the tape measure, and read it off to you in inches. (If your assistant is too young to do this with confidence, you can come up to the ruler to help him or her with this task.) Estimate the shift in position to within a fraction of an inch – your measurements might be 2.3 inches or 2 3/4 inches, rather than just 2 or 3 inches. Write down this number in the first column of the first line of Table 5.3.

Now repeat this measurement (the apparent shift against the wall ruler) with the thin object placed at Positions 2 and 3, marking the ruler with small "2" and "3" symbols. Remember to leave the coins undisturbed at their positions, so that you can go back to them later. Record these data in the second and third lines of the first column (labeled Trial 1) of Table 5.3. Then have your assistant carefully cross out the two "1"s, the two "2"s, and the two "3"s on the ruler, so that they will not be confused with later marks.

Once you have made your measurements once for all three objects, return the thin object to the first position and repeat your measurements two more times. Be sure that you go through one full set of measurements (closest, middle, and farthest distances) before you repeat the process. You will perform each measurement three times, recording the data in the columns for Trial 1 through Trial 3, to estimate how repeatable your measurements are.

DO NOT perform all three measurements of any object at the same time – that would defeat the purpose of taking three independent measurements.

If your assistant is curious, you may switch places and let him/her take a set observations! However, do not enter them into Table 5.3 unless your assistant has exactly the same size head (the distance between the eyes, or "baseline," as labeled in Figure 5.2) as you do – can you see why?

Estimate the *uncertainty* in your measurement of the object's apparent shift. For example, do you think your recorded measurements could be off by a foot? An inch? A quarter of an inch? Compare the measurements made at each position from trial to trial, to help you estimate the reliability of your measurements. (2 points)

5.2.3 Dependence of parallax on vantage point separation

Now that we understand how the apparent shift of an object changes as its distance from the observer changes, let's explore what happens when the distance between the vantage points changes.

What would happen if the vantage points were farther apart? For example, imagine that you had a huge head and your eyes were two feet rather than several inches apart. How

Table 5.3: Parallax Measurements

Record all measurements in fractions of inches, or in fractions of degrees.			
	Trial 1	Trial 2	Trial 3
Eye-to-eye shifts (apparent linear shifts) along parallax ruler for objects, in inches.			
Position 1			
Position 2			
Position 3			
Measuring the entire parallax ruler. *Record the number of degrees per inch to three decimal places (n.nnn).*			
Angular width (degrees) Avg:			
Linear width (inches)		Degrees per inch	
Eye-to-eye shifts (apparent angular shifts) along parallax ruler for objects, in degrees.			
Position 1			
Position 2			
Position 3			
Baseline (inches) Avg:			

(9 points)

would you expect the apparent shift of the object relative to the parallax ruler to change? (Note that there is no wrong answer to this question. The point is to take a guess, and then to verify or to disprove it.) (1 point)

Repeat the experiment with the object at its farthest distance, but this time measure the apparent shift by using just one eye, and moving your whole head roughly one foot to each side to get more widely separated vantage points.

By how many inches did the object move using the more widely separated vantage points? _______________. (1 point)

For an object at a fixed distance, how does the apparent shift change as you observe from more widely separated vantage points? (1 point)

5.2.4 Measuring distances using parallax

We have seen that an object's apparent shift relative to background objects (such as the parallax ruler) depends both on the distance between the object and the observer and on the separation between the observer's two vantage points. We can now turn this around: if we can measure the apparent shift and the separation of the two vantage points, we should be able to calculate the distance to an object. This is very handy, as it provides a way of measuring distance without actually having to go all the way to an object. Since we cannot travel to the stars, this is an excellent way to measure their distances from us.

We will now see how parallax can be used to determine the distances to the objects in your experiment based only on your measurements of their apparent changes in position ("apparent shifts") and the measurement of the separation of your two vantage points (your two eyes), your "baseline."

Angular shift

As we now know, the apparent shift of the object across the parallax ruler is caused by looking at the object from two different vantage points, in this case, from the different positions of your two eyes. Qualitatively, what do you see changing from eye to eye? As an object gets farther away from you, is its apparent shift smaller or larger? (1 point)

Up until this point, we have measured the apparent shift in inches along our parallax ruler. Since this is truly a length measurement, we can refer to this as an apparent "linear" shift. Are inches, however, really the most appropriate units? The linear shifts that we have measured actually depend on the distance of the parallax ruler from us. If we had placed our parallax ruler farther away, the actual number of inches that the object would have appeared to move along the ruler would have been larger. Consider what would happen to the measured "eye-to-eye shift" in Figure 5.2 if the ruler were moved farther to the right (farther away from the observer).

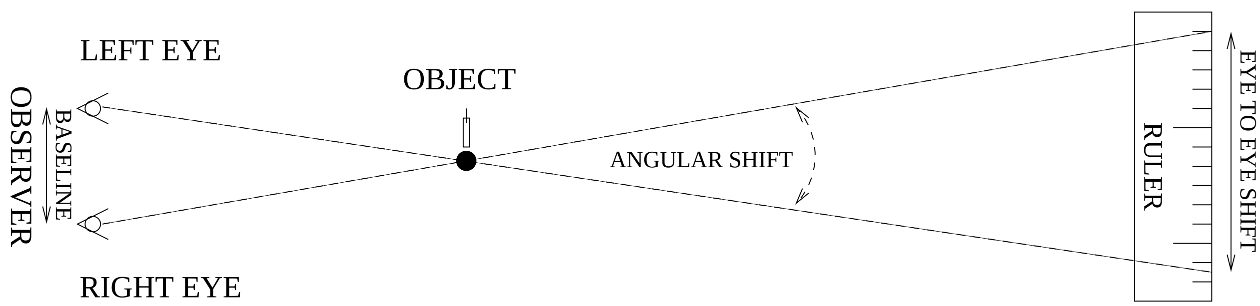


Figure 5.2: Layout of the parallax experiment, defining the baseline, angular shift, and eye-to-eye shift.

A much more useful measurement is the apparent "angular" shift of the object, the *angle* by which the object shifts relative to the background. As can be seen in Figure 5.2, the angular shift does not depend on the location of the background.

The apparent angular shift is measured in *degrees*, where 360 degrees make up a full circle. How do we measure the apparent angular shift for our object at its three positions?

First, let's get a qualitative feel for what to expect. Let's revisit the question posed at the beginning of this section: As an object moves farther away from the observer, does its apparent shift increase or decrease?

To check your answer, consider the apparent angular shift for the two objects shown in Figure 5.3. Use the protractor provided at the end of this lab chapter to measure the apparent shift for each object. If you are not sure how to use your protractor, see the section below. (You should measure angles of roughly 12 and 19 degrees.) Is the apparent shift larger for Object 1 or for Object 2? Check your answer to the previous question. (1 point)

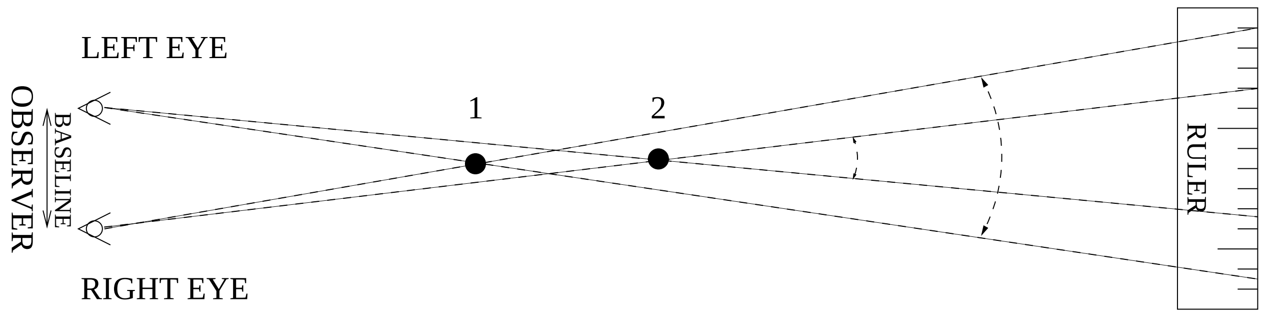


Figure 5.3: Layout of the parallax experiment, comparing the angular shift for objects at two positions.

Using your protractor

The “origin” of your protractor is the center of the circle with the dot in the middle. To measure the apparent angular shifts for the objects in Figure 5.3, center the origin of the protractor on the dot marking the object. Line up the bottom edge of the protractor (the 0–180 degree line) along the downward-sloping dotted line for the object. Read off the angle of the upward-sloping dotted line for the same object. Be careful that you are reading off the angle for the correct line. For Object 1, you should be measuring the angle between the two outer lines; for Object 2, you will be measuring the angle between the two inner lines.

You may find that it will be easier to read off the angles by holding the figure and protractor up to a bright light or against a window.

Determining the apparent angular shift

In order to determine the apparent angular shifts of our object at the three different positions, let us first figure out the angular separation of the inch marks on the parallax ruler as seen from your observation spot. To do this, you will need your protractor and the long piece of string. Hold the end of the string at your coin on the “observation spot.” Ask your assistant to take the end of the string that was under the center of the parallax ruler and hold it on the ground directly below one end of your parallax ruler. Pull the string taut. Now carefully place the protractor on the ground underneath the string, and align it so that 0 degrees lies exactly along the string. The origin of the protractor should be centered on your observation spot.

Now, holding the string and protractor stationary at the observation spot, ask your assistant to move his/her end of the string to the other end of the parallax ruler. Carefully read off the angle of the string at its new position, and record it the next line of Table 5.3. Record each value to the nearest thousandth of a degree, writing 0.213 or 0.245 rather than just 0.2, for example.) Repeat this procedure three times, then average your measurements to obtain an estimate of the uncertainty of your measurement technique. Record the average value in the box under "measuring the entire parallax ruler" marked "angular width (degrees)" in Table 5.3.

To determine the angle equivalent to a one-inch length along the ruler, divide (the total angle covered by the entire ruler) by (the total number of inches along the ruler). Record these numbers in Table 5.3.

You can now convert your measurements of apparent *linear* shift at each position (in inches) to apparent *angular* shift (in degrees) by multiplying the number of inches the object shifted at each position by the number of degrees per inch that you just calculated. Do so, and enter the numbers into the next three lines of Table 5.3.

Based on your estimate of the uncertainty in the number of inches each object moved, what is your estimate of the uncertainty in the number of degrees that each object moved? (1 point)

Distance between the vantage points (the "baseline")

You now need to measure the distance between your two different vantage points, the distance between your two eyes. Have your assistant measure this (carefully!) with a ruler. Since you observe the world out of the central pupil of your eyes (the dark region in the center of the eyeball), you want to measure the distance between the centers of your two pupils. As the measurement is made, try to hold your eyes still and focus on a point in the distance. Enter this value into Table 5.3 as the "baseline." Measure it three times, recording each value, and then also record the average value in the box under "eye-to-eye shifts" marked "baseline (inches)" in Table 5.3.

Tables 5.2 and 5.3 should now be complete (all empty spaces should contain numbers). Your assistant has done his/her part, and is free to go!

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 5.4.

The apparent angular shifts that you have just calculated correspond to the angle α on the diagram, and the distance between your pupils (your "baseline") corresponds to the distance b. The distance to the object, which you wish to determine, is d.

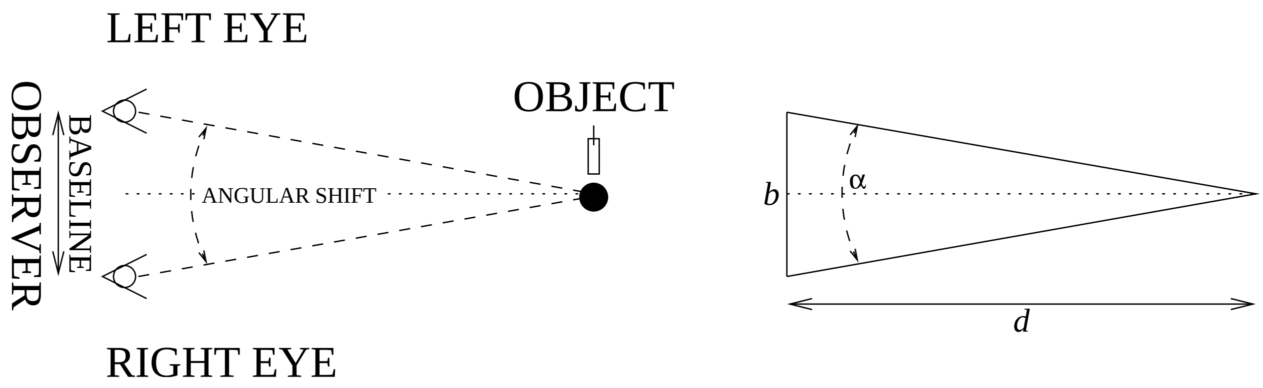


Figure 5.4: The parallax experiment, with real objects (left) and expressed mathematically (right). Can you find the same triangle on both sides?

There are two methods by which you can now calculate d. Method 1 involves a little bit of trigonometry, while Method 2 does not. You will use both methods to calculate the distance of your object in Trial 1 of Position 1. You will compare your results, and then proceed with one method for the rest of your distance calculations.

Method 1: The "Tangent" Way

The three quantities b, d, and α are related by a trigonometric function called the *tangent*. If you can't quite remember what a tangent is, don't worry – we will help you through this step-by-step and then show you how to do this using an easier (but slightly less accurate) way (Method 2).

To find the distance to an object using parallax the "tangent" way, first divide your triangle in half (along the dotted line in Figure 5.4b). This splits both the apparent angular shift, α, and your baseline, b, in half. The tangent of an angle described by a particular triangle is the ratio of the height to the length of the triangle. The tangent of $(\alpha/2)$ is thus equal to the quantity $\frac{(b/2)}{d}$:

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

Since you want to find the distance d, the equation can be rearranged to give:

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

To determine the tangent of an angle, use the *tan* button on your calculator. There are several other units for measuring angles besides degrees (such as radians), so **make sure that your calculator is set up to use degrees** for angles before you use the *tangent* function.

Just as a quick check, calculate $tan(10)$. You should get a value of 0.1763.

You are now ready to calculate d via the tangent method, from the angular shift and baseline measurements for Trial 1 of Position 1. Plug the numbers into the equation above, and record your answer here: ______________. (1 point)

Method 2: The Small Angle Approximation Way

Because the angles in astronomical parallax measurements are very small, astronomers do not have to use the tangent method to determine distances from angles – they can use the "small angle approximation" formula. If an angle θ is a small angle (less than 10 degrees), then

$$\tan(\theta) \approx \theta$$

where θ is measured in units of radians. Because there are 57.3 degrees in a radian, we can rewrite this relation as

$$\tan(\theta) \approx \frac{\theta}{57.3}$$

if we wish to express θ in degrees rather than radians. (There are 2π radians, or 360 degrees, in a full circle. The ratio of 360 to 2π is 57.3, so there are 57.3 degrees in a radian.) Replacing $\tan(\alpha/2)$ with $(\alpha/2)/57.3$ in our expression for $\tan(\alpha/2)$, we see that it becomes

$$\frac{(\alpha/2)}{57.3} \approx \frac{(b/2)}{d}.$$

In this equation, α, b, and d are the same angle and distances, respectively, as in the earlier equations (and in Figure 5.4). Rearranging the equation to find d gives:

$$d \approx \frac{57.3 \times (b/2)}{(\alpha/2)} \approx 57.3 \times \frac{b}{\alpha}.$$

Remember that to use this equation your angular shift "α" must be measured in degrees.

Calculate d using the Small Angle Approximation method for Trial 1 of Position 1 by plugging in the appropriate numbers in the equation above. Record your answer here: ______________. (1 point)

To compare the two methods, let's calculate the "percent error" between the values that you got from the two different methods: (2 points)

$$\%\ \text{error} = \frac{|\text{Value 1} - \text{Value 2}|}{\text{Value 1}} \times 100.$$

Where Value 1 is measured with the more accurate Method 1, and Value 2 is derived using the Small Angle Approximation. How close were your two values? (1 point)

Now that you have shown that the two methods yield similar answers, choose your favorite method to calculate the rest of your parallax-derived distances.

Use the measurements that you recorded in Table 5.3 and the equation for your method of choice to calculate the distance of the object for all three Trials of each Position of the object. The units of the distances which you determine will be the same as the units you used to measure the distance between your eyes; in this case, inches. Record these values in Table 5.4.

Table 5.4: Parallax-Derived Distances

	Trial 1	Trial 2	Trial 3
Parallax-derived distances from observer to object, in inches (nn.nn).			
Position 1			
Position 2			
Position 3			

(3 points)

Based on your estimate of the uncertainty in the angular measurements and the uncertainty of your measurement of the separation of your eyes, estimate the uncertainty in your measurements of the object distances. (Note that there is no wrong answer to this question. The point is to take a guess, and then to verify or to disprove it.) (1 point)

Now look at the spread in the three values for each position in Table 5.4. Is this spread consistent with your estimated uncertainty? (1 point)

How good are your parallax-derived distances?

At this point, you are ready to average your distance measurements together, and compute an error. Access the plotting tool listed for this lab exercise from the GEAS project lab exercise web page (see the URL on page 70 in §5.1.2). Use the plotting tool to create histograms of your distance measurements, entering the three values measured in Trials 1 through 3 for each quantity in turn. You will not need to save the histogram plots. Instead, simply record the averaged values shown for each plot (labeled "mean value"), and the associated errors. In order to see how good your distance measurements are, you will calculate these averages and errors for each of the quantities recorded three times in Table 5.2 and Table 5.4. Copy these values into Table 5.5.

Just for fun, let's consider how these errors are calculated. Though you will not need to reproduce this calculation yourself, it is helpful to understand how it works.

We can calculate the average value of a set of measurements by adding the numbers together and then dividing by the total number of measurements. Mathematically, we say: *for n data points, we sum the n values and divide by n.* Here is how we write that as an equation:

$$\bar{v} \equiv \tfrac{1}{n} \sum_{i=1}^{n} v_i .$$

Having found the average value, $\bar{v}$, we would now like to know how accurate it is. We will assume that the scatter, or spread, in the measured values reflects the dominant source of error. To calculate this, we will compare each measurement in turn to the average value, and see how far off each one lies.

Mathematically, we say: *for n data points, we calculate the offset of each point from the average value, we square the offsets, we divide their total by $n-1$, and then for the grand finale we take the square root of the result.* Here is how we write that as an equation:

$$s \equiv \sqrt{\tfrac{1}{n-1} \sum_{i=1}^{n} (v_i - \bar{v})^2} .$$

Let's work through a quick sample case with real numbers. Say that you measured the distance to an object, and recorded values of 11.6, 11.9, and 12.1 inches. We can now calculate the average value, $\bar{v}$:

$$\bar{v} = \tfrac{1}{3}\,(11.6 + 12.1 + 11.9) = 11.87 \text{ inches},$$

and the standard deviation (the error), s:

$$s = \sqrt{\tfrac{1}{2}\left[(11.6 - 11.87)^2 + (12.1 - 11.87)^2 + (11.9 - 11.87)^2\right]} = 0.25 \text{ inches}.$$

Your value for the distance is 11.87 ± 0.25 inches! Go ahead and enter "11.6, 12.1, and 11.9" into the plotting tool and plot a histogram of their distribution, to verify these values.

Now compare the distances that you calculated for each position using the parallax method to the distances that you measured directly at the beginning of the experiment (see Table 5.2). How well did the parallax technique work? Are the differences between the direct measurements and your parallax-derived measurements within your errors? (1 point)

If the differences are larger than your errors, can you think of a reason why your measurements might have some additional error in them? We might call this a "systematic" error, if it is connected to a big approximation in our observational setup. *Hint: astronomers can measure parallax angles to stars which are 100 parsecs away, using background stars which are 10,000 parsecs away. Was your background ruler 100 times farther away from you than Position 3 was? If you focused very carefully on a single thin black line on the parallax ruler, would it shift position slightly when viewed through one eye or the other against the distant horizon?* (3 points)

Table 5.5: Comparison of Average Distances

	Direct Distance (from Table 5.2)	Parallax Distance (from Table 5.4)	% error
Measured and parallax-derived distances from observer to object, in inches. Record the average values of the three trials, and the errors calculated with the plotting tool in this form: nn.nn $\pm$ n.nn.			
Position 1			
Position 2			
Position 3			

(3 points)

Calculate the percent error between the parallax-derived and directly measured distances using the equation provided earlier, and enter it into Table 5.5. Does this percent error seem reasonable, given your measurement errors and your systematic errors? (1 point)

5.3 Calculating Astronomical Distances With Parallax

Complete the following section, answering the five questions in turn. (Each question is worth either 1 or 2 points.)

5.3.1 Distances on Earth and within the Solar System

We have just demonstrated how parallax works in the classroom, so now let us move to a larger playing field. Use the small angle approximation to determine the angular shift (in degrees) for Organ Summit, the highest peak in the Organ Mountains, if you observed it first with one eye and then the other from NMSU. Organ Summit is located 12 miles (20 kilometers) from Las Cruces. (*If you are working from another location, select a mountain, sky scraper, or other landmark at a similar distance to use in place of the Organ Summit.*) There are 5,280 feet in a mile, and 12 inches in a foot. There are 1,000 meters in a kilometer. (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 could we create a bigger baseline? Surveyors use a "transit," a small telescope mounted on a (fancy!) protractor, to carefully measure angles to distant objects. By positioning the transit at two different spots separated by exactly 300 feet (and carefully measuring this baseline), they will observe a much larger angular shift. Recall that when you increased the distance between your two vantage points by moving your head from side to side to view your object, the angular shift increased. What this means, then, is that, if an observer has a larger baseline, an object can be farther away from the observer yet still have a measurable shift. With a surveyor's transit's 300-foot baseline, it is thus fairly easy to measure the distances to faraway trees, mountains, buildings or other large objects here on Earth.

What about an object farther out in the solar system? Consider Mars, the planet that comes closest to the Earth. At its closest approach, Mars comes to within 0.4 A.U. of the Earth. (Remember that an A.U. is the average distance between the Earth and the Sun, or 149,600,000 kilometers.) At such a large distance we will need an even larger baseline than a transit could provide, so let us assume we have two telescopes in neighboring states, and calculate the parallax angle for Mars (using the small angle approximation) for a baseline of 1000 kilometers. (2 points)

Wow! Again, a very small angle.

5.3.2 Distances to stars, and the "parsec"

The angular shifts for even our closest neighboring planet are clearly quite small, even with a fairly large baseline. Stars, of course, are *much* farther away. The nearest star is 1.9×10^{13} miles, or 1.2×10^{18} inches, away! At such a tremendous distance, the apparent angular shift is extremely small. When observed through the two vantage points of your two eyes, the angular shift 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 eye.

Like geological surveyors, we can improve our situation by using two more widely separated vantage points. In order to separate our two observations as far as possible from each other, we will take advantage of the Earth's motion around the Sun. The Earth's orbit forms a large circle around the Sun, and so by observing a star from first one position and then waiting six months for the Earth to revolve around to the other side of the Sun, we will achieve a separation of two A.U. (twice the distance between the Earth and the Sun). This is the distance between our two vantage points, labeled b in Figure 5.5.

An A.U. (astronomical unit) is equal to 1.496×10^8 kilometers, so b is equal to twice that, or 299.2 million kilometers. Even though this sounds like a large distance, we find that the apparent angular shift (α, in Figure 5.5) of even the nearest star is only about 0.00043 degrees. This is unobservable by eye, which is why we cannot directly observe parallax by looking at stars with the naked eye. However, such angles are relatively easy to measure using modern telescopes and instruments.

Let us now introduce the idea of angles that are smaller than a degree. Just as a clock ticks out hours, minutes, and seconds, angles on the sky are measured in degrees, arcminutes, and arcseconds. A single degree can be broken into 60 arcminutes, and each arcminute contains

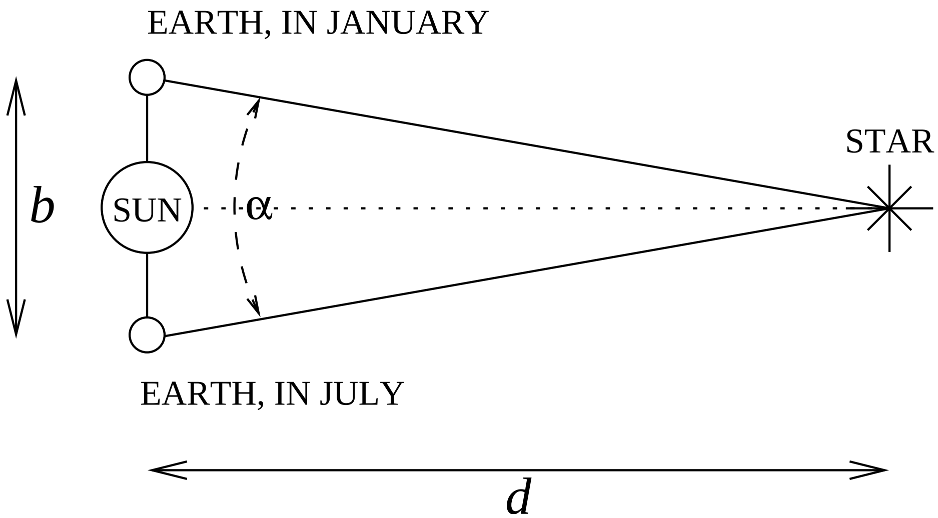


Figure 5.5: The parallax experiment, as done from Earth over a period of six months.

60 arcseconds. An angular shift of 0.02 degrees is thus equal to 1.2 arcminutes, or to 72 arcseconds. Since the angular shift of even the nearest star (Alpha Centauri) is only 0.00043 degrees (1.56 arcseconds), we can see that arcseconds will be a most convenient unit to use when describing them. Astronomers append a double quotation mark ($''$) at the end of the angle to denote arcseconds, writing $\alpha = 1.56''$ for the nearest star.

Remember that when converting an angle into a distance (using either the tangent or the small angle approximation), we used the angle $\alpha/2$ rather than just α. When astronomers talk about the "parallax" or "parallax angle" of a star, they use this angle: $\alpha/2$. For easier reference, we will give this angle its own symbol, "θ," so the small angle approximation equation now becomes:

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

It is now time to introduce a new distance unit, the "parsec." How far away is a star with parallax angle of $\theta = 1''$? The answer is 3.26 light-years, and this distance is defined to be one parsec. The word parsec comes from the phrase "**par**allax **sec**ond." By definition, an object at 1 parsec has a parallax of $1''$.

An object at 10 parsecs has a parallax angle of $0.1''$. Remember that the farther away an object is from us, the smaller its parallax angle will be. The nearest star has a parallax of $\theta = 0.78''$, and is thus at a distance of $1/\theta = 1/0.78 = 1.3$ parsecs. To convert parsecs into light years, you simply multiply by 3.26 light-years/parsec.

You might read the words parsec, kiloparsec, megaparsec and even gigaparsec in this class. These names 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 a whopping one billion parsecs! The parsec may seem like a strange unit, but you have probably already encountered a few other strange units this semester!

Let's go through a couple of examples:

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

- If a star is 5 parsecs away from Earth, what is its parallax angle? (1 point)

- If a star lies 5 parsecs from Earth, how many light-years away is it? (1 point)

5.4 Final (post-lab) Questions

1. How does the parallax angle of an object change as it moves away from us? As we can only measure angles to a certain accuracy, is it easier to measure the distance to a nearby star or to a more distant star? Why? (3 points)

2. Relate the experiment you did in the first part of this lab to the way that parallax is used to measure the distances to nearby stars. Describe the process an astronomer goes through to determine the distance to a star using the parallax method. What did

your two eyes represent in the experiment? (5 points)

3. Imagine that you observe a star field twice, with a six month gap between your observations, and that you see the two sets of stars shown in Figure 5.6:

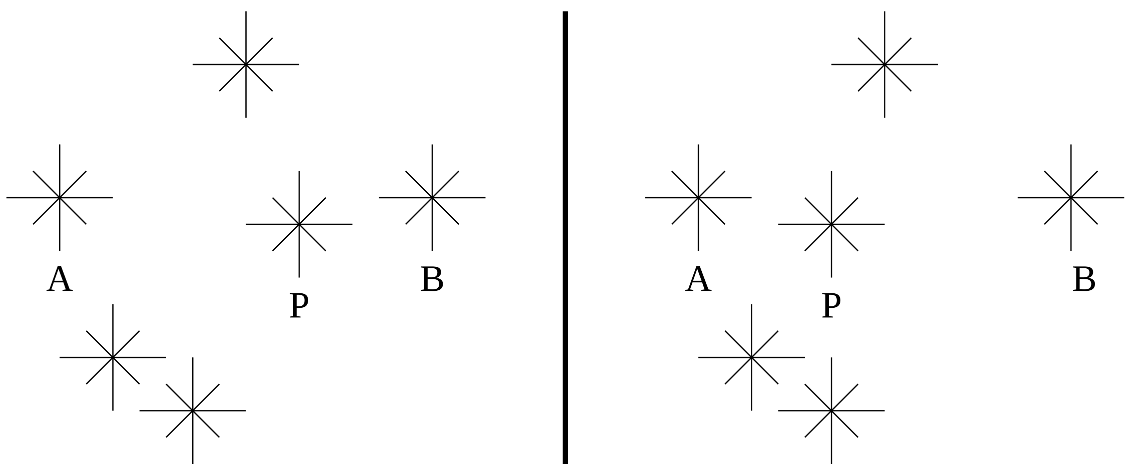


Figure 5.6: A star field, viewed from Earth in January (left) and again in July (right). Which star do you think lies closest to Earth?

The nearby star marked P appears to move between the two images, because of parallax. Consider the two images to be equivalent to the measurements that we made in our experiment, where each image represents the view of an object against the parallax ruler as seen through one of your eyes. All the stars except P do not appear to change position; they correspond to the background ruler in our experiment.

If the angular distance between Stars A and B is 0.5 arcminutes (recall that 60 arcminutes = 1 degree), then how far away would you estimate that Star P lies from Earth?

First, estimate how far Star P has moved between the two images relative to the constant distance between Stars A and B. This tells you the apparent angular shift of P. You also know the distance between the two vantage points (the Earth at two opposite points along its orbit) from the number given in Section 5.3.2. You can then use either the tangent or the small angle approximation parallax equation to estimate the distance to Star P. Remember that you need to convert the angle from arcminutes to degrees (by dividing by 60 arcminutes/degree) before you plug your angle into the equation. (7 points)

4. Imagine that when you performed your experiment, your assistant held an object all the way to the far wall, up against the parallax ruler. How big would the apparent shift of the object be relative to the marks on the ruler? What would you infer about the distance to the object? Why do you think this estimate would be incorrect? Where should the background objects in a parallax experiment be located? (4 points)

5.5 Summary

Summarize the important concepts discussed in this lab. Include a brief description of the basic principles of parallax and how astronomers use parallax to determine the distances to nearby stars. (35 points)

Be sure to think about and answer the following questions:

- Does the parallax method work for all of the stars we can see in our Galaxy? Why, or why not?
- Why is it so important for astronomers to determine the distances to the stars which they study?

Use complete sentences, and be sure to proofread your summary. It should be 300–500 words long.

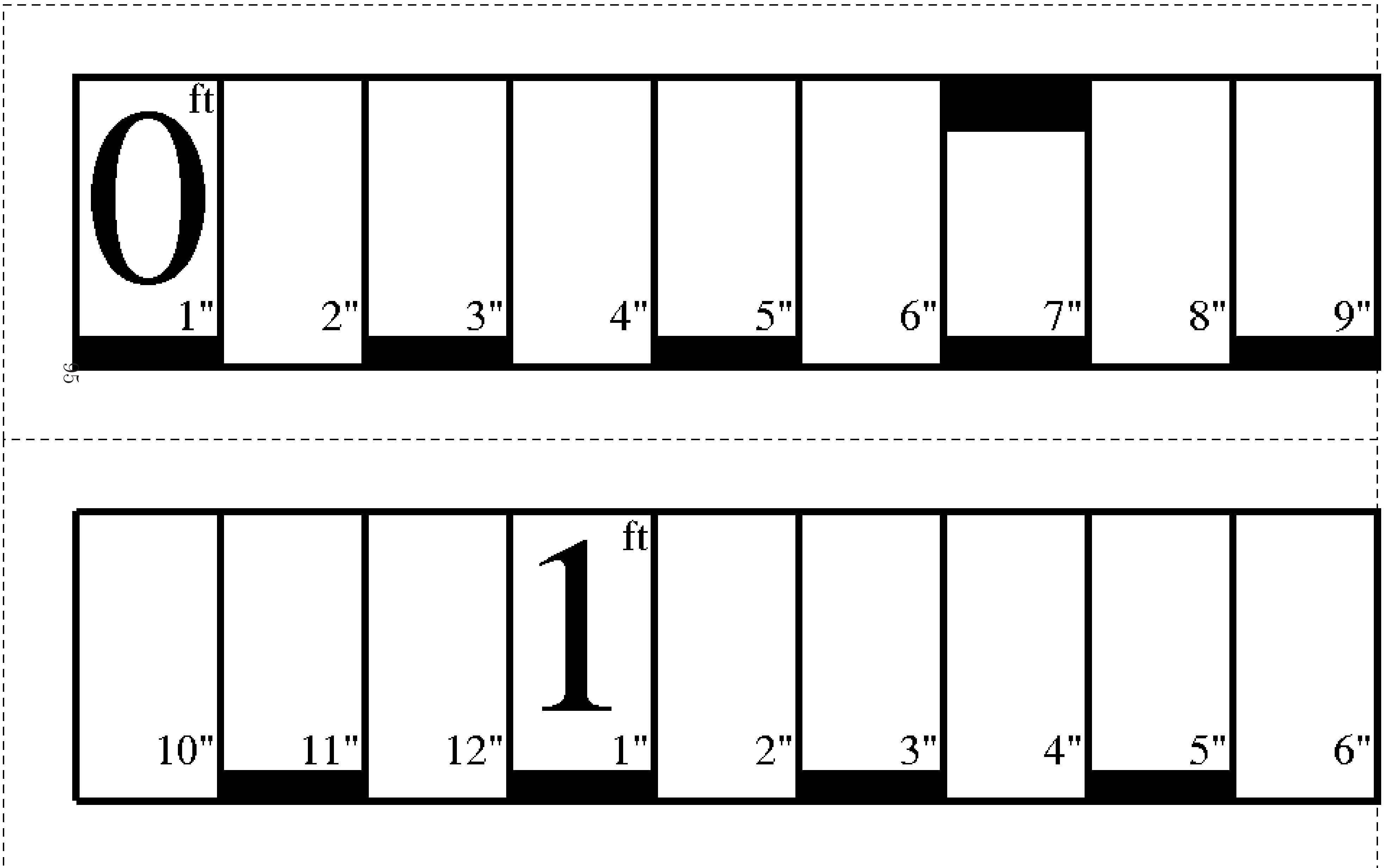
5.6 Extra Credit

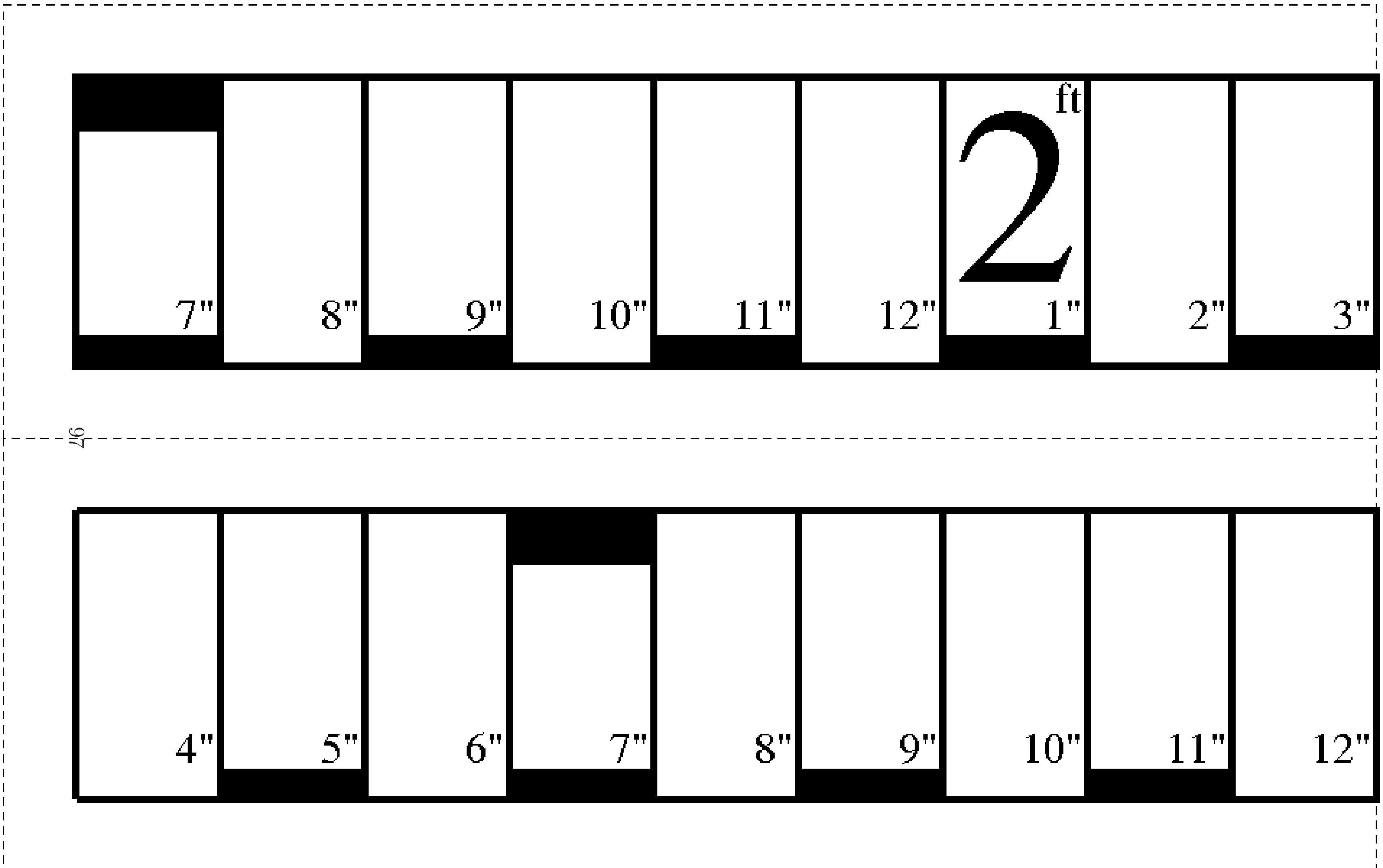
Use the web to learn about the planned Space Interferometry Mission (SIM). What are its goals, and how will it work? How accurately will it be able to measure parallax angles? How much better will SIM be than the best ground-based parallax measurement programs? Be sure that you understand the units of milliarcseconds ("mas") and microarcseconds, and can use them in your discussion. (4 points)

Be sure to cite your references, whether they are texts or URLs.

Parallax Ruler

Cut along dotted lines, and connect pieces with tape to form a six–foot ruler.

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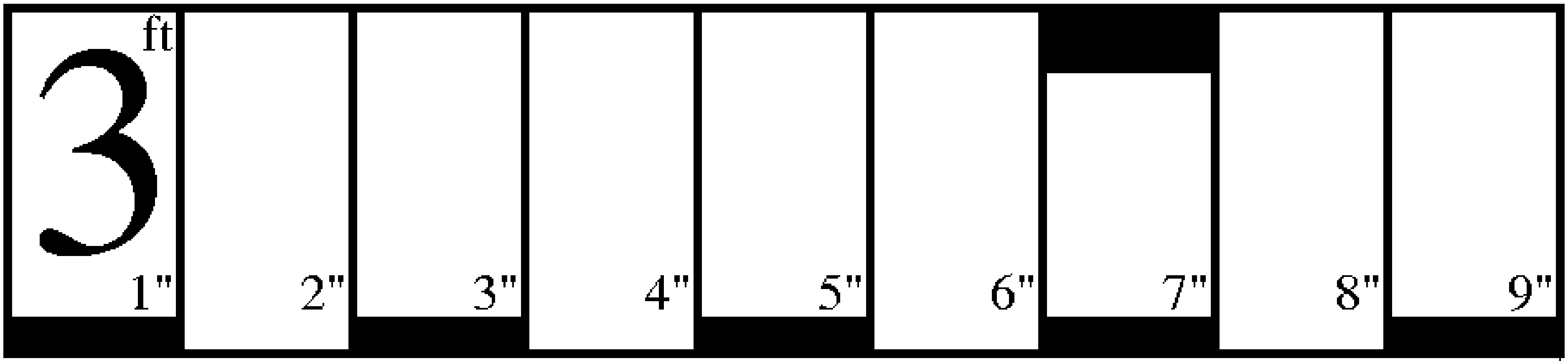
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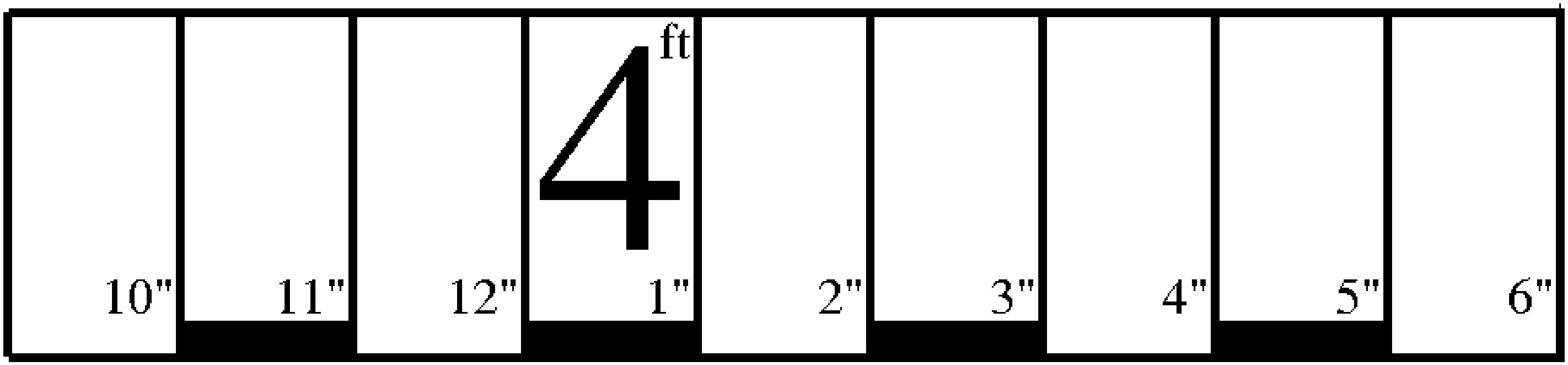
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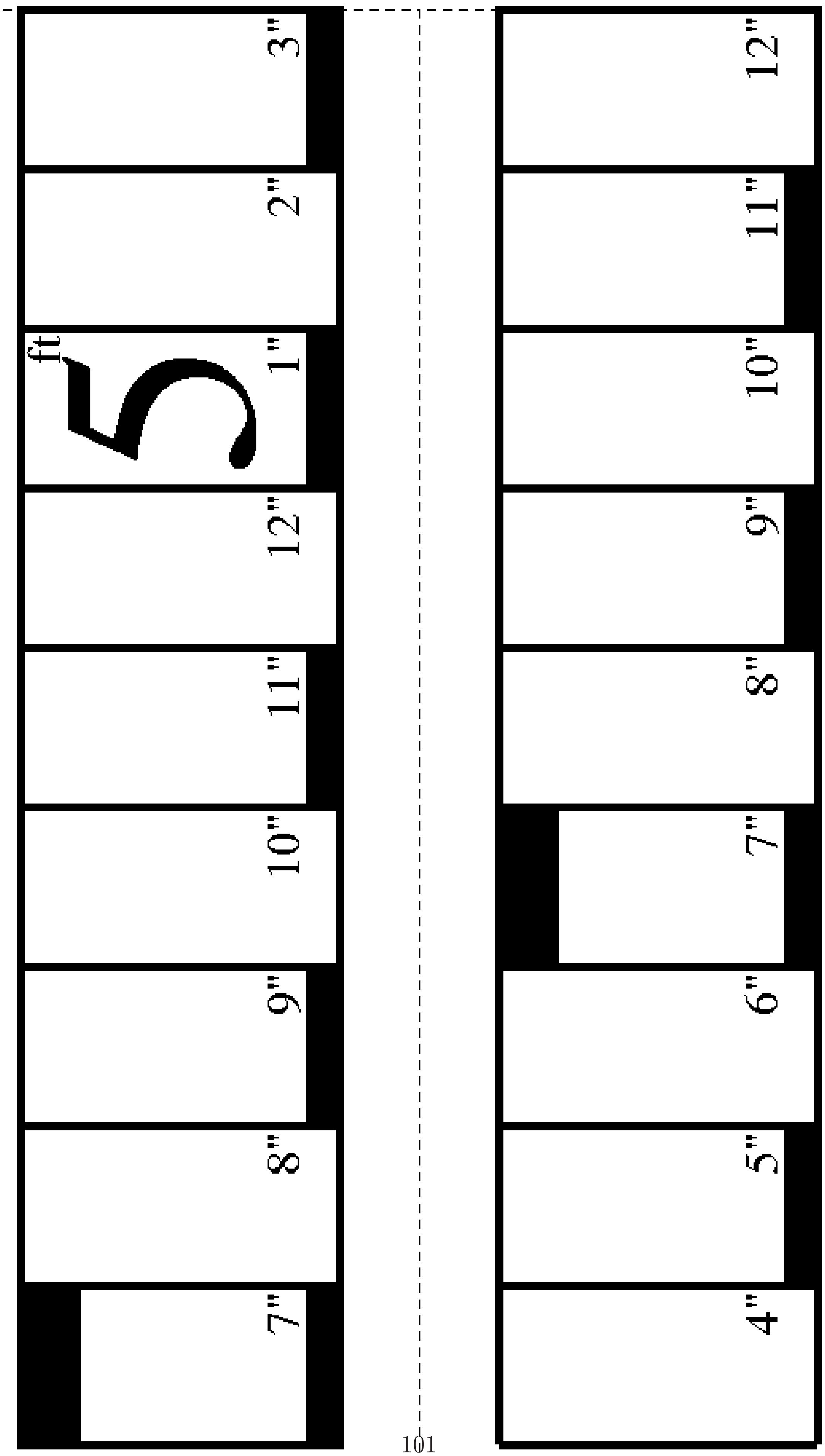
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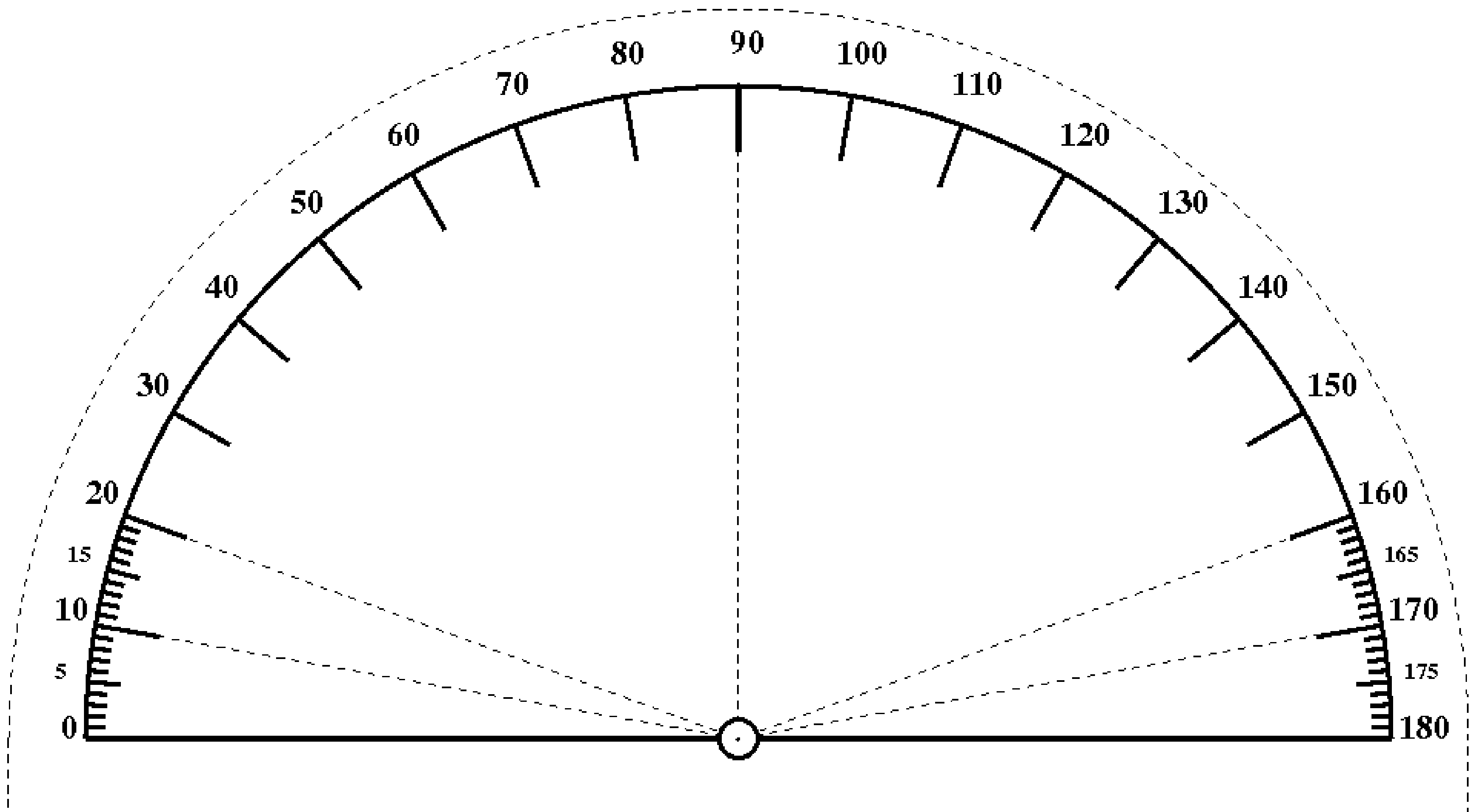
Protractor

Cut along dotted lines.



Name:

Lab 6

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

6.1 Introduction

In the first 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. We find that when the solar system was very young, there were many, many more small bodies floating around the solar system impacting the young planets and their satellites. 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

6.2 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, below.

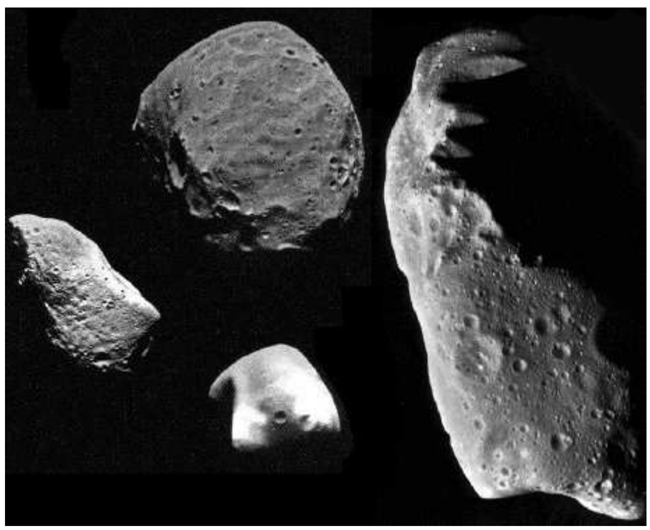


Figure 6.1: Four large asteroids. Note that these asteroids have craters from the impacts of even smaller asteroids!

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 6.2). Some asteroids, however, are in orbits 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.

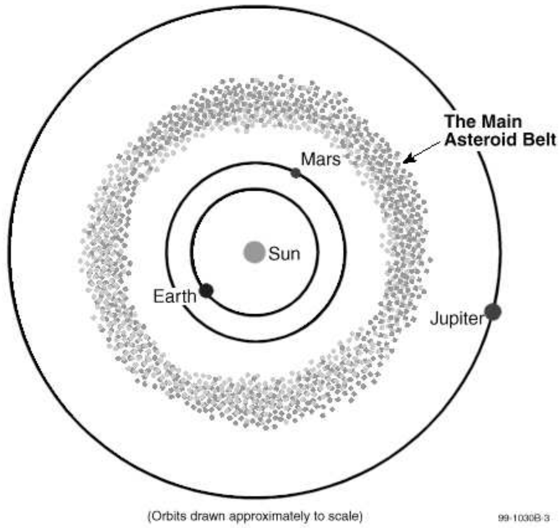


Figure 6.2: The Asteroid Belt.

6.3 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.

6.4 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."

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 the diagram, below.

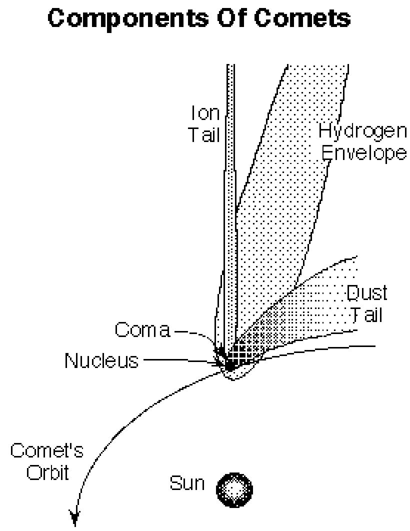


Figure 6.3: The main components of a comet.

6.5 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 $\sim$ 20,000 – 150,000 AU from the Sun. 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.

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. Kuiper Belt objects have only been definitely confirmed to exist in the last several years.

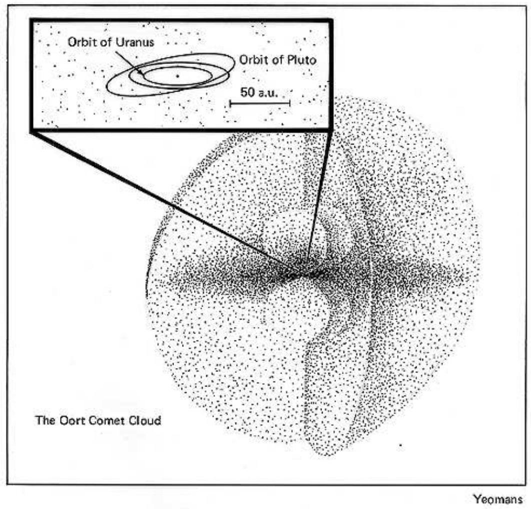


Figure 6.4: The Oort cloud.

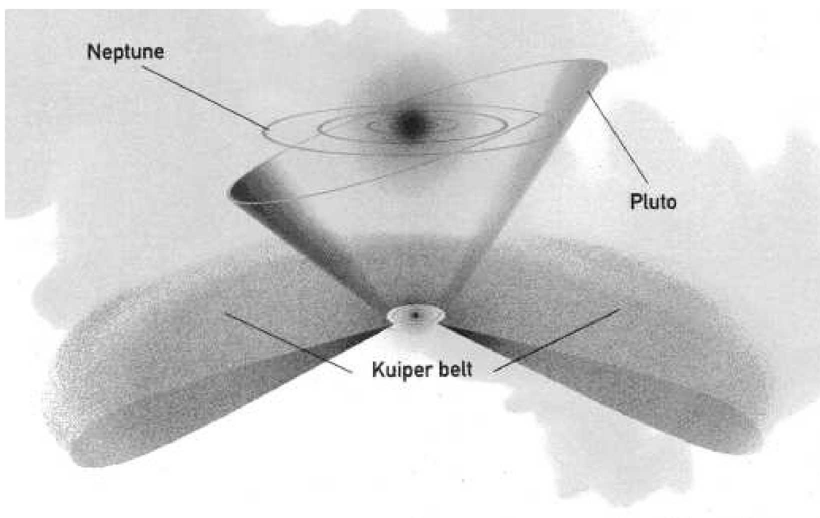


Figure 6.5: The Kuiper Belt.

6.6 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. = $1/2(mv^2)$, 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.

6.7 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 $v = (2a\mathrm{y})^{1/2}$. 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 collected on graph paper. Put the impact velocity on the *x axis*, and the crater diameter on the *y* axis. i *(10 points)*

6.7.1 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 affect your

results. How does the speed of the impacting body affect your results? What have you just proven? *(5 points)*

6.8 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 semseter!] *(1 point)*

6.9 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. Use a freezer bag to line the bottom of your bucket.
2. Place 1 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 lining!!)
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 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 using the plastic liner and shape it for a few seconds as if you were building a snowball (use gloves!).
10. Add 1/2 cup water and wait until mixture is frozen.
11. Unwrap the comet once it is frozen enough to hold its shape.

6.9.1 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 the light source (overhead projector) and place it on top. Observe what happens to the comet.

6.9.2 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.

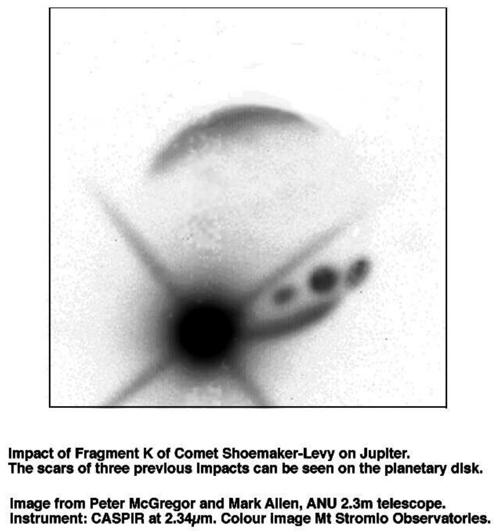


Figure 6.6: The Impact of "Fragment K" of Comet Shoemaker-Levy/9 with Jupiter.

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

6.9.3 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.). (*5 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? (*5 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? (*5 points*)

6. Which object do you think has more internal strength, an asteroid or a comet, and

why? (*3 points*)

6.10 Summary

(*30 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.

6.11 Extra Credit

Look up one (or more) of the following current spacecraft missions on the web and briefly describe the mission, its scientific objectives, and the significance of these objectives: (*2 points each*)

- Deep Impact (http://www.nasa.gov/mission_pages/deepimpact/)
- Spitzer (http://www.spitzer.caltech.edu/spitzer/index.shtml)
- Cassini (http://www.nasa.gov/mission_pages/cassini/main/index.html)
- Mars Rovers (http://www.nasa.gov/vision/universe/solarsystem/mer_main.html)

6.12 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?

Name:

Lab 7

Introduction to the Geology of the Terrestrial Planets

7.1 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. While the Jovian planets are giant balls of gas. Table 7.1 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 Lab #3).

Table 7.1: 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

Table 7.2: 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

It is clear from Table 7.1 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 7.2.

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 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.

7.2 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 7.1, 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 7.2. 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.

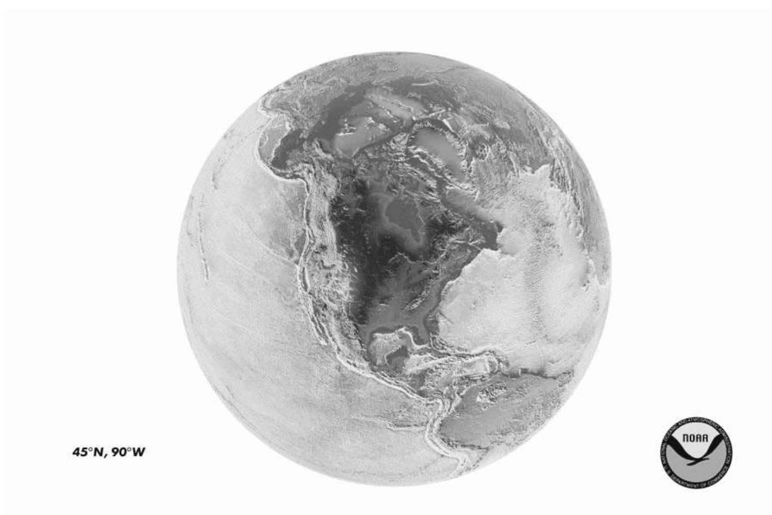


Figure 7.1: A topographic map showing one hemisphere of Earth centered on North America. In this 3D representation the continents are correctly rendered.

7.3 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. Note that Mercury has only been visited by a single space craft (Mariner 10) way back in 1974. So, we do not have the same quality of data for that planet–but new data will soon be coming from the Messenger spacecraft!

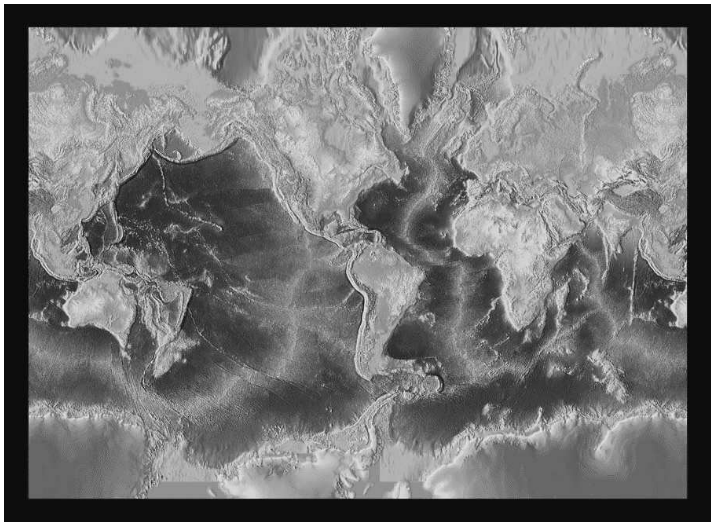


Figure 7.2: A topographic map showing the entire surface of the Earth. In this 2D representation, the continents are incorrectly rendered. Note that Antartica (the land mass that spans the bottom border of this map) is 50% smaller than North America, but here appears massive. You might also be able to compare the size of Greenland on this map, to that of the previous map.

Exercise #1: At station #1 you will find images of Mercury, Venus, the Earth, the Moon, and Mars. The images for Venus and the Earth are in a false color to help emphasize different features, while the image of Mars 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 planets are large meteorite impact craters obvious? *(1 point)*

2. Does Venus or the Earth show any signs of large, round maria (like those seen on 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 meteroids 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: Global topography of Venus, Earth, and Mars. At station #2 you will find topographic maps of Venus, the Earth, and Mars. 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, 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? *(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)*

7.4 Detailed Comparison of the Surfaces of the Terrestrial Planets

In this section 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, 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)*

7.5 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 Mounument, 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 resevoirs.]

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 dilineated 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)*

7.6 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 7.3, 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. 7.4), 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.

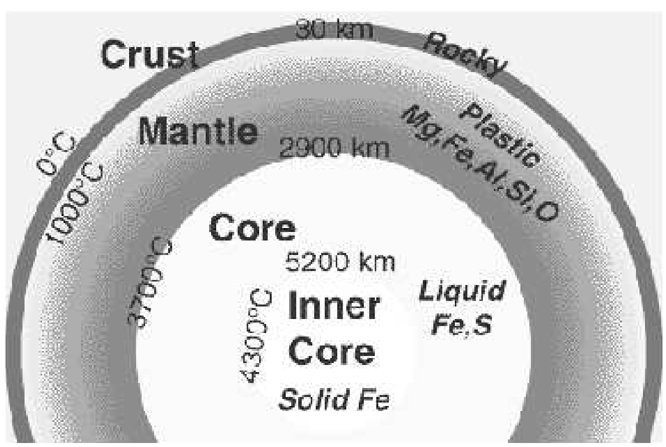


Figure 7.3: A cutaway diagram of the structure of the Earth showing the hot core, the mantle, and the crust. The core of the Earth is very hot, and is composed of both liquid and solid iron. The mantle is a zone where the rocks are partially melted ("plastic-like"). The crust is the cold, outer skin of the Earth, and is very thin.

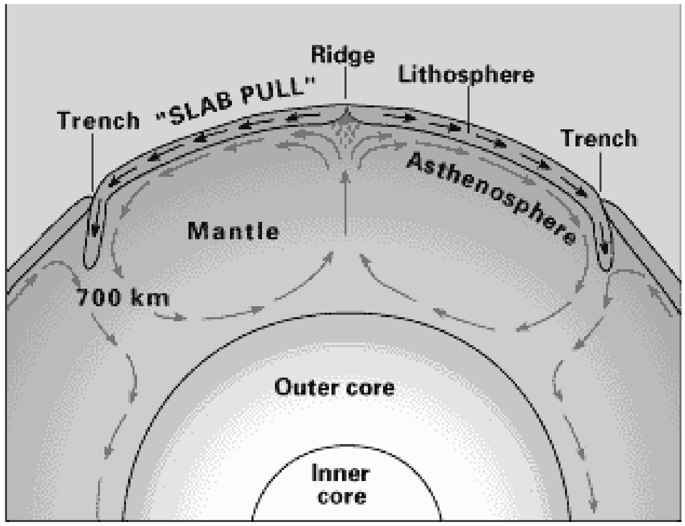


Figure 7.4: The escape of the heat from the Earth's core sets-up a boiling motion in the mantle. Where material rises to the surface it pushes apart the plates and volcanoes, and mountain chains are common. Where the material is cooling, it flows downwards (subsides) back into the mantle pulling down on the plates ("slab-pull'). This is how the large crustal plates move around on the Earth's surface.

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 distinct 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? *(2 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 exagerrated 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)*

7.7 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?

7.8 Extra Credit

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?*(2 points)*

7.9 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?

Name:

Lab 8

Optics

8.1 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 an optics kit and worksheet

- *Materials:* optics kit, ray trace worksheet, ruler

8.2 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 8.1 since they relate to the reflective (mirrors) and refractive (lenses) optics which will be discussed in this lab.

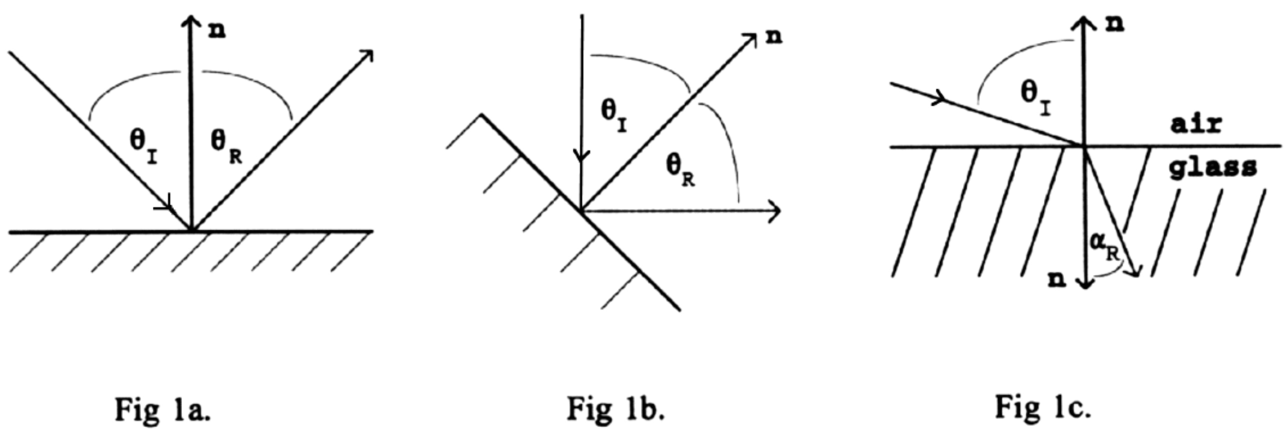


Figure 8.1: The definition of the "normal" direction **n**, and other angles found in optics.

- **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

8.3 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.

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. 9.1.a). Fill in the following table of angle of incidence vs. angle of reflection. *(3 points)*

Table 8.1: Data Table

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

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

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 sections 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 section 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 8.2. *(5 points)*

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 points)*

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 points)*:

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 points)*

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 point)*

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 point)*:

8.4 Refractive Optics: Lenses

OK, how about lenses? Do they work in a similar way?

At your table is an apparatus called an "optical bench". It is basically a meter stick with some lens holders and a source of light to allow you to mount various bits of optics and experiment with how lenses work. As with mirrors, there are two types of lenses: convex and concave. But in the case of lenses, you have two surfaces, so one side can be convex, and one side can be concave. Or, you can have both sides being convex, or concave. The latter types of lenses are called "double convex" and "double concave". We will be experimenting with these two types of lenses.

Mount the light source on the right hand end of the bench by sliding the shaft into the hole and clamping it tight with the small screw. Connect the light source to the battery or transformer using the alligator clips. Take the double convex lens (the larger of the two lenses) and mount it in the middle of the optical bench (tightening or loosing the clamping screw to allow you to slide it into the mounting hole, and the horizontal screw to hold it in place on the bench). At the opposite 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.

The focal length of the lens is: cm

Now replace the double convex lens with the double concave lens. Repeat the process. Can you find a focus with this lens? What appears to be happening? *(5 points)*

How does the behavior of lenses compare with the behavior of mirrors? Draw how light behaves when encountering the two types of lenses using Figure 8.3. Note some similarities and differences between what you have drawn in Fig. 8.2, and what you drew in Fig. 8.3 and write them in the space below. *(5 points)*

What can optics do for you?

Write down a list of different objects in your everyday experience which use optics. *(5 points)*

Consider a camera, binoculars, microscope, and telescope. What is the function of optics in each of these objects? *(5 points)*

Making Images

One important function of optics is to make images of things. In fact, your eyes contain small lenses that produce images on our retinas which allow us to see! This is also what a camera does (but instead of a retina, you have film, or a digital detector).

To make an image, optics takes the light which comes from an object and concentrates it all in one place. Considering your experiments with mirrors and lenses above, which shape of mirror and which shape of lens makes the light converge? *(5 points)*

To demonstrate how images are made, look at some object inside the classroom (such as an overhead light) or outside the window. Hold up a white piece of paper towards the object. Note that you cannot see the object on the paper! Now place the double convex lens in front of the paper; you should locate it about one focal length (measured above) in front of the paper. Can you see the image of your object?

8.5 Magnifying/Demagnifying

Another function of optics is to magnify or demagnify things, that is, to make them appear larger or smaller. Use your double concave and convex lenses to look at nearby objects (for example, the table top, or the lab manual, etc.) and see how magnification works. Experiment with placing the lens near to the object you want to look at and then move it farther away.

First try the convex lens. Does it magnify or demagnify? How does the magnification depend on the distance of the lens from the object? *(5 points)*

Next try the concave lens. Does it magnify or demagnify? How does the magnification depend on the distance of the lens from the object? *(5 points)*

Note that the behavior of magnification can get a bit complicated: it can change depending on both the location of the lens from the object and also how far your eye is from the lens. However, the behavior of a lens and its magnification actually follows a relatively simple mathematical behavior. We won't go into it here, but ask your instructor if you are curious about learning more.

Collecting Light

Finally we come to the main function of optics in astronomical telescopes, namely, to collect light. When optics are used to make images, light coming to different locations is all focussed to a single location. As a result, if you use a bigger optical element, you can collect more light into your image, and, as a result, make the image appear *brighter*. This is the main function of telescopes: to make faint objects appear brighter, and is the reason why telescope optics are so big. Astronomical objects are faint, so to get enough light, we collect light which is going to fall over a wide area and concentrate it all in a certain point.

To demonstrate this, use your convex lens to look at the outdoor object again. Now use a piece of paper to cover up a portion of the lens. How does the appearance of your image change as different portions of the lens are covered? *(5 points)*

8.6 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.

8.7 Extra Credit

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://www2.keck.hawaii.edu/geninfo/about.php). 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. How do you think the next generation of 30 or 100 m telescopes will be built, like Gemini, or Keck? Why? *(4 points)*

8.8 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?

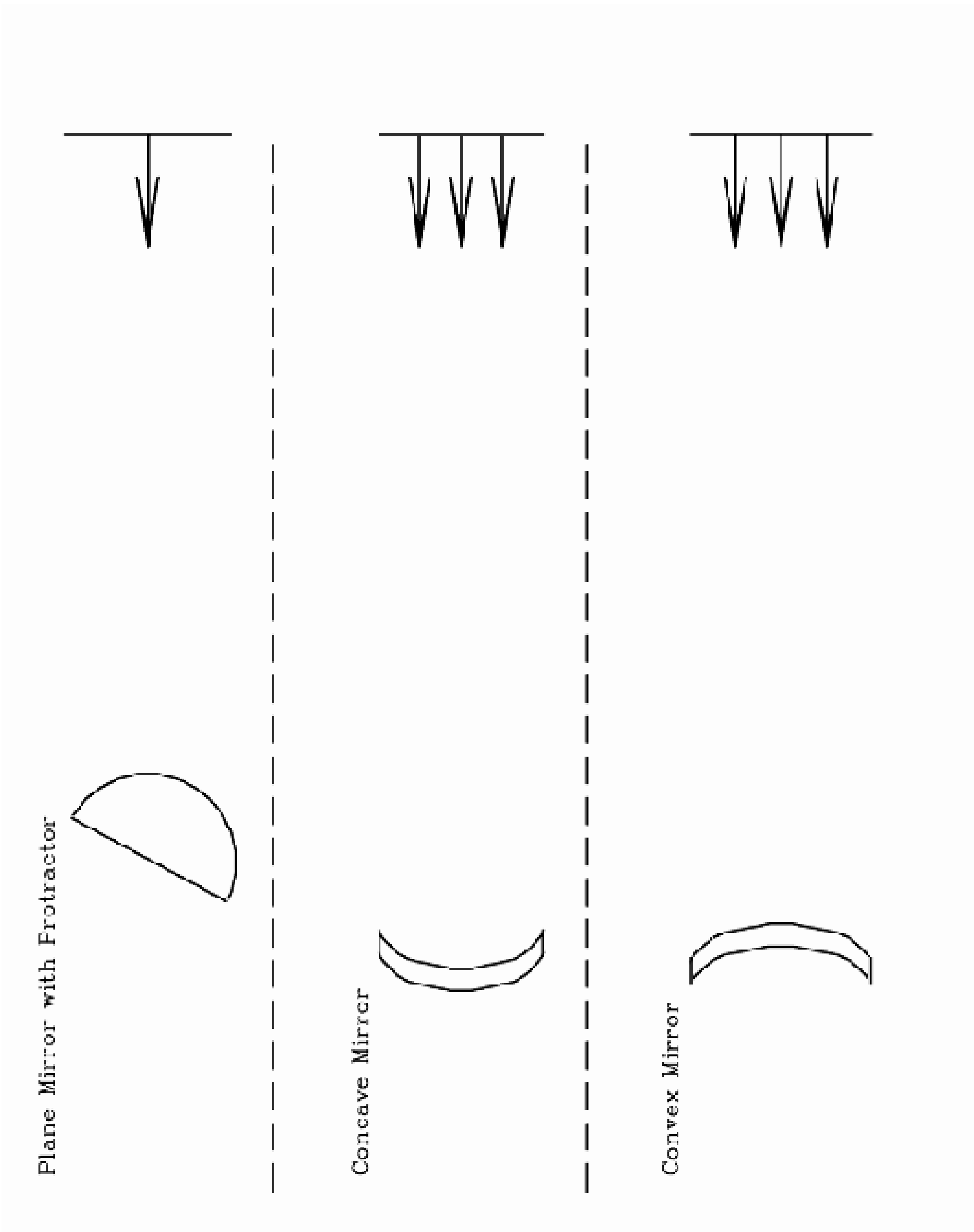


Figure 8.2: The worksheet needed in section 8.2

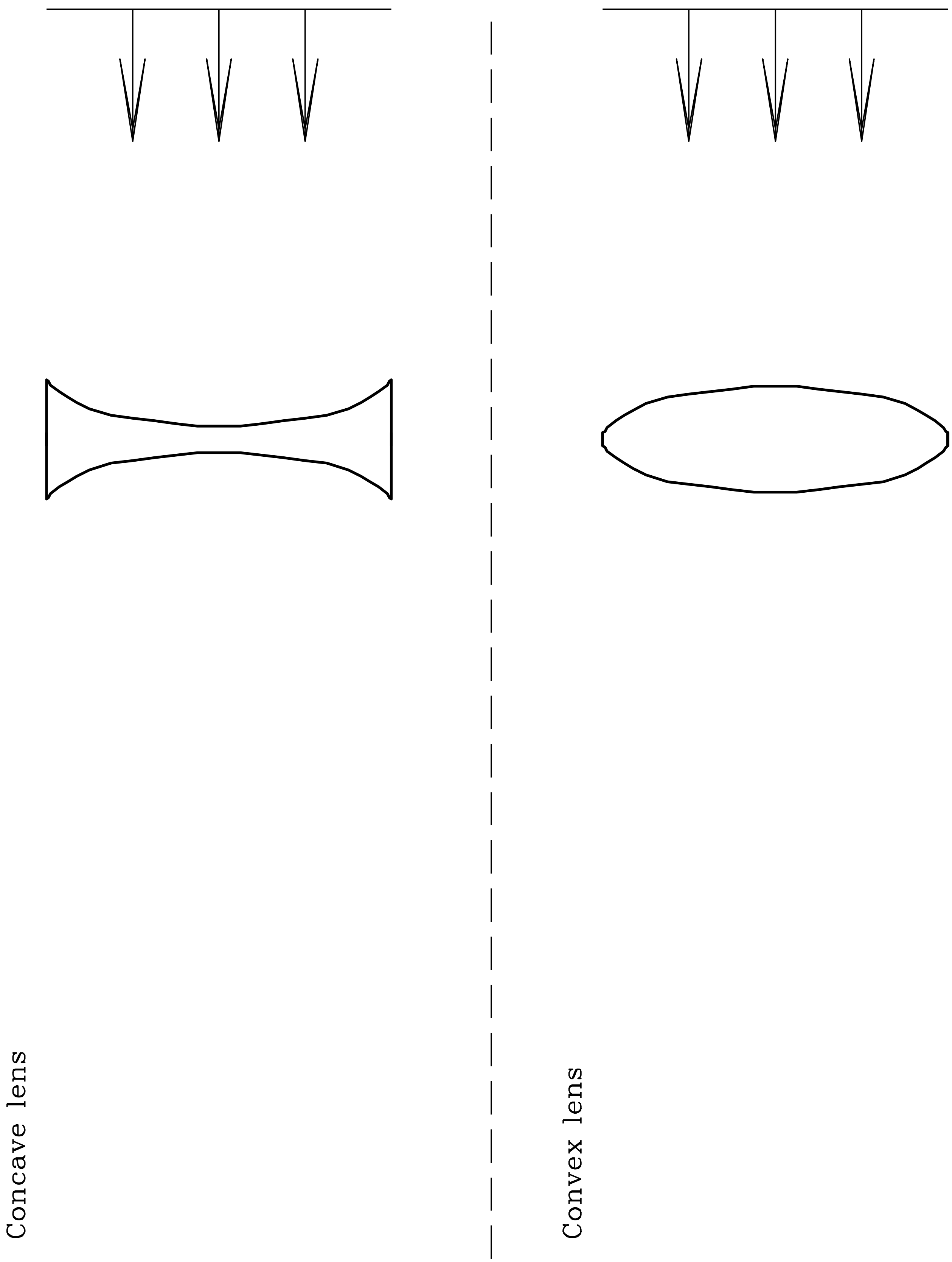


Figure 8.3: The worksheet needed in section 8.3

Name:

Lab 9

The Power of Light: Understanding Spectroscopy

9.1 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 quanititative 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

9.2 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 9.1 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.

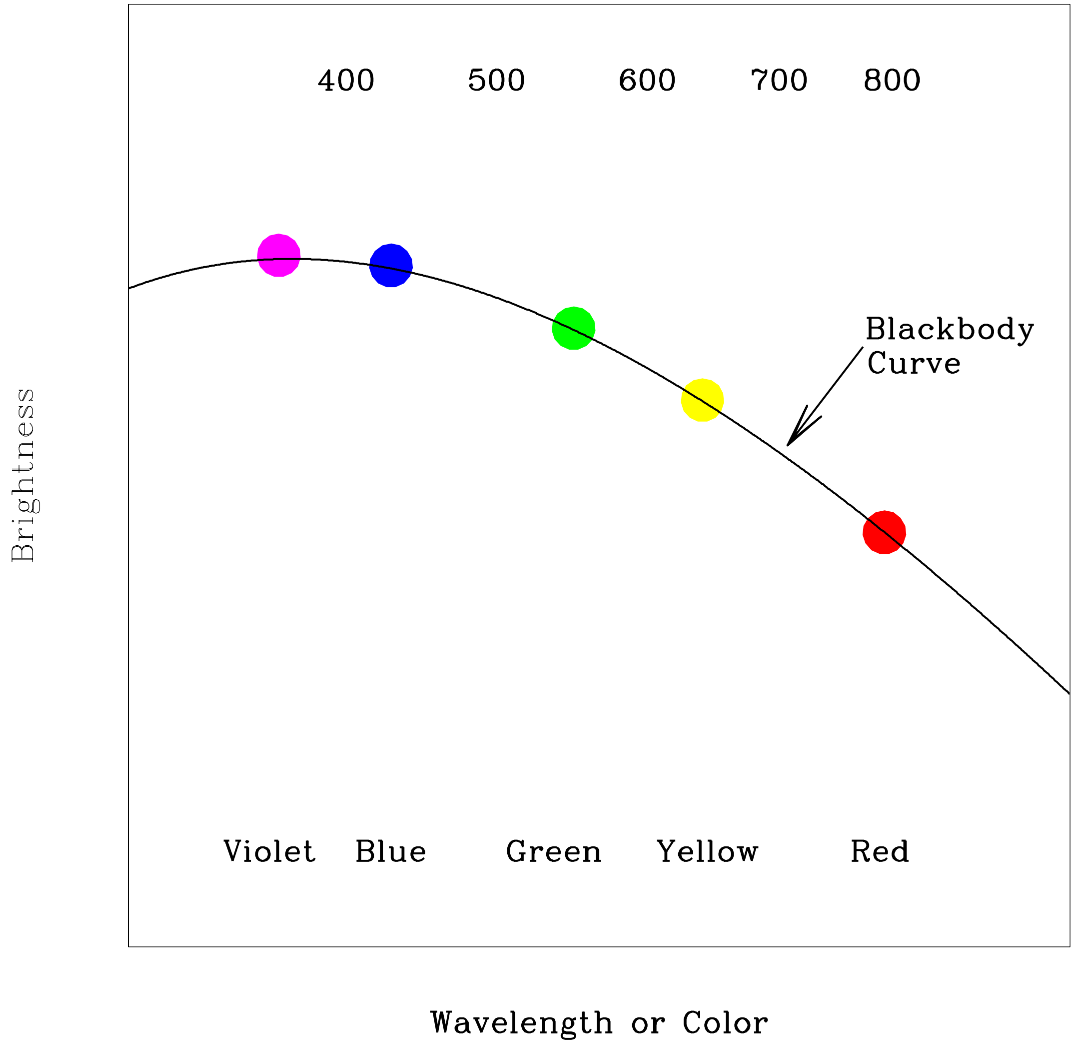


Figure 9.1: Astronomers measure the amount of light at a number of different wavelengths (or colors) to determine the temperature of a blackbody source. Every blackbody has the same shape, but the peak moves to the violet/blue for hot sources, and to the red for cool sources. Thus we can determine the temperature of a blackbody source by figuring out where the most light is emitted.

9.3 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*.]

9.3.1 The Bohr Model of the Atom

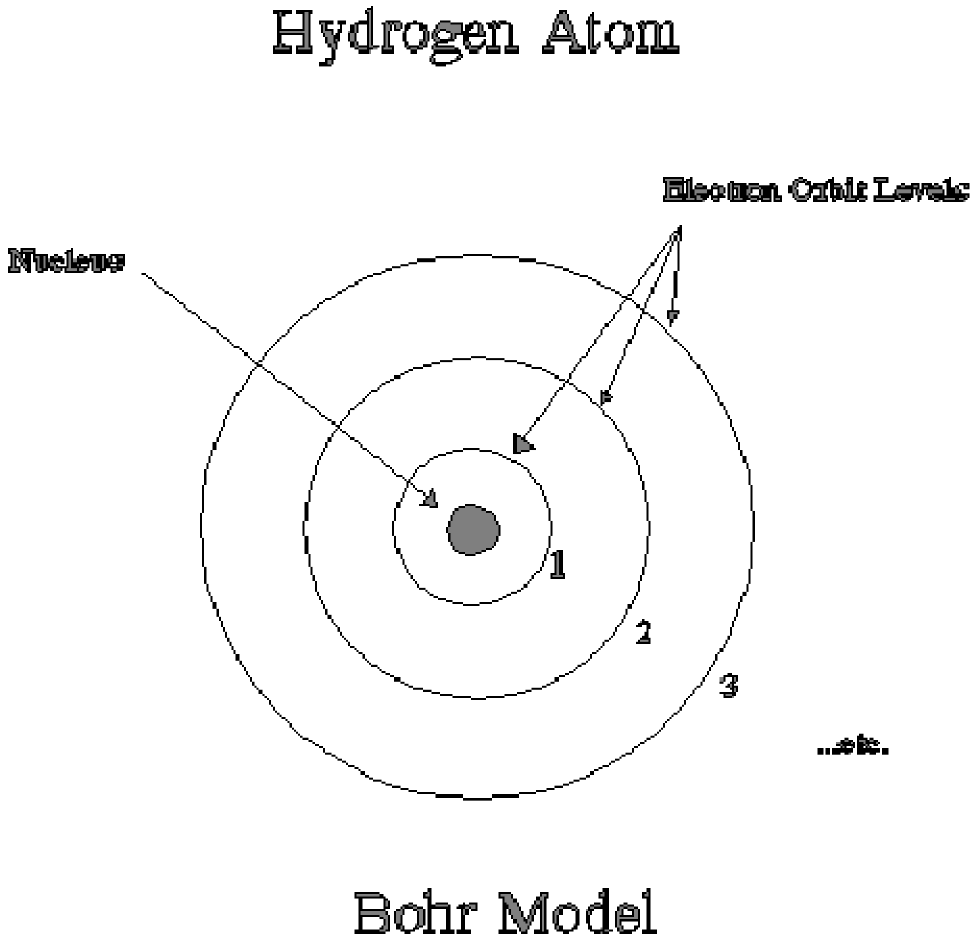
In the early part of this century, a group of physicists developed the *Quantum Theory of the Atom*. Among these scientists was a Danish physicist named Niels Bohr. His model of the atom, shown in the figure below, is the easiest to understand. In the Bohr model, we have a nucleus at the center of the 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, 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.

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

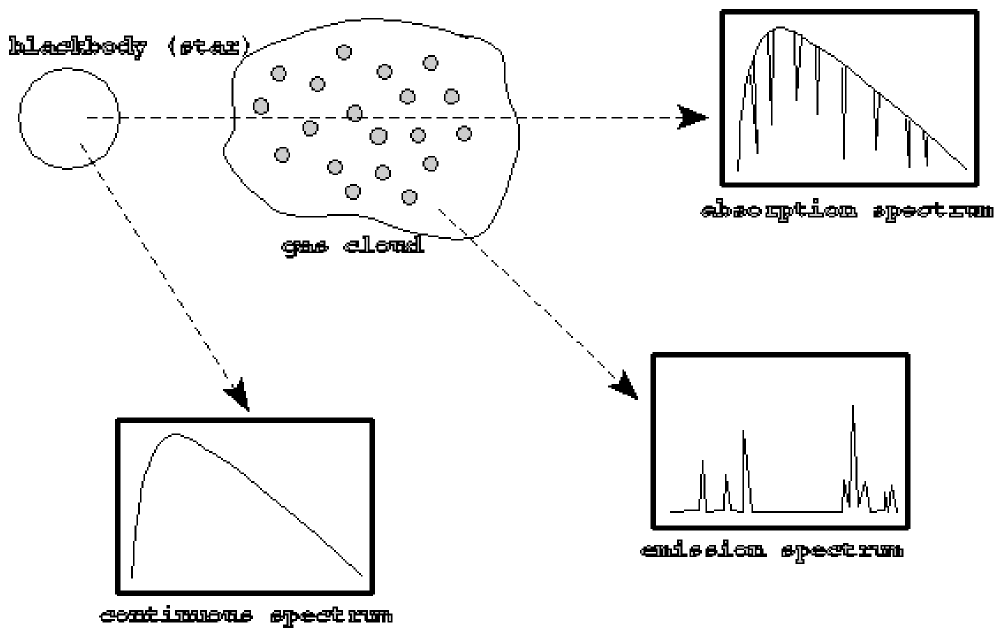


different number of electrons, you may think that studying “electron gymnastics” would get very complicated. Actually, nature has been kind to us because at any one time, only a single electron in a given atom jumps around. This means that each element, when it is excited, gives off certain colors or 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.

9.3.2 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:



Kirchoff's Laws

- **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.

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 Kichoff'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 section of the lab is to observe these emission lines and to understand their formation process.

9.4 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 matchine 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.

9.5 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 9.2 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.

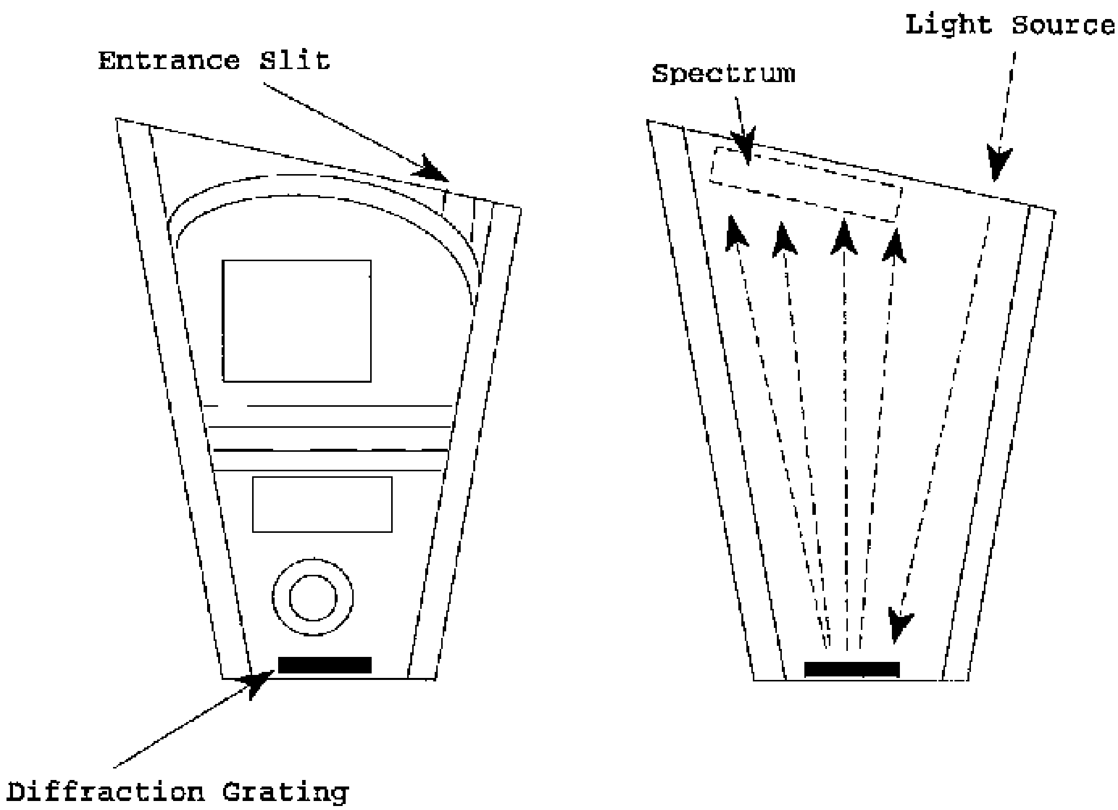


Figure 9.2:

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. Observe the light source at the fainter (cooler) setting.

6. 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*)

7. 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*)

8. Betelguese is a Red Giant Star found in the constellation Orion. Sirius, the brightest star in the sky, is much hotter and brighter than Betelguese. Describe how you might

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

9.6 Quantitative Behavior of Blackbody Radiation

This section, 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*)

9.7 Spectral Lines Experiment

9.7.1 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.

9.7.2 Emission-line Spectra Experiment

For the third, and final section 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)*

9.7.3 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 9.1: 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 9.2: 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)*

9.8 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.) *(6 points)*

2. What causes a spectrum to have more lines than another spectrum (for example, Helium has more lines than Hydrogen)? *(5 points)*

3. In this lab, what energy source is causing the electrons in the atoms to become excited? *(3 points)*

4. Which element showed the fewest spectral lines? Which element showed the most

spectral lines? Why? *(3 points)*

5. Using your knowledge of spectral lines from elements, how do you think all those bright colors in "neon" signs are made? *(4 points)*

9.9 Summary

(*35 points*) Summarize the important ideas covered in this lab. Some questions to answer are:

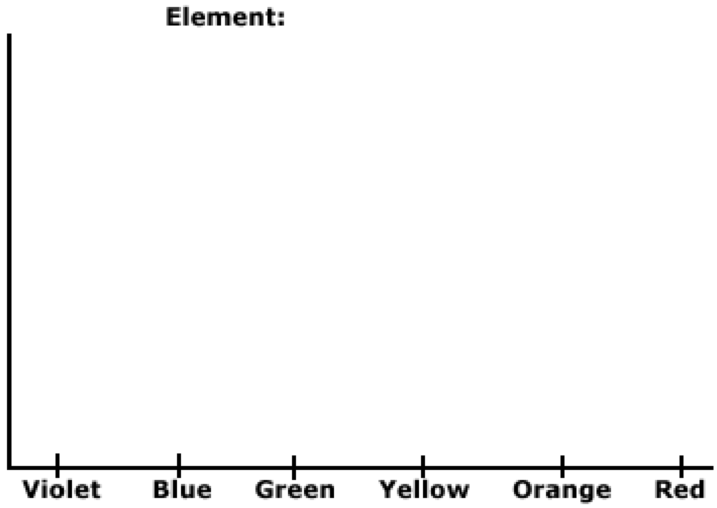
- What information you can learn about a celestial object just by measuring the peak of its blackbody spectrum?
- What does a blackbody spectrum look like?
- How does the peak wavelength change as the temperature of a blackbody changes?
- How can you *quantitatively* measure the color of an object?
- 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 spect rum?
- Explain how you would get this information from a spectrum.

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

9.10 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?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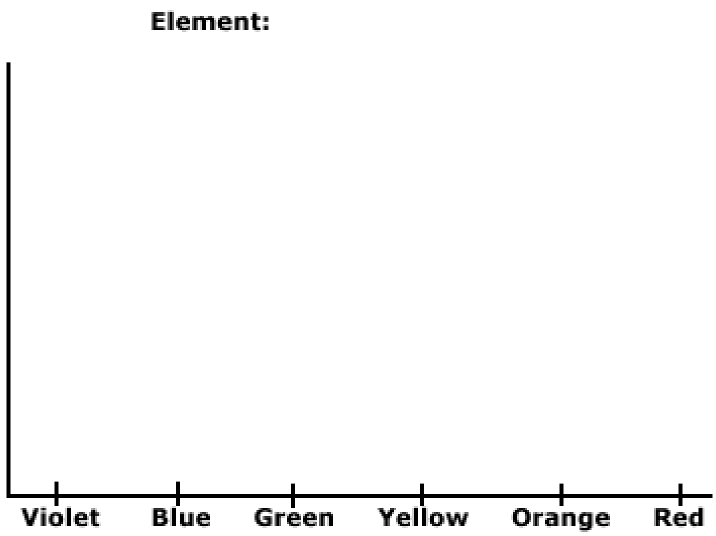
Blue
Green
Yellow
Orange
Red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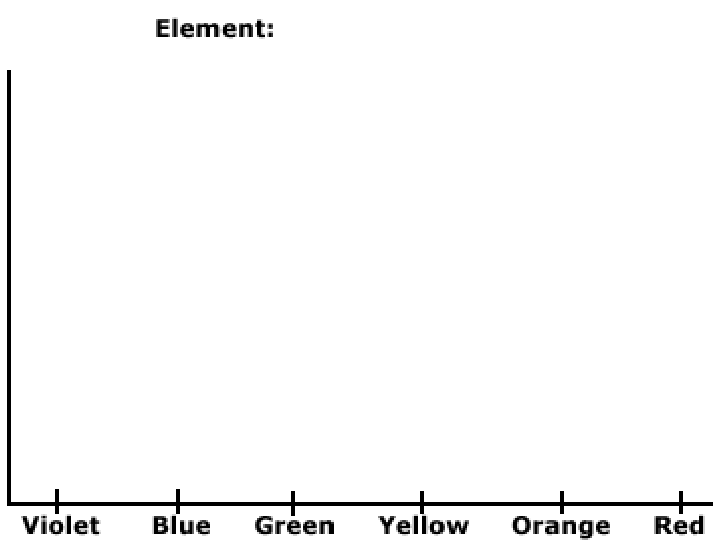
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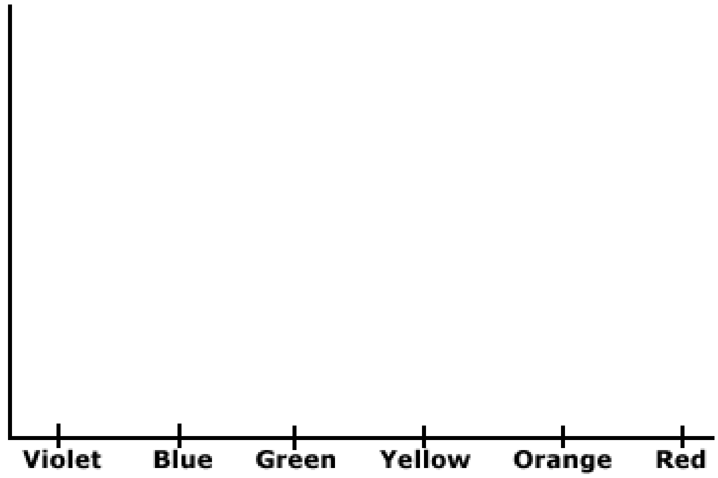

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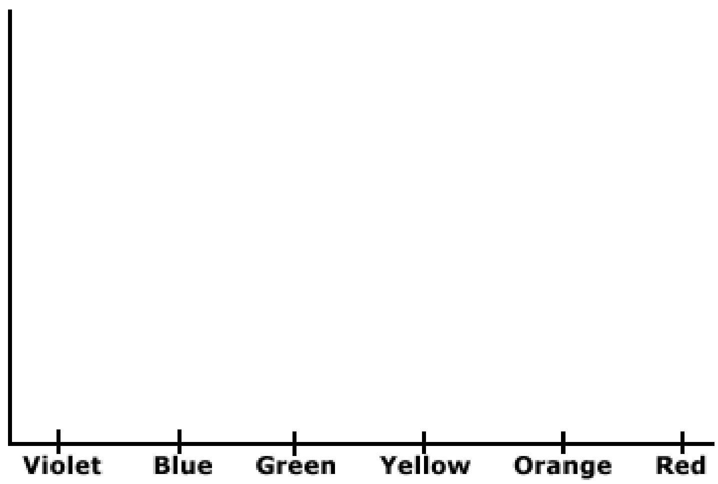

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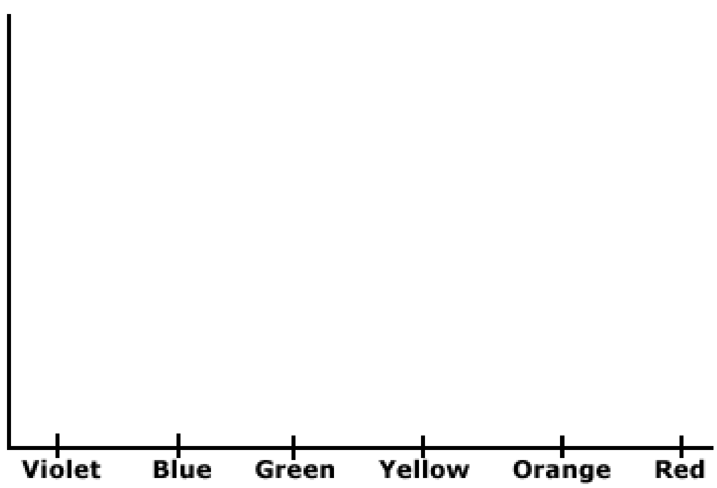

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Lab 10

The Hertzsprung-Russell Diagram and Stellar Evolution

10.1 Introduction

On a clear, dark night, one might see more than two thousand stars. Unlike our distant ancestors, we recognize that each one is a huge ball of hot gas that radiates energy, like our own (very nearby) star, the Sun. Like the Sun, the stars shine by converting hydrogen into helium via nuclear fusion reactions. Unlike the Sun, they are tremendously far away. While the Sun is located a mere 93 million miles from us and seems dazzlingly bright, the next nearest star is roughly 270,000 times farther away (25 trillion miles distant, or 4.3 light years, or 1.3 parsecs) and appears millions of times fainter to us on Earth.

The Sun can be thought of as a nuclear reactor in the sky that we all depend on, planning our days secure in the belief that it will continue to send us warmth and life-sustaining energy. But will it always do so? Just as a candle eventually uses up its oil and flickers out, someday the Sun will exhaust its fuel reserves. This is not surprising when you consider that, in converting mass to energy, the Sun turns 600 million tons of hydrogen into 596 million tons of helium with every passing second (losing four million tons in the process). Knowing this, you might justifiably fear for its imminent demise – but fortunately, the Sun has lots of mass!

We refer to the part of a star's lifetime when it's most dependable and stable – when it has plenty of hydrogen fuel to burn at its core – as the Main Sequence phase. It can be unstable and erratic soon after its formation from a collapsing cloud of gas and dust and later in life when it begins to run out of fuel and experience "energy crises," but not during the Main Sequence phase. How long will the Sun exist in this stable form?

Before this question could be answered, astronomers had to learn to distinguish stable, well-behaved stars from their more erratic, very young or very old neighbors. They did this by plotting two basic observed quantities (brightness and color) against each other, forming a plot called a Hertzsprung-Russell (H-R) Diagram, after the two astronomers who pioneered it usage nearly a hundred years ago. Astronomers realized that the positions of stable, well-behaved stars in the prime part of their lives were restricted to a small part of this diagram, along a narrow band that came to be called the Main Sequence. They also discovered that as one scanned the Main Sequence from one end to the other, the fundamental stellar property that changed along it was stellar mass.

Mass is critically important because it determines how long stars can exist as stable, well-behaved objects. We have learned this by studying H-R diagrams, particularly for large groups of stars (like the Pleiades and M67 clusters featured in this lab exercise). The most massive, luminous stars will spend only a few million years in the Main Sequence phase, while their least massive, faintest cousins may amble along like this for hundreds of billions of years. What about the Sun? We know from geological evidence that the Sun has existed in its current state for 4.5 billion years, and astronomical evidence suggests that it has another five to seven billion years to go in this state. In this lab we will evaluate the observational evidence behind that conclusion, and address the question of whether the Sun is a typical star by comparing it to other stars.

10.1.1 Goals

The primary goals of this laboratory exercise are to understand the significance of the H-R diagram in interpreting stellar evolution, to learn how observations of a star's physical properties define its position on the diagram, and to visualize how it will shift positions as it ages.

10.1.2 Materials

You will need a computer with an internet connection, and a calculator.

All online lab exercise components can be reached from the GEAS project lab URL, listed here.

http://astronomy.nmsu.edu/geas/labs/labs.html

10.1.3 Primary Tasks

This lab comprises three activities: 1) an H-R diagram explorer web application, 2) a Pleiades cluster activity, and 3) an M67 H-R diagram web application. Students will complete these three activities, answer a set of final (post-lab) questions, write a summary of the laboratory exercise, and create a complete lab exercise report via the online Google Documents system (see http://docs.google.com).

All activities within this lab are computer-based, so you may either read this exercise on a computer screen, typing your answers to questions directly within the lab report template at Google Documents, or you may print out the lab exercise, make notes on the paper, and then transfer them into the template when you are done.

10.1.4 Grading Scheme

There are 100 points available for completing the exercise and submitting the lab report perfectly. They are allotted as shown below, with set numbers of points being awarded for individual questions and tasks within each section. Note that Section 10.7 (§10.7) contains 5 extra credit points.

Table 10.1: Breakdown of Points

Activity Section Page	H-R Diagram §10.3.1 172	Pleiades Cluster §10.4.1 178	M67 Cluster §10.4.2 182	Questions §10.5 187	Summary §10.6 191
Points	19	13	24	19	25

10.1.5 Timeline

Week 1: Read §10.1–§10.4, complete activities in §10.3.1 and §10.4.1, and answer questions 1–4 in §10.5. We strongly suggest that you also attempt the activity in §10.4.2 and read through questions 5–8 in §10.5, so that you can receive feedback and assistance from your instructors before Week 2. Enter your preliminary results into your lab report template, and make sure that your instructors have been given access to it so that they can read and comment on it.

Week 2: Complete activity in §10.4.2, finish final (post-lab) questions in §10.5, write lab summary, and submit completed lab report.

10.2 The Brightness of Stars

Astronomers describe the brightness of stars in two different ways: apparent brightness, based on how bright an object looks to us here on Earth, and intrinsic brightness (or luminosity), based on how bright an object actually is, independent of how far away it lies from a viewer. We have devised a scale of relative brightness called the "magnitude scale." All objects of the same apparent magnitude appear equally bright when viewed from Earth. The 25 brightest stars in the sky are said to be first magnitude or brighter. The unaided eye can find about two thousand stars from first down to sixth magnitude in a dark sky, and large telescopes can reveal trillions more. In this lab exercise, you'll learn how astronomers measure the magnitudes of stars.

There are two important features of the magnitude scale: 1) brighter objects have smaller magnitudes, and 2) the scale is not linear (it is logarithmic). This means that a first-magnitude star is brighter (not fainter) than a second-magnitude star, and it is more than two times brighter than a second-magnitude star. If two stars differ by one magnitude, they differ in brightness by a factor of about 2.5; if they differ by five magnitudes, one is brighter than the other by a factor of 100; if they differ by ten magnitudes, they differ by a factor of 100×100, or 10,000.

<u>Example 10.1</u>
A first-magnitude star is about 2.5 times brighter than a second-magnitude star, and 100 times brighter than a sixth-magnitude star. A magnitude-6.0 star is 2.5 times brighter than a magnitude-7.0 star, 100 times brighter than a magnitude 11.0 star, and 10,000 times brighter than a magnitude 16.0 star.

Astronomers use a similar magnitude scale to gauge intrinsic brightness, but it depends on a thought experiment. They imagine an object lies a certain distance away from Earth; a standard distance of ten parsecs (32.6 light years) is typically used. They then ask "how bright would this object appear from a distance of ten parsecs?" The resulting measure of brightness is called its absolute magnitude. While the Sun appears to be tremendously bright and thus has the smallest apparent magnitude of any star (-26.7), if it were placed ten parsecs away, it would appear no brighter than a fifth-magnitude star. Given its close proximity, the Sun is extraordinarily special to us. Its apparent brightness exceeds that of the next brightest star, Sirius, by a factor of ten billion.

<u>Example 10.2</u>
The apparent magnitudes of the Sun and Sirius are -26.7 and -1.6 respectively. Note two things: 1) the brightest objects have the smallest magnitudes and magnitude values can be negative (smaller than zero), and 2) if two objects differ by 25 magnitudes – like the Sun and Sirius, the one with the smaller apparent magnitude appears ten billion times brighter than the one with the larger magnitude.

A star's apparent brightness depends on both its intrinsic brightness and its distance from Earth. Viewed from 30 times further away, or from Pluto, the Sun would appear 30^2, or 900 times fainter (though still very bright). What if we could view it from far outside the solar system?

Example 10.3

Viewed from a distance of 10 parsecs (32.6 light years), the Sun would look forty trillion times fainter. With a magnitude of 4.8, it would barely be visible to the unaided eye. This value represents the Sun's absolute magnitude. Comparing absolute magnitudes (imagining objects are viewed from the same distance) enables us to compare their intrinsic brightnesses, and to confirm that bright stars emit more energy per second than faint ones.

Example 10.4

Sirius is a bright, massive Main Sequence star, and emits twenty times more light than the Sun. If both stars were viewed from a standard distance of ten parsecs, Sirius would appear much brighter than the Sun (3.4 magnitudes brighter, given 1.4 magnitudes for Sirius versus 4.8 magnitudes for the Sun).

The magnitude scale is initially used to specify how bright a star appears, to quantify its apparent brightness. If the distance to the star is known, apparent magnitude and distance can be combined to compute an intrinsic brightness, or absolute magnitude. We can then easily convert absolute magnitude into energy output per second, or luminosity.

We can connect luminosity to other important physical quantities, by treating stars as idealized spherical radiators. The luminosity of a star depends primarily on its size and its surface temperature, in a fairly straightforward fashion. We can use the Stefan-Boltzmann Law to compute a star's luminosity L, where $L = (4\pi\sigma)R^2T^4$ and $4\pi\sigma$ is a constant, R is the star's radius, and T is its surface temperature. Given two of these three variables, we can use this relationship to estimate the third one.

10.3 The Main Sequence and the H-R Diagram

A casual glance at the night sky reveals that stars span a wide range of apparent magnitudes (some are bright, and some are faint). Closer inspection suggests that they also have different colors. It turns out that the color of a star is related to its surface temperature. Blue stars (stars which radiate most of their light at blue wavelengths) are hot, yellow stars (like the Sun) are cooler, and red stars are the coolest of all. Suppose we plot apparent magnitude (vertically) and color (horizontally) for a set of stars. Does a pattern emerge? The answer is no – our graph is just a random scatter of points (see Figure 10.1a). If we instead plot absolute magnitude (or luminosity) versus color (creating an H-R Diagram), a pattern emerges.

While the diagram's overall appearance depends on the actual sample of stars we use, for many stellar populations lots of points lie within a narrow strip (as in Figure 10.1b), which we link with the Main Sequence phase of stellar evolution.

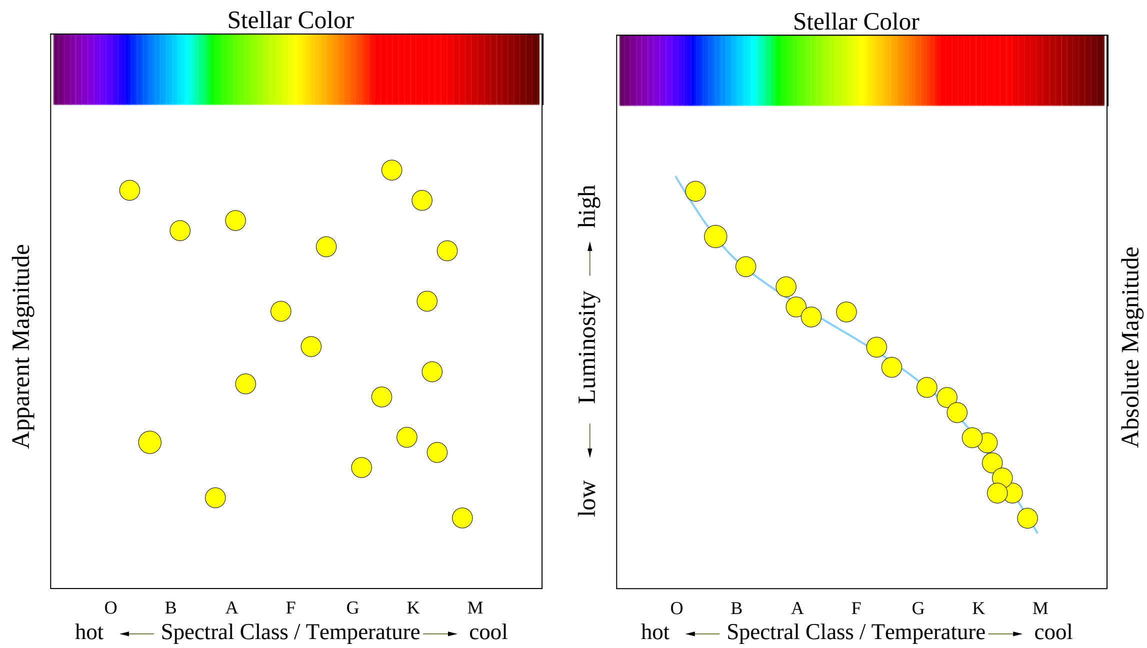


Figure 10.1: Plotting (a) apparent magnitude against color, we observe a random scattering of points. When (b) we convert to absolute magnitude, or luminosity, a clear pattern emerges. This is the fundamental form of an H-R Diagram.

10.3.1 The H-R Diagram and Stellar Properties Activity

In this activity we'll concentrate on two special samples of stars – the nearest stars, and those that appear the brightest from Earth – and consider H-R diagrams for each. These diagrams can be constructed in somewhat different ways. The ones we'll initially examine have luminosity (in units of the Sun's luminosity) plotted vertically versus surface temperature (plotted horizontally). The red X cursor initially marks the point plotted for the Sun, with a luminosity of 10^0, or 1, and a surface temperature of 5800 Kelvins (characteristic of a yellow star). Note that the Sun is a member of both the nearest star and the brightest star sample populations. Table 10.2 contains the basic stellar data for the Sun, collected in one place for easy reference.

Table 10.2: Basic stellar data for the Sun

Luminosity (solar units)	Radius (solar units)	Surface Temperature (K)	Spectral Class	Color (B–V)	Absolute Magnitude
1.00	1.00[a]	5800	G2	+0.66	4.8

[a]The radius of the Sun is nearly 1/2 million miles, making its diameter nearly one million miles.

Access the first web application (H-R Diagram) for this lab exercise from the GEAS project lab exercise web page (see the URL on page 168 in §10.1.2). Complete the following, filling in blanks as requested. (Each of the 36 filled blanks, and 2 circled answers, is worth 1/2 point.)

1) Beneath the H-R Diagram that appears on the right side of the screen, under "Options," uncheck the box to the left of "show main sequence." The red line that will disappear represents the Main Sequence. Stars plotted on (or very near to) it are in a fairly stable evolutionary phase. Re-check the box to get the Main Sequence back. Note that the Sun appears on this line – the initial red X represents its position. The Sun also lies on a second, green, line. Check the box to the left of "show isoradius lines." The parallel lines that disappear represent lines for groups of stars with the same radius. Re-check this box to get these lines back. The Sun appears on the line labeled 1.0 $R_{\odot}$. All stars of this size , regardless of their luminosity or surface temperature, will lie along this line.

In which corner of the diagram (upper right, upper left, lower right, or lower left) would stars with radii 1000 times larger than that of the Sun be plotted? ___________

In which corner would stars with radii 1000 times smaller than that of the Sun appear?

____

2) The H-R Diagram is fundamentally a plot of two variables (luminosity, L, versus surface temperature, T), but it also contains a third important variable: radius, R. (Recall that we reviewed the relationship between these three variables in §10.2.) To investigate this relationship further, click on the red X for the Sun (it is actually a cursor). The "Cursor Properties" box at the lower left now shows the corresponding values for T, L, and R, with the latter two expressed in terms of values for the Sun (in solar units). Use the mouse to move the cursor (noting how the size of the first star in the "Size Comparison" box changes), to answer the following six questions (write your answers in the table below).

What is the relative luminosity (in solar units) of a star with the same surface temperature as the Sun but (a) only one-tenth the radius? (b) twice the radius?

What is the relative luminosity of a star which is the same size as the Sun but has (c) twice the surface temperature (11600 K)? (d) only one-half the surface temperature (2900 K)?

Finally, what is the relative luminosity of a star with (e) one hundred times the Sun's radius, but only one-half the surface temperature (2900 K)? (f) only one-hundredth its size, but twice the surface temperature (11600 K)?

Table 10.3: Basic stellar data for selected stars

Star	Luminosity (solar units)	Radius (solar units)	Surface Temperature (K)
Sun	1.00	1.00	5800
Star a		0.10	5800
Star b		2.00	5800
Star c		1.00	11600
Star d		1.00	2900
Star e		100	2900
Star f		0.01	11600

When you are finished, return the cursor to the position of the Sun. (One easy way to do this is to reload the web-app in your browser.)

We hope that you're beginning to realize that the H-R Diagram can take many forms. The vertically plotted variable can be luminosity, or it can be another quantity related to intrinsic brightness, such as absolute magnitude. The horizontally plotted variable is often surface temperature, but it can also be color, or spectral class. To illustrate these different forms of the diagram, do the following. Under "Options," to the right of "x axis scale: temperature," click the down arrow and select "spectral type" as the new x-axis label. Note that the Sun lies within the spectral class G (run a vertical line down from the X for the Sun and check where it intersects the x-axis).

3) Beneath the H-R Diagram under "Plotted Stars," check the circle for "the nearest stars." The properties of the nearest hundred or so stars will be shown. Examine the plot, and answer the following questions.

(a) Considering the measurement uncertainty inherent in the data, do most of the points lie on (or near to) the Main Sequence line (within the Main Sequence strip)? ________________

If you can't decide (or to double-check), under "Options," click the box to the left of "show luminosity classes." The green band that appears marked "Dwarfs (V)" is the Main Sequence strip.

(b) Match the four regions marked A, B, C, and D in Figure 10.2 with the areas where white dwarfs, blue supergiants, red giants, and red dwarfs are found.

REGION A = ______________________, REGION B = ______________________

REGION C = ______________________, REGION D = ______________________

What object's position is marked by the X? _________________

What two lines intersect at this spot?

(c) The "Dwarfs (V)" label for the Main Sequence strip is unfortunate because the most luminous stars at the upper end of this strip have radii roughly ___________ times that of the Sun – they are hardly "dwarfish." But we still haven't compared the Sun to typical stars, so let's rectify that. Assume that the hundred or so stars nearest to us form a representative sample that we might find in a typical volume of our Milky Way galaxy. Let's think about how the Sun compares to these stars.

(d) Of the hundred nearest stars, only ___________ are obviously intrinsically brighter than the Sun.

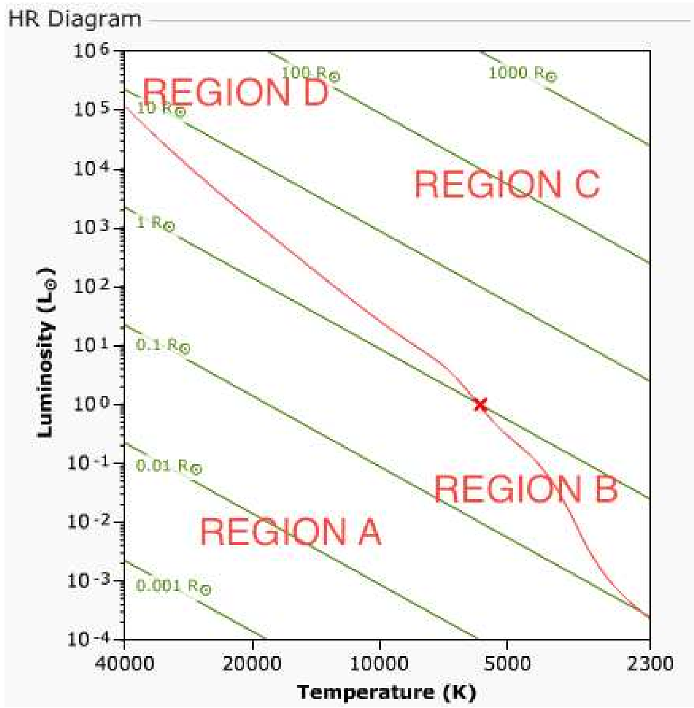


Figure 10.2: Which types of stars (white dwarfs, blue supergiants, red giants, and red dwarfs) are found in each of the four marked regions?

(e) Move the cursor to the middle of the nearest star sample, where many of them are concentrated. This region is labeled ________________ on the diagram. The luminosities for these typical stars are ____________ that of the Sun's, their radii are ____________ that of the Sun's, and their surface temperatures are around ____________ K.

(f) The nearest star sample shown is technically incomplete; at least five nearby white dwarfs were omitted. The most famous is the companion to the bright, nearby star Sirius A; Sirius B has a luminosity of 0.027 $L_\odot$ and a surface temperature of 25,000 K. Moving the cursor to where this star would be plotted, its radius is ____________ that of the Sun's (justifying the descriptive term dwarf). When finished, return the cursor to the position of the Sun.

Now consider another population of stars. Under "Plotted Stars," check the circle for "the brightest stars." The new points plotted on the diagram correspond to the 150 or so brightest stars which can be seen from Earth. Examine the plot and answer the following questions.

(g) Of these 150 brightest stars, only ____________ is/are intrinsically fainter than the Sun. While all the nearest stars were predominantly Main Sequence (V) stars, the brightest stars sample also includes many objects of luminosity classes ____________ and ____________.

(h) Move the cursor to the star representing the most luminous star in this sample. Its luminosity is ____________ $L_\odot$, its radius is ____________ $R_\odot$, its surface temperature is ____________ K, and its B–V color is ____________. The region where the cursor is now located is labeled ________________ on the diagram.

(i) Move the cursor to the star representing the largest star in this sample. Its luminosity is ____________ $L_\odot$, its radius is ____________ $R_\odot$, and its surface temperature is ____________ K; its B–V color is ____________. The region where the cursor is now located is labeled __________________ on the diagram. When finished, return the cursor to the position of the Sun.

(j) There are ____________ stars that are members of both samples (both nearest and brightest stars). Under "Plotted Stars," check the circle for "overlap" to verify your answer.

(k) In summary, the nearest / brightest (circle one) star sample is more representative of a typical volume of stars in our Galaxy, whereas the nearest / brightest (circle one) star sample is a specially selected sample, heavily weighted towards relatively rare, highly luminous objects.

Congratulations, you have completed the first of this lab's three activities. You may want to answer post-lab questions 1 through 3 on page 187 at this time.

10.4 The Evolution of Stars

The Sun is a yellowish spectral type G star, with a diameter of 864,000 miles, a surface temperature of 5800 K, and an intermediate luminosity. Its physical properties place it in the middle of the H-R Diagram. To its lower right, cooler, redder Main Sequence stars (with spectral types of K and M) are plotted, while hotter, bluer Main Sequence stars (spectral types O, B, A, and F) are found to the upper left. Will the Sun's position in this diagram change as it ages? Yes! As it runs out of hydrogen fuel in its core, it will become a cooler, more luminous, and much bigger red giant star. Similar giants appear to the upper right of the Sun's current position (which means that they are brighter and redder than the Sun). As the aging Sun runs out of fuel, it will eventually shed its bloated outer atmosphere and end its days as a white dwarf. White dwarfs are hotter, bluer and much less luminous than the Sun, so they are plotted to the lower left of the Sun's current position.

It would be fascinating to conduct a time-traveling experiment and observe how the Sun's position in the H-R diagram changed over time (charting its future path), but, alas, this is not possible. Though we can't conduct such a controlled experiment with the Sun, we can still get a good idea of its future evolutionary path.

Given all the diversity among observed stellar properties, you may be surprised to learn that it is the mass and the chemical composition of a star at formation which determine most of its other properties, and (provided it is not a member of a binary system) its subsequent life history. In addition to mass and chemical composition, two other variables can make stars differ: stars can have different ages (they form at different times) and they typically lie different distances away from us. Fortunately, astronomers can simplify our studies of stars and remove three of these four variables by using dense star clusters as "laboratories."

In doing this, we assume that all of the stars in a given cluster have the same chemical composition and age, and lie the same distance from Earth. Mass is thus the critical variable.

The more massive a star is, the faster it burns through the hydrogen reserve in its core and evolves off the Main Sequence into a red giant. Figure 10.3 shows how a cluster's H-R diagram changes as it ages. We can't observe a single cluster for long enough to see these changes, as we'd need to observe it for millions of years. Instead, we can examine many clusters of varying ages and compare their H-R diagrams.

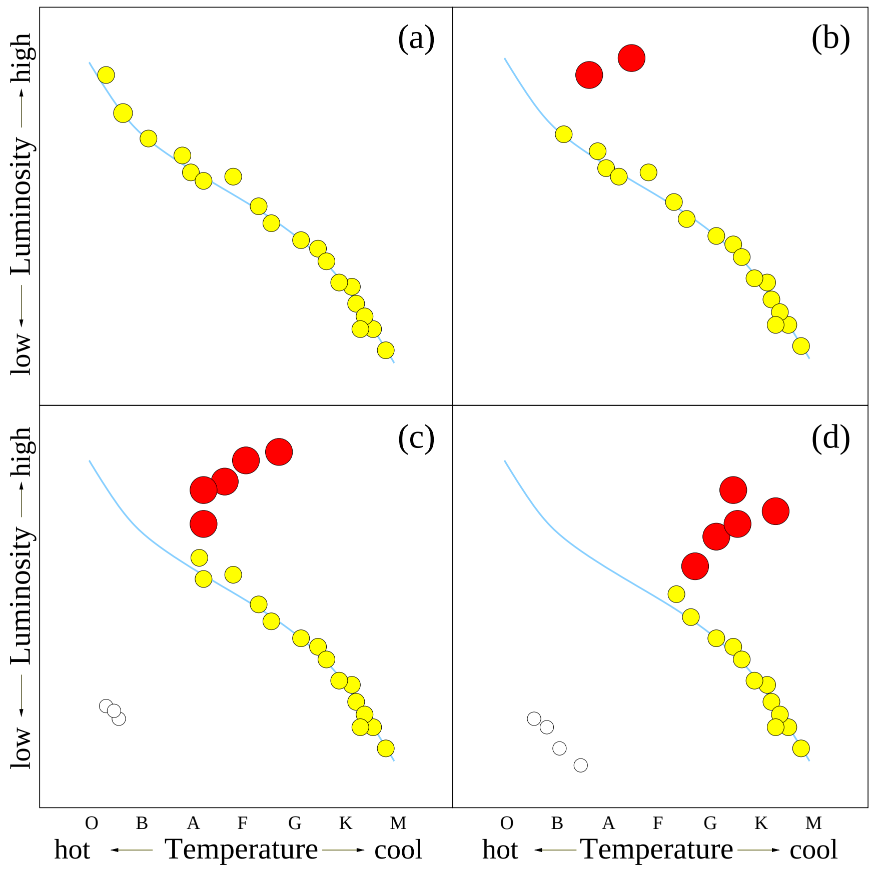


Figure 10.3: A star cluster's H-R diagram evolves with time. (a) A young cluster, with plenty of hot, blue, high-mass stars. All objects shown are on the Main Sequence (the highest mass stars, exploding as supernovae, are not shown). (b) A fairly young cluster, missing only the highest mass stars which have gone supernova or evolved off Main Sequence to become giant stars. (c) A moderate-age cluster missing the highest, high, and a few intermediate mass stars which have evolved off the Main Sequence. Note the presence of both red giants and white dwarfs. (d) An older cluster, with many intermediate mass stars evolving off the Main Sequence and turning into giant stars. Note the increasing number of white dwarfs.

The diagrams shown in Figure 10.3 represent clusters which are 50 million, 500 million, two billion and six billion years old. We want you to appreciate how astronomers estimate how many more years the Sun, a lower intermediate mass star, will spend on the Main Sequence. There is growing evidence that the Sun was actually born in a cluster, one three to ten light years in size and containing 1500 to 3500 stars. It's believed that one of the most massive of these stars died in a cataclysmic supernova explosion. This event is thought to have occurred within just a few million years of the Sun's birth. Indeed, the telltale signs it left behind are the main evidence suggesting that the Sun was born in a star cluster.

Since all the stars in a cluster lie at essentially the same distance from Earth, we can use apparent magnitudes to gauge their relative luminosities on H-R diagrams. We'll construct such a diagram using data for stars in the Pleiades bright star cluster, in the constellation of Taurus, the bull. These data come from two telescope images taken of the cluster, one with a V (for visual) filter, and one with a shorter wavelength B (for blue) filter. (We need images taken in two filters to determine the colors of the stars.) Our Pleiades cluster H-R diagram (shown in Figure 10.4) plots V filter magnitudes vertically and colors horizontally (instead of surface temperature, or spectral class). The color indices were obtained by measuring apparent magnitudes from both B filter and V filter images and subtracting these two magnitudes to produce a B–V color. (Note that "apparent magnitude" typically refers to an apparent brightness, often measured through a V filter, expressed on a magnitude scale.)

The Pleiades is a young cluster, and its H-R diagram will look similar to Figure 10.3(a). We can imagine that the Sun was once a young star in such a cluster. The Pleiades contains stars similar to the Sun in mass, luminosity, and color, as does the other star cluster whose H-R diagram we'll study later (M67). How can we identify solar-like stars in these star clusters? We can simply search for Main Sequence objects of the appropriate color. While such stars have a characteristic intrinsic brightness, their apparent V magnitudes will depend on their distance from us, as Table 10.4 illustrates.

Table 10.4: The Apparent Brightness of the Sun from Different Distances

Distance	Apparent magnitude	Significance
93 million miles	−26.7	Earth–Sun separation
10 parsecs	4.8	standard distance[a]
135 parsecs	10.5	distance to Pleiades cluster
770 parsecs	14.2	distance to M67 cluster

[a]Absolute magnitudes are calculated assuming this distance.

10.4.1 The H-R Diagram for the Pleiades, a Young Star Cluster

1) The Sun lies a mere 93 million miles from the Earth and seems incredibly bright, as illustrated by its very small apparent magnitude in Table 10.4. If we could move the Sun farther and farther away from us, however, it would grow fainter and fainter in the sky. By the time it approached the Pleiades cluster (at 135 parsecs, or 2,500 trillion miles), it would have an apparent magnitude of 10.5 and a small telescope would be needed to see it at all.

Check your understanding of the data listed in Table 10.4 by completing the following two statements. As the Sun is viewed from farther and farther away, explain any changes (trends) in its

(a) apparent magnitude: ____ (1 point)

(b) absolute magnitude: ____ (1 point)

As you work through this activity, keep in mind that the faintest objects have the biggest magnitude values.

2) The Pleiades are sometimes called "The Seven Sisters" since this cluster contains seven stars which are bright enough to be found by eye on a clear, dark night. Use the data in Table 10.5 to complete the following questions and explore the properties of the cluster stars.

(a) Identify the seven brightest Pleiades stars from their apparent V magnitudes:

#_______________, #_______________, #_______________, #_______________,

#_______________, #_______________, #_______________. (1 point total)

Remember that the unaided eye can only see stars down to sixth magnitude, and stars fainter than that will have even larger magnitudes. The seven sisters should thus each have apparent magnitudes quite a bit smaller than 6.

(b) The brightest cluster star is #____________, with an apparent V magnitude of ____________ and a B–V color of ____________. (1 point total)

Study the data for this star, and explain how the color index was computed. (1 point)

Some of the Pleiades stars listed are too faint to be seen without a telescope. Refer back to Example 10.1 (on page 170), and use apparent V magnitudes to make the following two comparisons.

(c) Star #9 is roughly __________________ times brighter than star #3. (1/2 point)

(d) Star #____________ is almost 100 times brighter than star #14. (1/2 point)

Figure 10.4 shows an H-R diagram for the Pleiades cluster, constructed from the data in Table 10.5 and observations of 31 additional cluster stars. Could you find the star most like the Sun in this diagram, or the star most like Sirius? Consider the examples below.

Example 10.5

Table 10.4 tells us that the Sun would have apparent (V) magnitude of roughly 10.5 if it were a member of the Pleiades cluster, and Table 10.2 gives its B–V color index as 0.66. Inspection of Table 10.5 reveals that star #16 (with an apparent V magnitude of 10.48 and a B–V color of 0.66) closely resembles the Sun. (It is boxed in red on Figure 10.4.)

Table 10.5: Apparent Magnitudes and Colors of Bright Pleiades Stars

Star	B	V	B–V	Star	B	V	B–V
1	3.58	3.70	−0.12	9	2.78	2.87	−0.09
2	4.19	4.30	−0.11	10	5.38	5.45	−0.07
3	3.80	3.87	−0.07	11	3.53	3.62	−0.09
4	5.42	5.46	−0.04	12	5.01	5.09	−0.08
5	5.58	5.65	−0.07	13	6.12	6.17	−0.05
6	5.72	5.76	−0.04	14	9.26	8.86	0.40
7	6.41	6.43	−0.02	15	7.31	7.24	0.07
8	4.12	4.18	−0.06	16	11.14	10.48	0.66

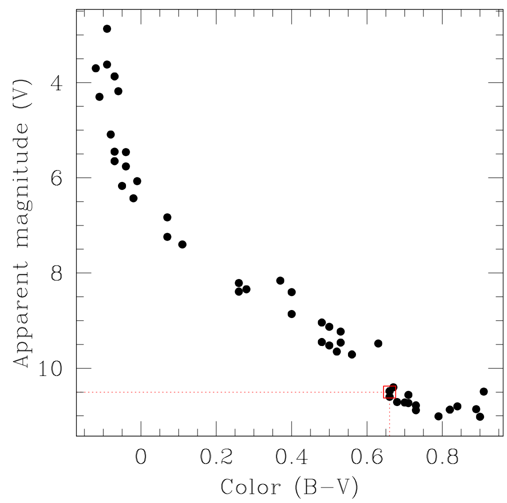


Figure 10.4: An H-R diagram for the Pleiades star cluster, with solar-type star #16 boxed in red. Note that the y-axis runs from large magnitudes to small, so that the brightest stars appear at the top of the figure.

3) If the stars in the Pleiades cluster lay only ten parsecs from Earth, their apparent magnitudes would be brighter / fainter / unchanged (circle one), while their absolute magnitudes would be brighter / fainter / unchanged (circle one). Solar-type star #16 would have an apparent V magnitude of ____________ and would just be visible to the unaided eye as a faint star. Star #16 is actually much farther away than ten parsecs (it lies around ____________ parsecs away) so it is even fainter: its actual apparent V magnitude is ____________. (2 points total)

Remember that any star which is fainter than sixth magnitude is not visible without a telescope.

<u>Example 10.6</u>
From Example 10.3, we know that Sirius is intrinsically 3.4 magnitudes brighter than the Sun. At the distance of the Pleiades, we would look for it on the Main Sequence at apparent

V magnitude $10.5 - 3.4 = 7.1$. Star #15, with an apparent V magnitude of 7.24 and B–V color of 0.07, is the closest match.

4) Imagine that you could go back to a time when the Sun was relatively young (say fifty million years old), and construct an H-R diagram for the star cluster in which it formed. This diagram would look like the one shown for the Pleiades in Figure 10.4, with star #16 representing the Sun, and the cluster's brightest star, Alcyone (star #9), highest up on the Main Sequence at the upper left.

What will happen to star #9 in the Pleiades (or to similar stars in the Sun's original cluster) as time marches on? Being 1000 times more luminous than the Sun, Alcyone is also much more massive, by a factor of seven. The more massive a star is, the faster it progresses through the phases of stellar evolution. Alcyone will spend less time in its stable (Main Sequence) phase, will run out of core nuclear fuel faster, and will move off the Main Sequence much sooner, compared to the Sun. While we believe that the Sun will ultimately spend around ten billion years on the Main Sequence, a star as massive as Alcyone will spend less than one hundred million years there. Given its current properties, we believe its age (and thus the age of the Pleiades cluster) to be less than one hundred million years. This is less than the blink of a cosmic eye, compared to the age of the universe (14 billion years).

(a) Review Figure 10.3. As a star cluster ages, its Main Sequence turn-off point steadily becomes brighter / fainter (circle one) and bluer / redder (circle one). The masses of the stars around the turn-off point decrease / increase (circle one). (1 point total)

(b) The difference between absolute and apparent magnitude is the same for all members of the Pleiades cluster, because it is purely a function of the cluster distance from Earth. Use the absolute magnitude of the Sun and the apparent magnitude of solar-type star #16 to estimate this difference, and then determine the absolute magnitude of star #9, Alcyone (the brightest star in the Pleiades). Show your work, as well as stating your final answer. (2 points)

The brightest, bluest star still remaining on the Main Sequence is sometimes used to define a cluster's turn-off point. The term "turn-off" comes from recognizing that this star will be the next one to leave (or turn off) the Main Sequence, and become a red giant. For the Pleiades, this turn-off point is currently at absolute magnitude ____________ and B–V color ____________. (1 point total)

(c) Review Example 10.6 (on page 180) and locate star #15 (resembling Sirius) in Figure 10.4. There are only _________ stars on the diagram that are brighter and bluer than it. (1 point)

Today, these massive, luminous blue stars give the Pleiades cluster its characteristic, youthful appearance. The cluster will look rather different in a few billion years, however, when these stars evolve off the Main Sequence. The next cluster that we will study, M67, lies in this age range. How different do you think its H-R diagram will be?

Congratulations, you have completed the second of this lab's three activities. You may want to answer post-lab question 4 on page 189 at this time.

10.4.2 An H-R Diagram for M67, an Older Star Cluster

You were given magnitudes and colors (computed by subtracting magnitudes) for many stars in the Pleiades cluster in Table 10.5. We did not discuss how these magnitudes were obtained, but we shall do so now. You will measure apparent magnitudes (and record colors) for several stars in the star cluster M67 in the constellation of Cancer, the crab. As you work, remember that the faintest objects have the biggest magnitude values.

1) Access the second web application for this lab exercise (M67 Cluster) from the GEAS project lab exercise web page (see the URL on page 168 in §10.1.2). This activity focuses on a color image of the star cluster M67. You will carefully measure the brightnesses of 14 individual stars, and use them as a basis for constructing an H-R diagram for the entire cluster. You will choose for yourself which of the hundreds of stars to measure, within certain guidelines.

When choosing stars to measure, try to avoid the two or three brightest stars on the image (those which bleed light into their nearest neighbors), stars which are very close to others and thus hard to isolate and sample without contamination, and the multitude of small, faint red-field stars in the background.

2) Begin by identifying a solar-type star, one with properties similar to those of the Sun (as it would appear if it was placed within M67). A recent study found sixty of these within the cluster, so this should be a fairly straightforward exercise. Re-examining the data in Tables 10.2 and 10.4, we note that the Sun has a B–V color of 0.66, and at a distance of 770 parsecs (the distance to M67) it would have an apparent V magnitude of 14.2. *We shall thus define a "solar-type" M67 star as one with a V magnitude between 14.7 and 13.7 and a B–V color between 0.76 and 0.56.* Stars with magnitudes less than 13.7 are too bright, while those greater than 14.7 are too faint. Those with B–V colors less than 0.56 are too blue, and those greater than 0.76 are too red. Select an intermediate to faint yellowish looking star near the center of the image to measure.

(a) Use your mouse to click on the center of the star's image. A green circle (called an aperture) will appear around the star, and related data will appear in two charts at the upper right: star # (for ID purposes), X and Y coordinates (indicating the position of the star on this image), radius R for the aperture (an angular size expressed in arcseconds), the number of counts registered by the detector for the pixels enclosed by the aperture and their distribution around the center of the aperture, the corresponding apparent V magnitude, and the star's color index B–V. This index is literally the difference between the number of counts recorded at blue wavelengths and the number recorded at visual wavelengths, in units of magnitudes. Because fainter fluxes (less light) are equivalent to larger magnitudes, very blue objects have small B–V colors and very red ones have large B–V colors.

(b) Refine your aperture to better match the star location and contain all of its light by using the Update Feature Panel in the upper-left of the screen. From there you can shift your circle left or right, or up or down, by clicking on the four rectangular directional arrow symbols, or you can increase or decrease its radius (to contain all of the light from the star, but none from its neighbors) via the two circular up or down arrow symbols. Note how the counts and corresponding apparent magnitudes and colors change as you vary the aperture properties. The distribution of counts around the center of the aperture should be tightly peaked when your aperture is properly centered. When you have centered the aperture as best you can, and adjusted its size to include all significant "starlight" counts, but not too many "dark sky background" counts and light from neighboring objects, examine its V magnitude and B–V color in the chart. Do they match the definition of a solar-type star? If not (and in general if you wish to abandon your attempt to measure any star) click the "delete feature" button in the "Update Feature Panel" at the upper left, and choose another candidate to continue your search for a solar-type star.

<u>Example 10.7</u>
Suppose you select star #132, and measure a V magnitude of 15.42 and B–V color of 0.76. This star lies within the color range of a solar-type star (as $0.76 \geq 0.76 \geq 0.56$), but it is too faint ($15.42 > 14.7$). You then look for a brighter star with a similar color and settle on star #152. It has a V magnitude of 14.21 and a B–V color of 0.54. This star lies within the required magnitude range ($14.7 \geq 14.21 \geq 13.7$), but is too blue ($0.54 < 0.56$), so you look for a redder star of similar brightness and settle on star #123. Your measurement yields a V magnitude of 14.02 and a B–V color of 0.62. This star is a solar-type star ($14.7 \geq 14.02 > 13.7$, and $0.76 \geq 0.62 \geq 0.56$).

(c) When you find an acceptable star, click the "Save" button in the Update Feature Panel. The green aperture will turn blue, and the data for the star will be permanently fixed in the data chart.

Below the data chart is a second chart, a graph showing the radial distribution of counts around the center of the selected aperture. This plot illustrates the distribution of light within the aperture (the green circle) as defined by two green bars, while the plot extends a bit farther out to show what light lies just beyond the aperture. This will help you select the best size for the aperture, a decision that determines how much light to count in measuring the star's brightness.

As you vary the position and size of the aperture around each star and simultaneously watch the displayed H-R diagram, you'll note that the point where the star is plotted in this diagram typically varies in the vertical direction, since the measured brightness varies depending on the size and position of the aperture.

3) After you've found and marked an acceptable solar-type star, you'll repeat this basic process to find 13 more stars that fit into four categories. We want you to find at least two stars fainter and bluer than the Sun, at least two fainter and redder than the Sun, at least two brighter and bluer than the Sun, and at least two brighter and redder than the Sun. Try to guess whether each star that you select is brighter or fainter, and redder or bluer, than the Sun before reading its magnitude and color from the chart. We want to confirm that you can correctly compare the brightnesses and colors of stars, so be sure to place each of the 13 stars that you mark into the appropriate category.

Example 10.8
Let us re-examine the first star which we rejected in our search for a solar-type star. We can classify star #132 as both fainter and redder than the Sun, since for apparent V magnitudes, $15.42 > 14.2$, and for B–V colors, $0.76 > 0.66$. This star thus qualifies for the redder, fainter category.

As you select your set of 14 stars, sort them into the five defined categories below. You will receive one point for the solar-type star and two points for each of the other four categories, if all stars are correctly categorized.

(a) The solar-type star is #____________.

(b) The 2 to 4 stars fainter and bluer than the Sun are #__________________________.

(c) The 2 to 4 stars fainter and redder than the Sun are #_________________________.

(d) The 2 to 4 stars brighter and bluer than the Sun are #________________________.

(e) The 2 to 4 stars brighter and redder than the Sun are #________________________.

You will print out your completed data chart and add it as a figure in your lab report. In the corresponding figure caption, identify the solar-type star by its ID, and also state which of the other 13 stars fall into each of the other four categories.

4) After all 14 stars have been measured and marked, points for an additional 400 stars within the M67 cluster (down to an apparent magnitude of 16) will suddenly appear on the H-R diagram plot. These stars were marked in the same way you marked your set, and their magnitudes were measured similarly. Keep the diagram on the screen for a few minutes; it will take awhile to properly interpret it, assess the quality of its data, and extract important information from it. If you have trouble reading it from within the application, go ahead and save a copy as a figure to your local disk. This version should be easier to view, as it will appear to be somewhat larger.

5) Your first task in interpreting the H-R diagram for M67 is to find the Main Sequence, which is not quite as obvious as it was for the much closer Pleiades cluster (recall Figure 10.3).

There are several important reasons for this. Some stars that we think lie in M67 may actually be closer foreground stars or more distant background stars; some stars which appear to be isolated may actually be unresolved binary stars; there may be small variations in chemical composition (the ratio of various metals) within this stellar population; and measurement uncertainties (every measured quantity has some uncertainty to it) and procedural errors (errors in technique) may exist. To simplify this task, note the four stellar evolutionary tracks (drawn in four colors), which merge into a single track in the diagram's lower center right. Let them define the center of the Main Sequence for low-mass stars.

6) When measuring the magnitudes of stars in M67, any errors in the sizes or positions of the stellar apertures will lead to poor measurements. Consider this point when answering the following four questions. (1 point each).

(a) What happens if an aperture is too small? Where will the associated star appear on the H-R diagram, relative to its correct position?

(b) What happens if an aperture is too large? Does it matter whether the extra space is dark sky, or contains a neighboring object?

(c) What happens if the aperture is offset from the center of the star?

(d) What happens if you place an aperture directly between two stars?

If you are unsure about any of your answers, go ahead and experiment by shifting one of your apertures on and off of its target, and examine the result in the radial plot of stellar fluxes. (Be sure to reset your aperture to its correct position and size when you are done experimenting!)

7) Having made our measurements and considered common sources of error, we can now use our derived H-R diagram to estimate the age of the M67 cluster. Examine the four evolutionary tracks (drawn in four colors) showing the expected brightnesses and colors of stars as they turn off the Main Sequence and evolve (moving upwards and to the right) into red giant stars. These tracks are based on sophisticated models of stellar evolution, which simulate the nuclear processes by which stars burn their fuel. Each track has a stellar age associated with it.

The low-mass stars at the bottom part of the Main Sequence (where the four tracks effectively merge into a single line) are of no help here. Instead, look above and to the right of this region – where stars "turn off" the Main Sequence as they become red giants – and decide which one of four tracks (if any) best fits the data. Base your age estimate for M67 on the corresponding age for that track, or interpolate between two adjoining tracks if you think that the best fit to the data lies between them.

Discuss your results (your age estimate) for M67 below, explaining how you came to your conclusion. Note the particular features on the H-R diagram which were most important to your decision-making process. (6 points)

8) Compare your results for M67 with those for the Pleiades, with respect to the following five factors. (1 point each)

(a) Cluster turn-off point:

(b) Presence of red giants:

(c) Presence of red dwarfs:

(d) Presence of massive blue Main Sequence stars:

(e) Age of cluster:

9) Besides answering the remaining post-lab questions (see below), you need to save three things for presentation in your lab report: (a) the sky image of the M67 cluster, with marked apertures, (b) the M67 data chart for your 14 stars, and (c) the M67 cluster H-R diagram. You may also include any radial charts of flux around a particular aperture, if you wish to do so to help in answering the four questions in part 7) above.

Congratulations, you have completed the third of this lab's three activities. You may want to complete your answers to post-lab questions 5 through 7 on page 189 at this time.

10.5 Final (post-lab) Questions

Questions 1 through 3 relate to the materials discussed in §10.3.1. Review this section if you are unsure of your answers.

1) How does the Sun compare to the other members of the nearest star sample? If one assumes this sample is representative of typical stars found throughout the universe, to what extent is the Sun a typical star? (3 points)

2) Consider the brightest stars in the sky, and why they appear so bright. Three students debate this issue. Student A: "These stars must be very close to us. That would make them appear brighter to us in the sky." Student B: "These stars are intrinsically very luminous, so they emit a tremendous amount of energy." Student C: "I think it's because these stars are very close and very luminous." Use what you've learned in this lab to support the views of one of the three students and answer the question "Why do the stars which appear the brightest in the night sky seem so bright?" (3 points)

3) Are these apparently bright stars very common (do stars like them make up a large percentage of all stars)? Explain your reasoning. (3 points)

Question 4 relates to the materials discussed in §10.4.1. Review this section if you are unsure of your answer.

4) Consider how the H-R diagram of the Pleiades would look far in the future.

(a) Suppose all of the Main Sequence stars above solar-type star #16 had run out of fuel and left the Main Sequence. What other regions in the diagram (besides the Main Sequence) would now be populated? (1 point)

(b) How old would this cluster be? Explain. (1 point)

Questions 5 through 7 relate to the materials discussed in §10.4.2. Review this section if you are unsure of your answers.

5) The best explanation for why the H-R diagram for M67 does not include any white dwarf stars is (a) this cluster is not old enough for any of its stars to have evolved to this stage, or (b) the data this H-R diagram is based on only includes stars brighter than an apparent V magnitude of 16, and we expect any white dwarfs in M67 to be fainter than this. Explain your choice of answer. (2 points)

6) When measuring apparent magnitudes for stars in M67, if two equal-mass stars were tightly clustered in a binary system and could not be separated (they appeared as one star), where would their combined properties place them on the H-R diagram (versus where they would be placed if they were separable)? (2 points)

7) The constellation of Cancer contains the star cluster M44, which, like the Pleiades, is visible to the unaided eye on a clear night.

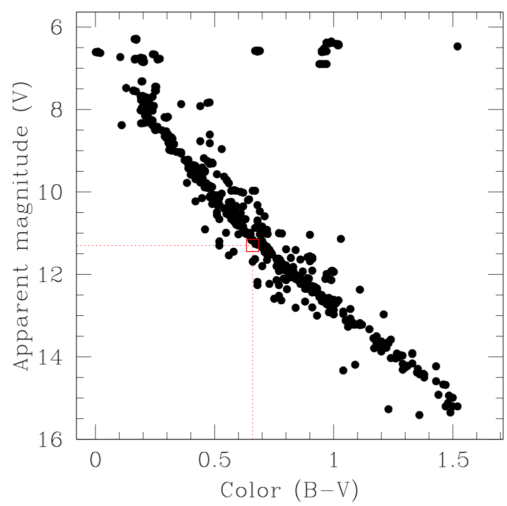


Figure 10.5: An H-R diagram for the M44 star cluster, with a solar-type star boxed in red. Note that the y-axis runs from large magnitudes to small, so that the brightest stars appear at the top of the figure.

(a) Using its H-R diagram in Figure 10.5, compare this cluster's age with that of of the Pleiades and M67 clusters. Explain how you arrived at your conclusion. (2 points)

(b) Is M44 closer to or farther away from us than the Pleiades, and closer to or farther away from us than M67? Explain your answer. (2 points)

10.6 Summary

After reviewing this lab's goals (see §10.1.1), summarize the most important concepts discussed in this lab and discuss what you have learned (include both techniques for data analysis and scientific conclusions). (25 points)

Be sure to consider and answer the following questions.

- How are H-R diagrams constructed? Why are they useful, and how are they used? Start with the necessary telescope observations and required data, explain how they are obtained, and then proceed to the use and significance of the derived diagrams.

- Astronomers say that the Sun has another five billion or so years remaining of stable, well-behaved existence on the Main Sequence. If someone were to express skepticism, saying, "How can we possibly know that?" what would you say in response?

Make use of the H-R diagram constructed for M67 as an illustrative example, and reference the three figures that you created at the end of §10.4.2.

Use complete, grammatically correct sentences, and be sure to proofread your summary. It should be roughly 500 words long.

10.7 Extra Credit

The brightest star in the sky, Sirius, has a faint companion (Sirius B) whose existence was predicted from orbital irregularities by Friedrich Bessel in 1844. It is ten magnitudes fainter than Sirius, and was at first assumed to be a cool, red dwarf. In 1914, observations showed that it was both hot and roughly the size of Earth. How was this discovery made? Describe the observations which were made, and the mathematical argument behind the size estimate. In 2005, the mass and size of Sirius B were measured to unprecedented precision. How was this done? (5 points)

Be sure to cite your references, whether they are texts or URLs.

Name:

Lab 11

Hubble's Law: Finding the Age of the Universe

11.1 Introduction

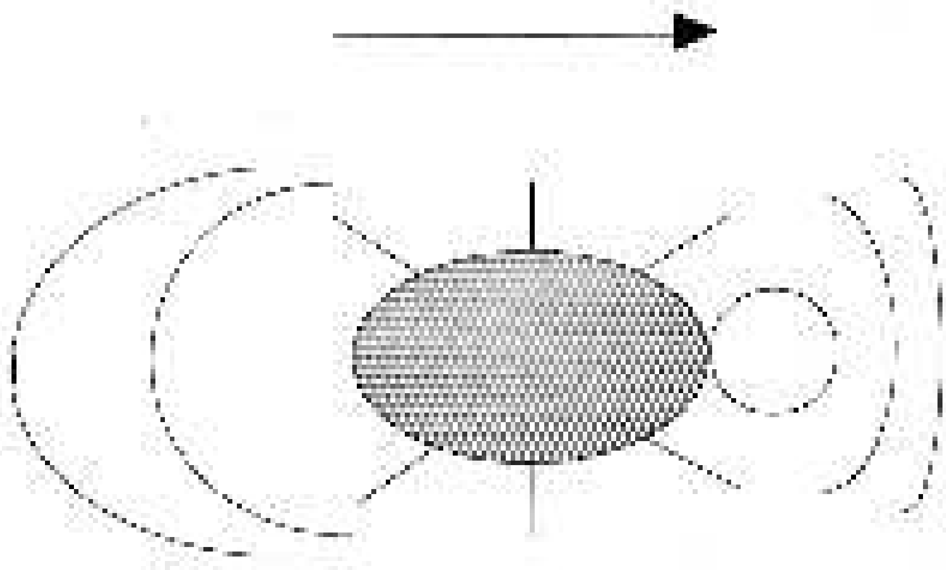
In your lecture sessions (or the lab on spectroscopy), you will find out that an object's spectrum can be used to determine the temperature and chemical composition of that object. A spectrum can also be used to find out how fast an object is moving by measuring the Doppler shift. In this lab you will 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

11.2 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 waterbug treading water in a pond.

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

[1] For this lab we will be measuring wavelengths in Ångstroms. 1.0 Å$= 1.0 \times 10^{-10}$ m.

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:

Excercise 1. *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)?

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.

11.3 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 $\times$ Mpc). Hubble's constant is basically the expansion rate of the Universe.

The problem with this formula is that the precise value of H isn't 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. *(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).

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 $\lambda_o =$ **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 procede for the other galaxies. **Show all of your work on a separate piece of paper and turn in that paper with your lab.**

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	

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!).

11.4 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. *(15 points)*

The Hubble constant is expressed in units of km/(s × 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

11.5 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. 11.1. 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. 11.1 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. 11.1, 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 $1/R^2$.

Exercise 4.

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

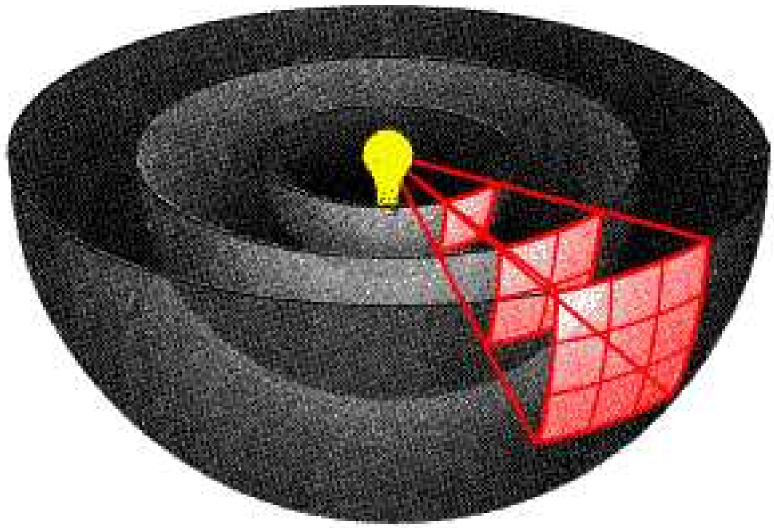


Figure 11.1: If you draw concentric spheres around a light source (we have cut the spheres in half for clarity), you can see how light spreads out as it travels. The light passing through one square on the inner sphere passes through four squares for a sphere that has twice the radius, and nine squares for a sphere that has three times the radius of the innermost sphere. This is because the area of a sphere is $4\pi R^2$.

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)*

11.6 Questions

1. Explain how the Doppler shift works. *(5 points)*

2. In the waterbug 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) *(3 points)*

4. Does the age of the Universe 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)*

11.7 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.

11.8 Extra Credit

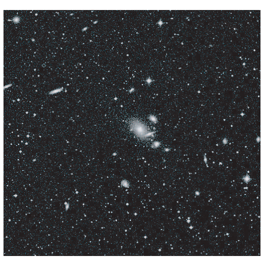
Recently, it has been discovered that the rate of expansion of the Universe appears to be accelerating. This means that the Hubble "constant" is not really constant! Using the world wide web, or recent magazine articles, read about the future of the Universe if this acceleration is truly occurring. Write a short essay summarizing the fate of stars and galaxies in an accelerating Universe. *(4 points)*

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?

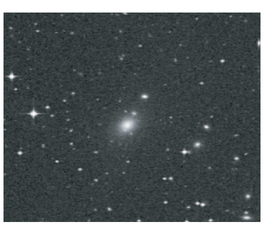
The Spectrum of the Sun

Galaxy Cluster #1

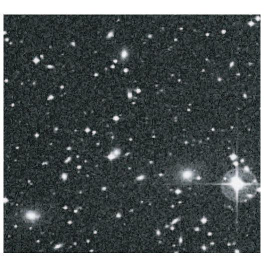
Galaxy Cluster #2



Galaxy Cluster #3



Galaxy Cluster #4



Galaxy Cluster #5

Name:

Extra-Credit Lab 1

World-Wide Web (Extra-credit/Make-up) Exercise

This extra credit project is intended to introduce you to the World Web while at the same time teaching you some interesting facts about astronomy and allowing you to see beautiful astronomy pictures which you might not otherwise see in your textbook or in class. This lab is worth half a lab grade. You should make sure your TA knows that you are planning on doing this lab and turn in this sheet in order for him/her to keep track of extra credit points.

Please allow yourself two hours to complete this extra credit exercise. The computer lab on campus in Jacobs Hall has Macintosh computers available with all of the appropriate software. Those more comfortable using PC's are welcome to use Explorer. We will assume that you are familiar with web surfing, and you do not need assistance. All web browsers work in a similar fashion–there is a box to enter a web address. To start this exercise type in the following address:

http://astronomy.nmsu.edu/astr110/www110.html

This will bring you to the Astronomy 110 World Wide Web (WWW) exercise. Once you are here, you may click on the underlined boldface titles called links ("Picture of the Day", "NSSDC Photo Gallery", etc.) and explore these sites, then return to the 110 exercise page by hitting the "Back" button. Note that you may have to do this a few times before you are returned to the Astro 110 WWW page. Some of the links may open up a separate Netscape window, so if the back button doesn't work, just look to see if your original window is behind the one you are looking at. Once you've explored a page, answer the question related to that page in the box provided. Use the mouse to click in the box; this makes the box active and anything you type will appear in this box. Make sure that when you click in a box you see the cursor appear and that when you type you are able to see the text. If this is not so, double check that you have clicked in the box you are typing in. Otherwise you may be typing in a previously active box. You may also want to write your answers down on a piece of paper in case the answers you typed for earlier questions gets erased. This should not happen, but if it does, just answer the questions on a piece of paper, and then type them all in at the end.

When you are finished with the six sections, type your name, professor's name, and your TA's name in the appropriate boxes (to go from one box to another, either click in the new one with the mouse, or simply hit the "Tab" key). We would also appreciate any comments and/or suggestions you may have on this exercise and homepage. Once you are all done, print out the entire lab and hand it in to your TA.

We have also provided you with some fun and/or useful links for your own browsing. If you enjoy the project and want to see more, click on the "What's New" and "What's Cool" boxes in the second row of buttons. There is a lot of information out there on the internet - now it's at your fingertips!

Once you've completed the exercise, a print out of your answers must be turned-in to your TA in the Astronomy Department. It's best to hand this sheet into your TA when you've finished the project. Your TA will look at your answers and give you extra credit points based on these answers.

If you have problems with this exercise, don't hesitate to ask the Jacobs Computer Lab personnel for help. They are well versed in the use of web, and if you explain to them that it's for a class, they will be more than willing to help. On the other hand, try to figure things out for yourself first – this is your project, not theirs!

Observing Projects

During the semester you may be required to make observations from your home while completing one or more of the projects described below. Your TA will tell you which ones (if any) you must complete. Note that not all of the projects listed here can be completed during every semester due to the changing positions of the planets. Everyone, however, will have to complete the "Observatory Notebook" section which requires you to attend two observing sessions conducted out at the campus observatory.

The goal of this semester-long project is to get you outside observing the night sky. This includes tracking the phases of the Moon, identifying and observing the planets and tracking their motions, and finding constellations. To perform this lab properly, you will have to record your work in an observing notebook, and learn how to use the star charts at the back of the lab manual. So, obtain a small spiral notebook, or some other set-up that allows you to write down your observations and keep them organized (having a bound notebook is useful due to the windy conditions that frequently occur in Las Cruces). This project is worth two regular lab grades, and should be taken very seriously! Your TA will tell you which exercises to do, and how many points each one is worth. Note that all of the observing projects must be started as soon as possible to insure that bad weather does not eliminate the possibility of making your observations. This is especially true of Exercise #3, since you need to track a planet for the entire semester to insure you detect its motion.

Warning: Due to the fact that sky is constantly changing, and astronomical events/objects can only be seen at certain times, it is impossible to cheat on these observing projects! We will know whether you actually observed what you said you observed. So, do not even think about risking the failure of this project (and possibly this course!) by faking your observations, or plagiarizing your friends or any other sources of information.

Setting Up Your "Observatory"

To enable you to complete the assigned exercises in this lab, you must find a site from which you can conduct your observations. This maybe your backyard, near your dorm, or somewhere else of your choosing. The key requirements for a good observing site are clear views of the southern and western horizons (it would also be nice to have a clear view to the East, but it is not always possible to find such a perfect location). You also must not have any bright lights at this site-no streetlights, etc. To conduct your observations it must be as dark as possible. One excellent location on campus to perform these observations is on the activity fields above the track, near the campus observatories. Mark your chosen location (mentally or otherwise) so that you can return to the same spot each time you observe.

After choosing the site for your observatory, you must then find the directions of the cardinal points (North, South, East and West). To find the direction of West is probably the easiest:

simply note the point of sunset on one evening early in the semester. *This is West.* If you face due West, and stick out your left hand horizontally, it will be pointing South. North is directly opposite South, and East is directly opposite West. Note these directions so that you can orient yourself each time you observe. You then need to have a watch, a flashlight, a pencil and your notebook for all of your observing projects.

Observing Project #1: The Ever-Changing Moon

The goal of the first project is to get you familiar with the motion of the Moon, and the changing phases of the Moon. Using a calendar, or asking your TA, find the dates of the next New and Full moons. For this exercise, you will track the phases of the Moon as it progresses from New to Full. This exercise will require you to go outside on eight different nights over a two week period, one time during the semester–DO NOT LEAVE THIS PROJECT UNTIL THE LAST MONTH OF THE SEMESTER!!! If so, you might not have good enough weather or time to allow you to complete this exercise. You need to conduct this project from your observatory site.

Step #1: Find the date of the next New Moon. As you have found out in your lecture class, during New Moon, the Sun, the Earth and the Moon are all on a straight line. At the time of New Moon, the un-illuminated side of the Moon is facing us, and the Moon is located close to the Sun in the sky. Thus we cannot see the Moon during its New phase (unless there is a solar eclipse!). It is usually not possible to see the Moon until two full days after New. Among amateur astronomers, there are contests on who can be the first to see the Moon after a New Moon. The record is 12.1 hours after New Moon. For most people though, it is difficult to see the Moon much less than 24 hours after New Moon. For people in the Northern Hemisphere, however, the days following the New Moons in February and March offer the best chances for seeing a "young Moon" because the tilt of the Earth's axis with respect to its orbit places the Moon vertically above the point of sunset during these months. Given a clear western horizon, and a pair of binoculars, you might be able to see a very young Moon yourself.

Step #2: Beginning (one or) two days after the chosen New Moon, go out about 20 minutes after sunset and look for a very thin crescent Moon near the western horizon. Can you find the Moon? Either way, note the time of your observation in your logbook, and whether you were successful at seeing the Moon. If you saw the Moon, draw a sketch of its appearance. [For this sketch, it might be handy to find a can, a bottle, or drinking glass that is about 2 to 4 inches in diameter and use this to make a perfect circle for the Moon, and then shade in the part you cannot see to render a drawing of the phase of the Moon. Use the same circle-maker for the entire exercise.] In your notebook note the time and date of this observation along with your drawing. Note whether there are any bright stars or planets near the Moon.

Step #3: You must attempt to observe the Moon three days after the time of New Moon. Make a drawing of the phase of the Moon and note the time and date. Observe the Moon about 30 minutes after sunset so that it is fairly dark (the time of sunset can be found in the newspaper or on one of the evening weather forecasts). Besides the bright crescent, can you see the other parts of the Moon glowing faintly? Within a few days after New Moon, it is often quite easy to see the "dark" portion of the Moon (the part not directly illuminated by the Sun). This phenomenon is called "Earthshine", or "the old Moon in the New Moon's arms". For step #3, you need to research the nature of Earthshine. You can use the web (for example enter “Moon and Earthshine” on Google or another search engine) or look in a book to find out the cause of Earthshine. Write-up a paragraph or two in your observatory logbook describing the phenomenon of Earthshine, with a drawing/diagram showing how it arises.

Step #4: Continue to observe the Moon every other day until the Full Phase, and make sure you observe on the night of the Full Moon! Note the time and dates of your observations, and make drawings of the appearance of the Moon. Note the locations of any nearby bright stars or planets. Use the online star charts at `http://astronomy.nmsu.edu/tharriso/skycharts.html` to see if you can identify which constellations the Moon happens to be passing through. Note that the star charts are different for each month, and that the positions of the constellations change throughout the night and month!

Step #5: Describe/summarize your observations of the Moon. When did the Moon reach a phase of “First Quarter” (when was exactly one half of the Moon illuminated)? Was it possible for you to tell on which date the Moon was perfectly Full, or did it look Full to you for several days? Which direction did the Moon move over the course of this two week period? Did it come close to any planets? Any other interesting observations?

Turn in your drawings and log book, including the write-ups to any of the questions asked above.

Observing Project #2: Locating the Naked-Eye Planets

There are five naked eye planets: Mercury, Venus, Mars, Jupiter, and Saturn. All five of these can be easily seen (even in bright city lighting) if they are well placed in the nighttime sky. Your goal is to observe as many of them as possible. Due to the motions of the planets, not all five planets can be seen at any one time. For example, the planet could be located on the other side of the Sun from Earth, and be invisible to us. Usually, however, one or more planets is visible in the evening sky (if not, they are visible in the morning sky!). Your TA will tell you which planets are visible this semester.

Note that Mercury will just about always be the hardest of the planets to observe. It is only easily seen near the times of greatest elongation (see the "Orbit of Mercury" lab for further details). Even then, you have to observe right before sunrise (greatest western elongations), or right after sunset (greatest eastern elongations). Mercury is fairly bright at these times, so it can be seen easily with the naked eye, but you must have a clear horizon to have any chance of seeing it. There are several methods to identifying the planets. Perhaps the easiest is to have one of the TA's at the observatory session point them out to you. But we would like you to be able to search for and find them on your own. One way is to use the sky charts at `http://astronomy.nmsu.edu/tharriso/skycharts.html` . Read about how to use those charts, and then orient yourself by identifying some of the constellations in the nighttime sky using the sky charts. So, if you are told that "Saturn is in Virgo", you can go out, find Virgo, and see that there is a big, bright star there that is not on the sky chart.

But there are two other good sources: online, or in a magazine. "Sky & Telescope" and "Astronomy" are magazines for the amateur astronomy community. Sky & Telescope is a more advanced magazine than Astronomy. Both magazines can be found in our library, or at a book store (such as that in the mall). Inside these magazines are monthly columns that talk about which planets are visible, and where they can be found (including sky charts). In addition, however, both magazines have websites (www.astronomy.com and www.skyandtelescope.com). Both websites have interactive sky charts that show where the planets are in the sky. At the Sky & Telescope website, hit the "Interactive Sky Chart" link. At the Astronomy magazine website, after you register (its free), you can access the skychart by clicking on the link "The Sky Online for Beginners" found on the lefthand side of the main webpage (note that it reads your zipcode to figure out your latitude to make a chart just for you!). The yellow line that runs across the resulting skymap is the "ecliptic" (the plane of the Earth's orbit), and all of the planets will be found close to this line. Note where these planets are with respect to the stars, and find the same constellations on your skycharts and make a little note on the chart so that you can find the planet when you go observing.

Step #1: During the semester identify as many planets in the night time sky as possible.

Write down the details of the time and date of your observations, and constellation in which you found the planet. Mark the location of the planet on the appropriate sky chart (make sure to turn-in this chart, or a photocopy/handmade version of this chart, with the rest of your materials at the end of the semester). Note that the planets are just about always the brightest "stars" in each constellation, and thus are very hard to miss! You should conduct this exercise from your observing site (unless your western horizon is not good enough to allow you to see Mercury-if so, you can observe Mercury from the campus observatory, or some other site with a good western horizon).

Observing Project #3: Tracking the Motion of a Planet Over the Semester

For this exercise you will be plotting the position of either Venus, Mars, Jupiter or Saturn about once per week during the entire semester. You need to make at least ten observations of the chosen planet spread out over the entire semester-you must start this by the second or third week of lab to insure that you have enough time and observations to complete this exercise. Your TA will tell you which planet you are to observe, and possibly hand out a worksheet on which to record your results (for some planets, such as Mars, the skycharts at: `http://astronomy.nmsu.edu/tharriso/skycharts.html` are sufficient for this project). This is the hardest of the observing exercises. If you need some help, ask your TA, or one of the TAs at the observatory. You can conduct this exercise from any location that works best for you.

Step #1: Identify the constellation where your TA says the planet is located. For all of the planets except Venus, go out after about 9 or 10 pm early in the semester (dress warmly!!). As the semester progresses your planet will rise earlier, and earlier, and near the end of it semester will be visible right after sunset. If the chosen planet is Venus, you will need to go out about 20 minutes after sunset to find Venus. Venus is the brightest star-like object in the entire sky (only the Sun and Moon are brighter). Note in your logbook the time and date when you finally identified the constellation containing your planet (it is quite possible that the planet will actually move from one constellation to another during the semester).

Step #2: Identify the chosen planet. This is easy-in fact, it might be easier for you to first find your planet AND then identify the constellation it is in! Normally, the planet chosen for this exercise will be the brightest object in the nighttime sky after the Moon. Sometimes, however, Mars and Saturn can be fainter than some of the brightest nighttime stars. Note the time and date when you first found your planet.

Step #3: Marking the position of your planet on the star chart. This is the hardest part of the lab. It is likely that you will require a better star map than the online skycharts to properly keep track of your planet. If so, your TA will give you a handout with a blown-up version of the constellation/sky region containing your planet. Use this star chart in concert with those online to identify the names/letters of the brightest stars closest to your planet. Note that the brightest star in a constellation was usually given the designation α (= "Alpha")), the first letter in the Greek alphabet. This progresses all the way to the last Greek letter Omega (ω) [For more on the Greek letters, see the little table on cover page for the sky charts.] After that, the fainter stars were given numbers. If you have too many bright lights near your observatory site, you might not be able to see very many of the stars marked on the close-up chart, and might have to conduct this exercise at a location where the sky is a bit darker. If you are still having trouble seeing many stars, see if you can borrow a pair of binoculars to help you better identify the stars near your planet.

Step #4: Tracking the motion of the planet by plotting it on the chart/map designated by your TA. Usually the planet will spend the entire semester on this chart. For some fast moving planets (Mars and Venus), you might need to use more than one chart. If you are given a worksheet, it is likely that there is a dotted line that goes from one side of the chart to the other: this line dilineates the ecliptic, the apparent path of the Sun through the sky (the projection of the Earth's orbital plane). Most planets are found close to the ecliptic. Use this worksheet for plotting the position of the planet. Using the skychart from the back of the lab manual, and/or the worksheet, locate the position of the planet in the sky. Mark its position on the star chart with the date of observation. Note in your logbook the time of this observation. Every week or ten days, go out and observe the planet, and plot its position on your worksheet. You should have ten observations spanning nearly the entire semester to complete this project.

Step #5: Summarize the motion of your planet during the semester. How far did the planet move? To do this, note that the little squares formed by the grid lines in the close-up sky chart are exactly one degree on a side. How many degrees did your planet move? Given that there are 360 degrees in a circle, how many months will it take your planet to move completely around the sky? Which direction did it move during the semester? Did it follow the ecliptic, or did it move north/south of the ecliptic? Why do you think it did this?

Write up your results and turn them in with your other observing materials.

Observing Project #4: Discovering a Constellation and its Mythology, and Creating One of Your Own

The goal of this project is very simple: use the online star charts identify a constellation in the night sky. You then have to research the origin of this constellation and its mythology and write it up and turn it in. In addition, you are required to go out and create your own constellation using the stars in this, or in any other constellations. You then must create a mythology for your new constellation and write it up and turn it in.

Step 1: Look at the various star charts *for the different months that occur during this semester*. Find a constellation that intrigues you [unless your TA gives you permission to do so, please do not choose any of the constellations "highlighted" in the online sky charts!]. Remember, not every constellation found on those charts is going to be visible to you. Sometimes a nearby building, tree, or mountain may block your view of a particular constellation. Note that over the course of the semester some constellations will disappear from view in the West, while others will appear in the East. This ever-changing sky is due to the Earth's motion around the Sun. After you have decided on a constellation, find out the best time to observe it (note that if you stay up late, the constellations seen in the later months of the semester can be seen near midnight at the beginning of the semester). Go out and find your constellation! Write-up a description of how you found it. What was the time and date that you first found your constellation? Was it in the West, straight overhead or in the Southeast, etc. ?

Step 2: Use the internet or a book from the library to research the mythology of your chosen constellation. Note that some constellations are modern creations, and do not have a mythology associated with them. If you chose one of these less interesting star patterns, why not go back and choose another (generally larger!) constellation. Most of our constellation names and their mythologies come from the Greeks and Romans. But just about all of the major cultures on our planet have created constellation mythologies. See if you can find one of these alternative stories for the stars of your chosen constellation (one example is the constellation Orion described in the constellation highlight for February). Are there any interesting or famous objects located in your constellation (star clusters, planets, galaxies)? Do any of the stars have interesting or unusual names with their own stories? Your mythology write-up should be one page singlespaced, two pages doublespaced. Please list the references/websites you used to learn the constellation's mythology.

Step 3: Creating your own constellation. Without using a star map, just sit back/lay down one evening and stare at the stars. Do you see any familiar patterns amongst the stars? As you have probably noticed, many of the classical constellations do not resemble the objects they are suppose to represent. They were created to honor an important character that occurred in one of that culture's stories (and sometimes history). So, your constellation doesn't have to be a perfect representation of the object it is suppose to represent.

Now, use the appropriate star chart and draw lines to connect the stars that make up your constellation. Turn this chart in with the rest of your observing project materials.

Step 4: Creating and writing-up your constellation's mythology. The final step is to create a mythology to go with your new constellation. Name the brightest stars in your constellation (for example, maybe your constellation represents the 2007 New England Patriots, and its brightest star is Tom Brady). Your mythology write-up should be at least a page long.

Turn in all of the materials from these four steps.

Observatory Notebook

(Check Lab Syllabus for Due Dates)

Introduction

Observations are the fundamental tool of the astronomer. Astronomers cannot go out and collect objects of study as a biologist, chemist, or geologist might. They must sit on Earth and study images or pictures of astronomical objects and learn what they can from these images. This may seem like a difficult task, trying to learn from pictures, but light holds a vast amount of information. By studying objects in the sky at different wavelengths, we may learn a great deal about what is happening at great distances.

Before the invention of photographic film, astronomers made images of the sky by sitting in front of a telescope and carefully drawing what they saw. Many fantastic discoveries were made this way. The discovery that the Horsehead Nebula changed shape over several years was made by comparing two accurate drawings made over a span of a few decades. Galileo observed the motions of Jupiter's moons which confirmed the Copernican model of the solar system. Galileo also observed and drew sunspots proving that the Sun was not a pristine perfect object, but was in fact active and changing all of the time.

Your task over the course of the semester will be to keep an Observatory Notebook. In this notebook you will draw pictures and give descriptions of many different types of objects you will see in the sky with the help of the telescopes at the campus observatory.

Instructions

You are REQUIRED to go to the campus observatory twice during each semester. At each visit you are required to see a specific number of objects. If you are unable to complete the necessary number of objects in one visit, make sure you return as many times as necessary to complete the required number of objects. Your observations will be due at the halfway point of the semester, and at the end of the semester (your TA will give you the exact dates). Because the skies change over the course of the semester, objects which are visible one month may not be visible the next month. For this reason you must complete all required observations within each (half semester) observing window. If you observe less than the required number of objects for the first half, you cannot make up the missed points during the second half. Please keep this in mind when you attend the observatory sessions. It is usually possible to obtain all of your observations in one night, especially if it is not too crowded, and the weather is clear. **Hint: GO TO THE CAMPUS OBSERVATORY NEAR THE BEGINNING OF OBSERVING PERIOD TO AVOID THE LAST WEEK RUSH!!** Also remember that even if it is cloudy the entire last week of each observing period, you are still responsible for the required number of observations if the weather has been clear enough earlier in each observing period!

The following sheets are the observation notebook worksheets; **TAKE THESE WITH YOU TO THE OBSERVATORY** and fill out one of these sheets for each object you observe. When you attend the observatory sessions, a TA will be present to assist you with the telescope and give you some important information about the objects you will be viewing. After you look at the object through the telescope, take some time to draw a sketch of what you saw. In the appropriate spaces, write down the date, time, description of the object, observing conditions, which of the telescopes was used, and any other details you think are important. Have the TA initial/stamp each sheet as proof of your attendance to the observatory session that night. Before turning in your notebook each month, you should also look up some information about each of the objects and write it down under the description section of the corresponding notebook page.

Campus Observatory Observation Sheet

Your Name: ____________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ____________________

Type of Object: ____________________ Object Name: ____________________

Object Description: ____

Fact about this object : ____

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Source of information: ____

Campus Observatory Observation Sheet

Your Name: ______________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ______________

Type of Object: _________________ Object Name: ___________

Object Description: ______________________________________

Fact about this object : __________________________________

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Source of information: ____________________________________

Campus Observatory Observation Sheet

Your Name: ______________________ T.A.: ______________________

Date & Time: ____________________ Telescope: ______________

Type of Object: _________________ Object Name: ___________

Object Description: ____

Fact about this object : ___________________________________

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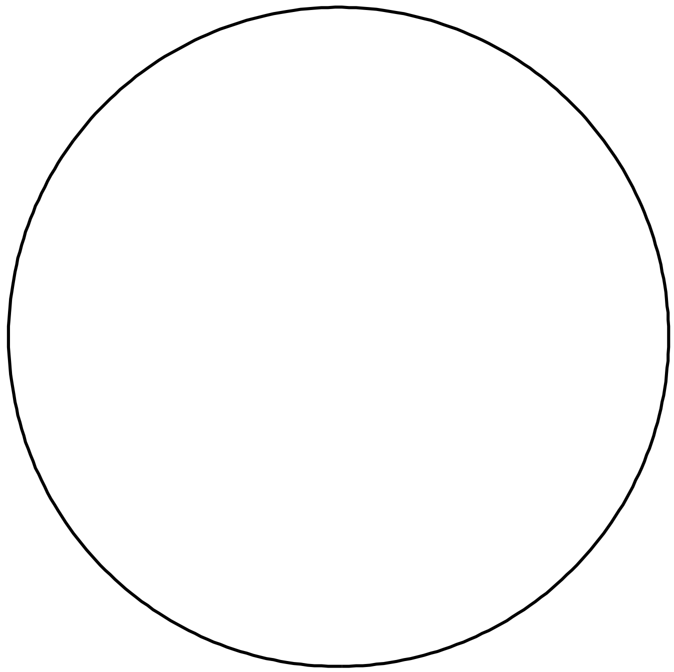
Source of information: ______________________________________

Campus Observatory Observation Sheet



Your Name: ____________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ______________

Type of Object: ________________ Object Name: ___________

Object Description: ______________________________________

Fact about this object : ___________________________________

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Source of information: _____________________________________

Campus Observatory Observation Sheet

Your Name: ______________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ______________

Type of Object: __________________ Object Name: ___________

Object Description: ____

Fact about this object : ____________________________________

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Source of information: ______________________________________

Campus Observatory Observation Sheet

Your Name: ____________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ____________________

Type of Object: ____________________ Object Name: ____________________

Object Description: ____

Fact about this object : ____

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Source of information: ____

Campus Observatory Observation Sheet

Your Name: ______________________ T.A.: ______________________

Date & Time: ____________________ Telescope: ______________

Type of Object: _________________ Object Name: ___________

Object Description: ____

Fact about this object : ______________________________________

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Source of information: ____

Campus Observatory Observation Sheet

Your Name: ______________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ______________

Type of Object: _________________ Object Name: ___________

Object Description: ____

Fact about this object : ____

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Source of information: ______________________________________

Campus Observatory Observation Sheet

Your Name: ______________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ______________

Type of Object: __________________ Object Name: ___________

Object Description: ____

Fact about this object : ____________________________________

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Source of information: ______________________________________

Campus Observatory Observation Sheet

Your Name: ________________ T.A.: ________________

Date & Time: ________________ Telescope: ________________

Type of Object: ________________ Object Name: ________________

Object Description: ________________________________

Fact about this object : ________________________________

Source of information: ________________________________