ASTR 105G Lab Manual

Astronomy Department
New Mexico State University

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Contents

Name:________________________________
Date:________________________________

1 Tools for Success in ASTR 105G

1.1 Introduction

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

1.2 The Metric System

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

As you have almost certainly learned, the metric system uses prefixes to change scale. For example, one thousand meters is one "kilometer." One thousandth of a meter is a "millimeter." The prefixes that you will encounter in this class are listed in Table 1.2.

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

Table 1.1: Metric System Prefixes

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

1.3 Beyond the Metric System

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

1.4 Changing Units and Scale Conversion

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

1. Convert 34 meters into centimeters:

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

2. Convert 34 kilometers into meters:

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

4. How many centimeters are there in 400 inches?

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

1.4.1 Map Exercises

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

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

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

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

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

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

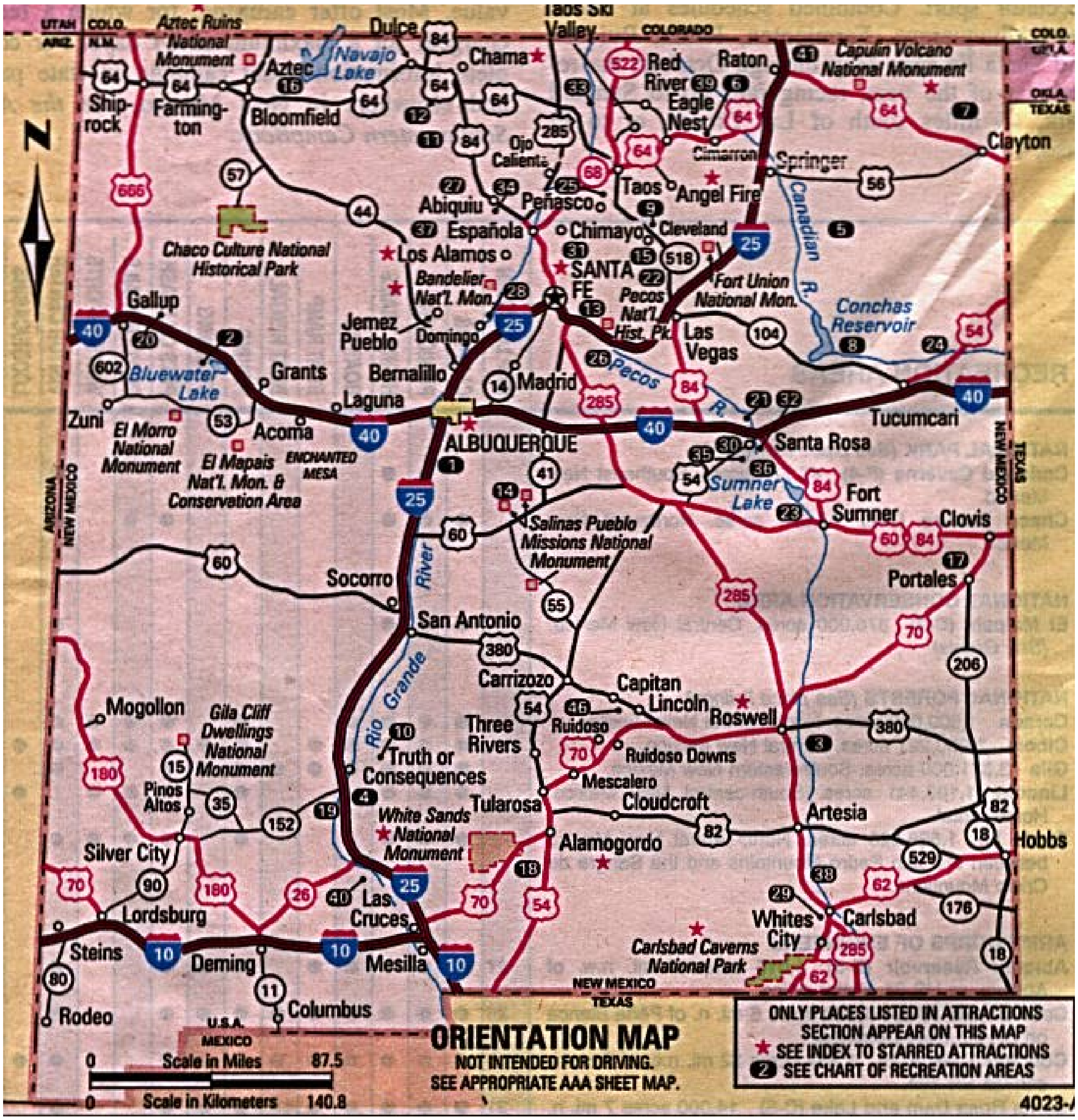


Figure 1.1: Map of New Mexico.

1.5 Squares, Square Roots, and Exponents

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

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

Your turn (2 points each):

10. $6^3 =$

11. $4^4 =$

12. $3.1^2 =$

The concept of a square root is fairly easy to understand, but is much harder to calculate (we usually have to use a calculator). The square root of a *number* is that number whose square is the *number*: the square root of 4 = 2 because $2 \times 2 = 4$. 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. Here are some example problems:

- $\sqrt{100} = 10$

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

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

1.6 Scientific Notation

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

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

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

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

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

- $1{,}345{,}999{,}123{,}456 = 1345999123456.0 = 1.345999123456 \times 10^{12} \approx 1.346 \times 10^{12}$

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

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

13. $121 = 121.0 =$

14. $735{,}000 =$

15. $999{,}563{,}982 =$

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

- $0.121 = 1.21 \times 10^{-1}$
- $0.000735 = 7.35 \times 10^{-4}$
- $0.0000099902 = 9.9902 \times 10^{-6}$

Your turn (2 points each):

16. $0.0121 =$

17. $0.0000735 =$

18. $0.0000000999 =$

19. $-0.121 =$

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

1.7 Calculator Issues

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

1.7.1 Scientific Notation on a Calculator

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

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

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

- 7.99921×10^{21}
- 2.2951324×10^{-6}

1.7.2 Order of Operations

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

i. Calculations must be done from left to right.

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

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

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

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

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

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

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

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

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

1.8 Graphing and/or Plotting

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

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

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

1.8.1 The Mechanics of Plotting

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

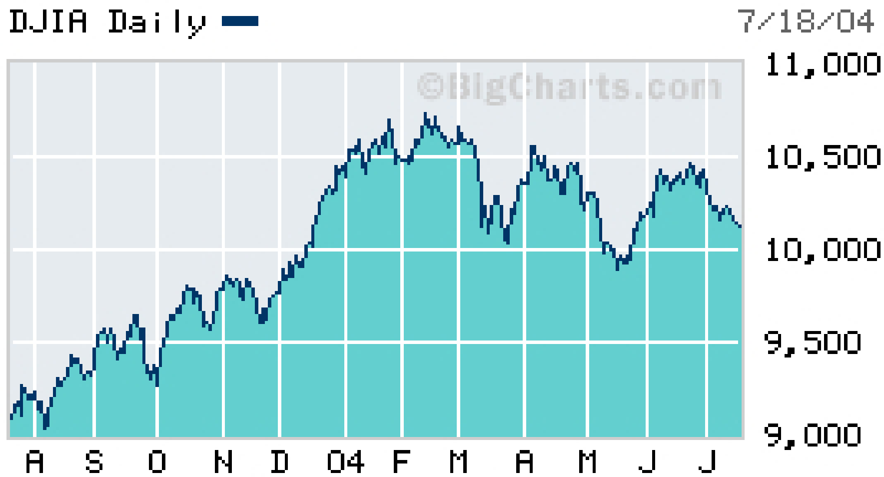


Figure 1.2: The change in the Dow Jones stock index over one year (from April 2003 to July 2004).

Table 1.2: Temperature vs. Altitude

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

First of all, the plot axes **must be labeled.** This will be emphasized throughout the semester. In order to quickly look at a graph and determine what information is being conveyed, it is imperative that both the x-axis and y-axis have labels.

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

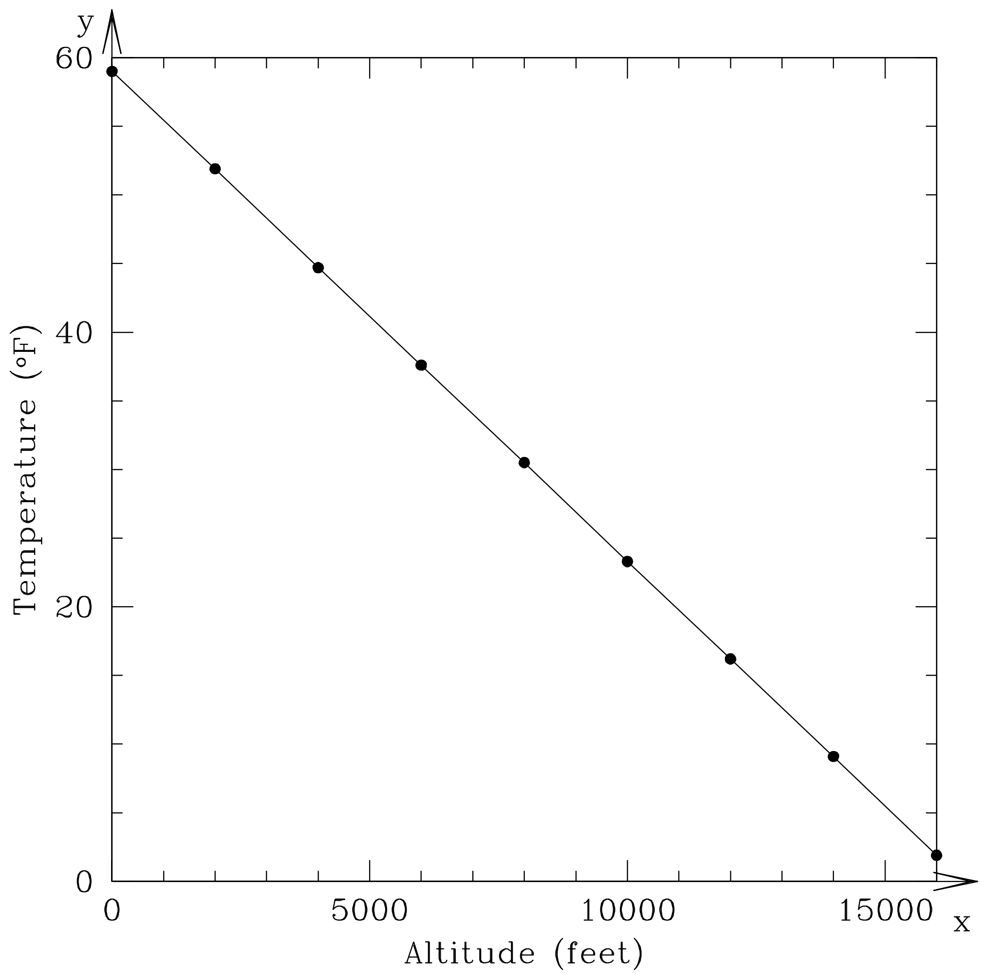


Figure 1.3: The change in temperature as you climb in altitude with the data from Table 1.2. At sea level (0 ft altitude) the surface temperature is 59°F. As you go higher in altitude, the temperature goes down.

1.8.2 Plotting and Interpreting a Graph

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

23. On the blank sheet of graph paper in Figure 1.4, plot the hourly temperatures measured for Tucson and Honolulu on 19 January 2006. (**4 points**)

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

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

Table 1.3: Hourly Temperature Data from 19 January 2006

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

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

While straight lines and perfect data show up in science from time to time, it is actually quite rare for *real* data to fit perfectly on top of a line. One reason for this is that all measurements have *error*. So even though there might be a perfect relationship between x and y, the uncertainty of the measurements introduces small deviations from the line. In other cases, the data are *approximated* by a line. This is sometimes called a *best-fit* relationship for the data.

1.9 Does it Make Sense?

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

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

One of our primary goals this semester is to help you develop intuition about our solar system. This includes recognizing if an answer that you get "makes sense." For example, you may be told (or you may eventually know) that Mars is 1.5 AU from Earth. You also know that the Moon is a lot closer to the Earth than Mars is. So if you are asked to calculate the Earth-Moon distance and you get an answer of 4.5 AU, this should alarm you! That would imply that the Moon is **three times** farther away from Earth than Mars is! And you know that's not right.

Use your intuition to answer the following questions. In addition to just giving your answer, state *why* you gave the answer you did. (**4 points each**)

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

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

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

1.10 Putting it All Together

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

30. To travel from Las Cruces to New York City by car, you would drive 3585 km. What is this distance in AU? (**4 points**)

31. The Earth is 4.5 billion years old. The dinosaurs were killed 65 million years ago due to a giant impact by a comet or asteroid that hit the Earth. If we were to compress the history of the Earth from 4.5 billion years into one 24-hour day, at what time would the dinosaurs have been killed? (**4 points**)

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

Name(s):______________________________
Date:___________________________________

2 The Origin of the Seasons

2.1 Introduction

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

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

- *Goals:* To learn why the Earth has seasons.
- *Materials:* a meter stick, a mounted 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.

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°) means? Yes, it is right on the equator. Remember, latitude runs from 0.0° at the equator to ±90° at the poles. If north of the equator, we say the latitude is XX degrees north (or sometimes "+XX degrees"), and

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

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.

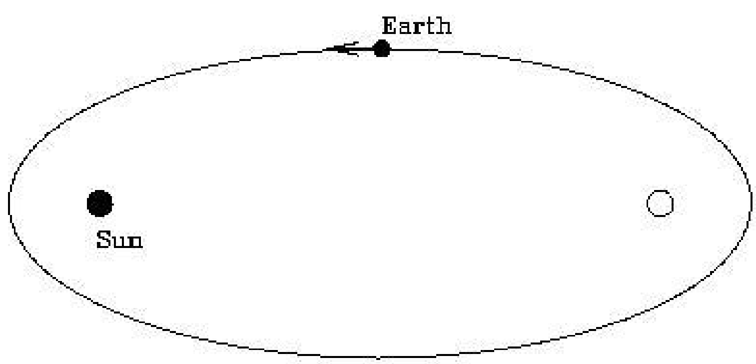


Figure 2.1: An ellipse with the two "foci" identified. The Sun sits at one focus, while the other focus is empty. The Earth follows an elliptical orbit around the Sun, but not nearly as exaggerated as that shown here!

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.

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

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

As the second photograph shows, the direction of the spin axis of the Earth does not

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

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°.

Set up the experiment in the following way. Place the halogen lamp at one end of the table (shining towards the closest wall so as to not affect your classmates), and set the globe at a distance of 1.5 meters from the lamp. After your TA has dimmed the classroom lights, turn on the halogen lamp to the highest setting (depending on the lamp, there may be a dim, and a bright setting). Note these lamps get very hot, so be careful. For this lab, we will define the top of the globe as the Northern hemisphere, and the bottom as the Southern hemisphere.

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

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

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

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		

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)

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

Latitude	Daylight Hours	Nighttime Hours
Equator		
45ºN		
Arctic Circle		
Antarctic Circle		

20) What about near the poles? In this orientation what is the length of the nighttime at the North pole, and what is the length of the daytime at the South pole? Is this consistent with the trends in Table 2.1, such as what is happening at Fairbanks or in Ushuaia? (4 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 180º 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		
45ºN		
Arctic Circle		
Antarctic Circle		

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

Latitude	Daylight Hours	Nighttime Hours
Equator		
45ºN		
Arctic Circle		
Antarctic Circle		

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

nighttime for the +45° degree latitude with that for Minneapolis. What season does this appear to be? (2 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 21st) there are more daylight hours, at the start of the Autumn (∼ Sept. 20th) and Spring (∼ Mar. 21st) the days are equal to the nights. In the Winter (approximately Dec. 21st) 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

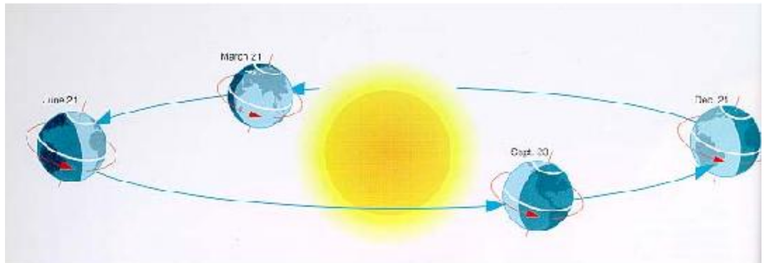


Figure 2.4: The Earth's spin axis always points to one spot in the sky, *and* it is tilted by 23.5° to its orbit. Thus, as the Earth orbits the Sun, the illumination changes with latitude: sometimes the North Pole is bathed in 24 hours of daylight, and sometimes in 24 hours of night. The exact opposite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

the Summer, the temperature barely rises above freezing! Why? We will discover the reason for this now.

2.4 Elevation Angle and the Concentration of Sunlight

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

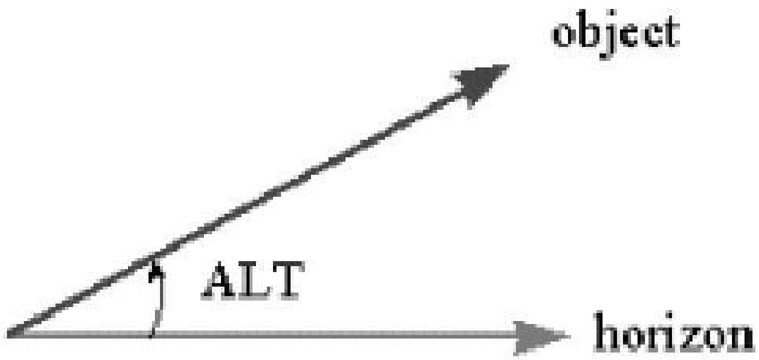


Figure 2.5: Altitude ("Alt") is simply the angle between the horizon, and an object in the sky. The smallest this angle can be is 0°, and the maximum altitude angle is 90°. Altitude is interchangebly known as elevation.

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 21^{st}. On both March 21^{st} and September 20^{th}, the altitude of the Sun at noon is 57.5°. On December 21^{st} 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. 3.4. 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 length of b = ___________ cm.

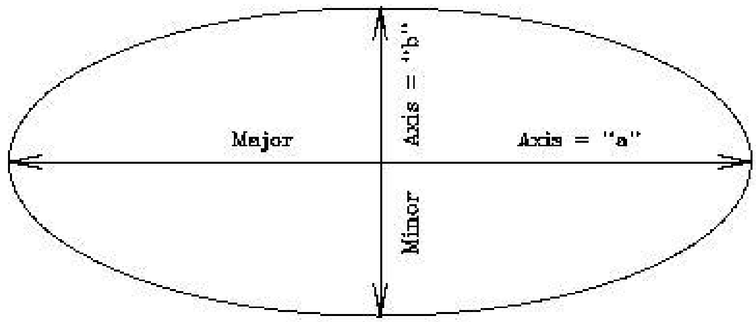


Figure 2.6: An ellipse with the major and minor axes defined.

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 night from everywhere on Earth. To try to understand this, take a look at Fig. 2.7. In this figure is shown the celestial geometry explicitly showing that the Celestial Equator is simply the Earth's equator projected onto the sky (left hand diagram). But the Earth is large, and to us, it appears flat. Since the objects in the sky are very far away, we get a view like that shown in the right hand diagram: we see one hemisphere of the sky, and the stars, planets, Sun and Moon rise in the east, and set in the west. But note that the Celestial Equator exactly intersects East and West. Only objects located on the Celestial Equator rise exactly due East, and set exactly due West. All other objects rise in the northeast or southeast and set in the northwest or the southwest. Note that in this diagram (for a latitude of 40°) all stars that have latitudes (astronomers call them "Declinations", or "dec") above 50° never set–they are circumpolar.

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

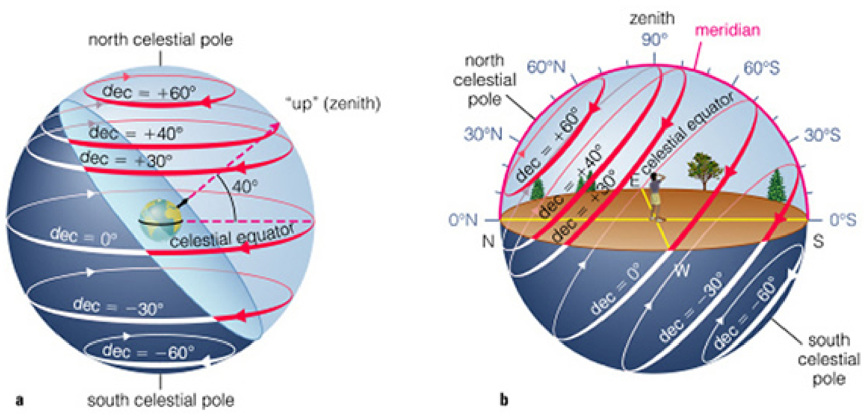


Figure 2.7: The Celestial Equator is the circle in the sky that is straight overhead ("the zenith") of the Earth's equator. In addition, there is a "North Celestial" pole that is the projection of the Earth's North Pole into space (that almost points to Polaris). But the Earth's spin axis is tilted by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

Name:______________________________
Date:______________________________

2.5 Take Home Questions *(35 points)*

- 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.

Name:______________________________

Date:______________________________

3 Kepler's Laws

3.1 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 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.

3.2 Gravity

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

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

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

A diagram detailing the quantities in this equation is shown in Fig. 3.1. 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.

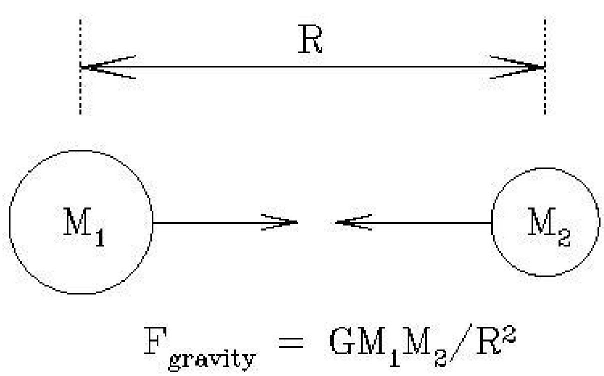


Figure 3.1: The force of gravity depends on the masses of the two objects (M_1, M_2), and the distance between them (R).

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

3.3 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: $\mathrm{P}^2 \propto a^3$"

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. 3.2.

Before we describe an ellipse, let's examine a circle, as it is a simple form of an ellipse. As you are aware, the circumference of a circle is simply 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. 3.3, 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. 3.4 is an ellipse with the two foci indentified, "F_1" and "F_2".

Exercise #1: On the ellipse in Fig. 3.4 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)

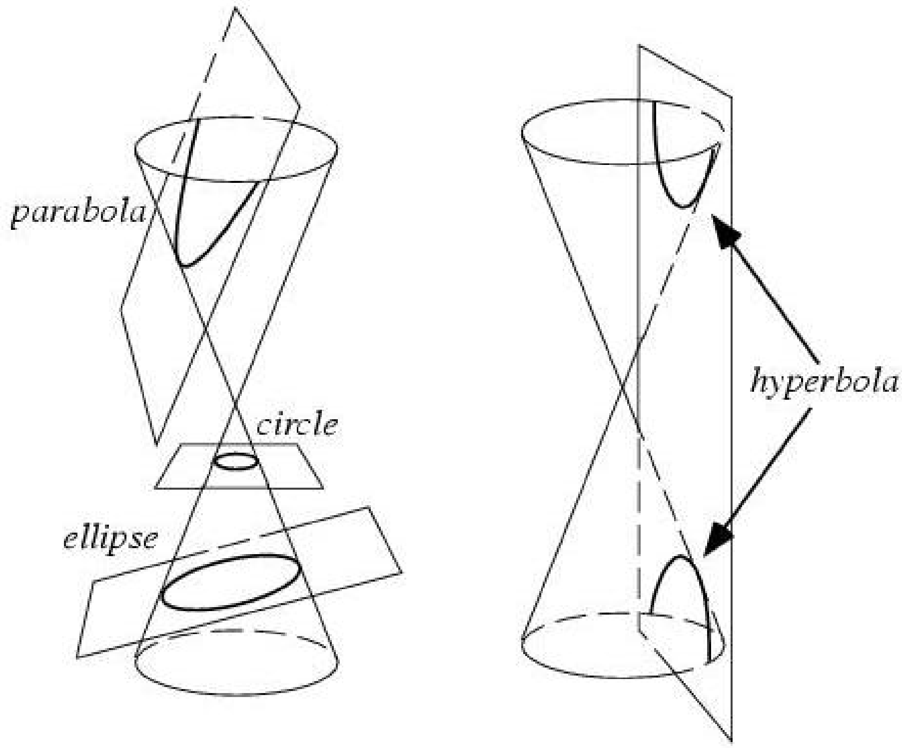


Figure 3.2: Four types of curves can be generated by slicing a cone with a plane: a circle, an ellipse, a parabola, and a hyperbola. Strangely, these four curves are also the allowed shapes of the orbits of planets, asteroids, comets and satellites!

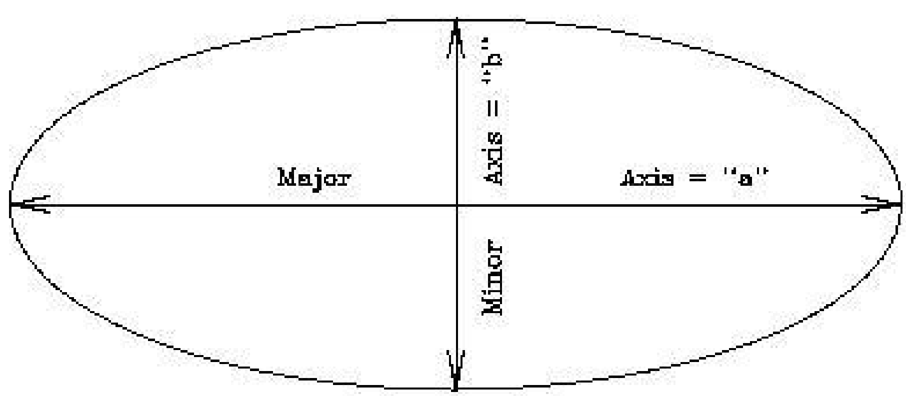


Figure 3.3: An ellipse with the major and minor axes identified.

Exercise #2: In the ellipse shown in Fig. 3.5, 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)

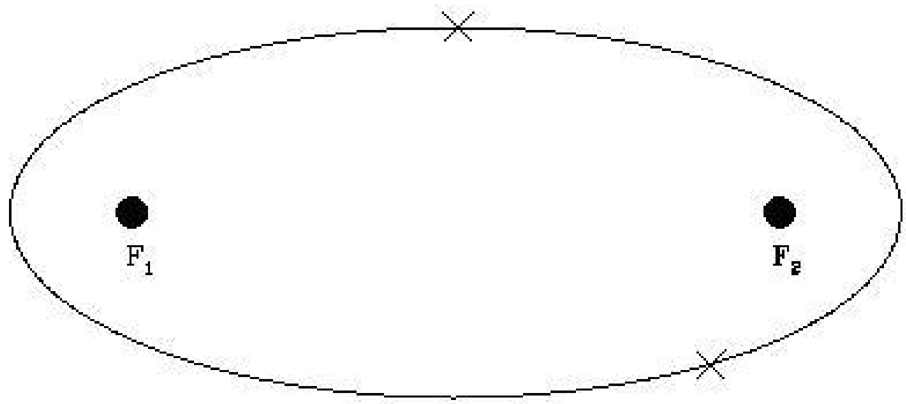


Figure 3.4: An ellipse with the two foci identified.

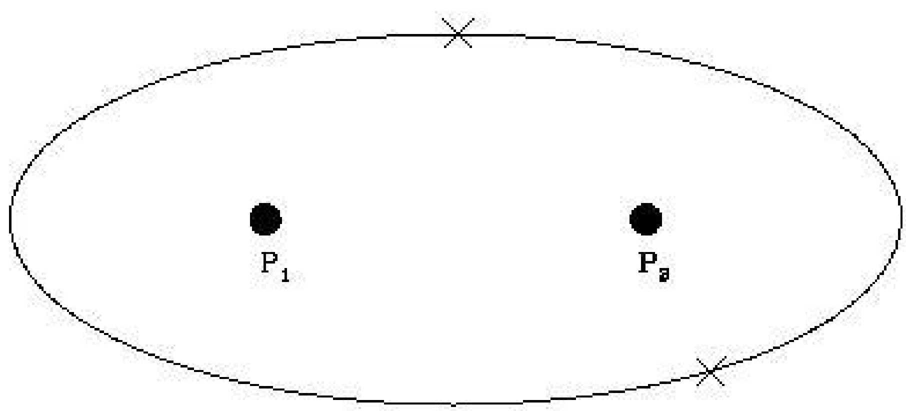


Figure 3.5: An ellipse with two non-foci points identified.

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:

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

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:

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

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

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

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

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

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

Let's use equation (5) to make some predictions. If the average distance of Jupiter from the Sun is about 5 AU, what is its orbital period? Set-up the equation:

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

So, for Jupiter, $P^2 = 125$. How do we figure out what P is? We have to take the square root of both sides of the equation:

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

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

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

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

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

Table 3.1: 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)

3.4 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. 3.6 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 ($\mathrm{M}_1 \approx \mathrm{M}_2$), but this is not always the case. In the first (default) binary star simulation, $\mathrm{M}_1 = 2\mathrm{M}_2$. The "mass ratio" ("$q$") in this case is 0.5, where mass ratio is defined to be $q = \mathrm{M}_2/\mathrm{M}_1$. Here, $\mathrm{M}_2 = 1$, and $\mathrm{M}_1 = 2$, so $q = \mathrm{M}_2/\mathrm{M}_1 = 1/2 = 0.5$. This is the number that appears in the "Mass Ratio"

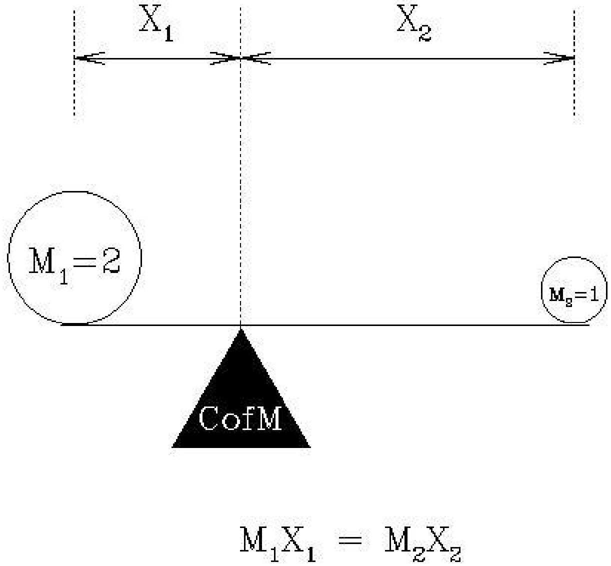


Figure 3.6: A diagram of the definition of the center of mass. Here, object one (M_1) is twice as massive as object two (M_2). Therefore, M_1 is closer to the center of mass than is M_2. In the case shown here, $X_2 = 2X_1$.

window of the simulation.

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

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

Ok, now we want to run a simulation where only the mass ratio is going to be changed. Go back to Input and enter in the correct mass ratio for a binary star system with $M_1 = 4.0$, and $M_2 = 1.0$. Run the simulation. Describe what is happening in this simulation. How are the stars located with respect to the center of mass? Why? [Hint: see Fig. 3.6.] (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. In the Comet lab, you can find some images where a comet ran into Jupiter. The orbits of comets are very long ellipses, and when they come close to the Sun, their orbits can get changed by passing close to a major planet. The gravitational pull of the planet changes the shape of the comet's orbit, it speeds up, or slows down the comet. This can cause the comet to crash into the Sun, or into a planet, or cause it to be ejected completely out of the solar system. (You can see an example of the latter process by changing the Planet–Star Distance = 0.4 in the current simulation.)

Name:____________________________________

Date:______________________________________

3.5 Take Home Questions

(35 points) Please summarize the important concepts of this lab. Your responses 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.

3.6 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)

Name:______________________________
Date:______________________________

4 The Orbit of Mercury

Of the five planets known since ancient times (Mercury, Venus, Mars, Jupiter, and Saturn), Mercury is the most difficult to see. In fact, of the 6 billion people on the planet Earth it is likely that fewer than 1,000,000 (0.0002%) have *knowingly* seen the planet Mercury. The reason for this is that Mercury orbits very close to the Sun, about one third of the Earth's average distance. Therefore it is always located very near the Sun, and can only be seen for short intervals soon after sunset, or just before sunrise. It is a testament to how carefully the ancient peoples watched the sky that Mercury was known at least as far back as 3,000 BC. In Roman mythology Mercury was a son of Jupiter, and was the god of trade and commerce. He was also the messenger of the gods, being "fleet of foot", and commonly dipicted as having winged sandals. Why this god was associated with the planet Mercury is obvious: Mercury moves very quickly in its orbit around the Sun, and is only visible for a very short time during each orbit. In fact, Mercury has the shortest orbital period ("year") of any of the planets. You will determine Mercury's orbital period in this lab. [Note: it is very helpful for this lab exercise to review Lab #1, section 1.5.]

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

Mercury and Venus are called "inferior" planets because their orbits are interior to that of the Earth. While the planets Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto are called "superior" planets, as their orbits lie outside that of the Earth. Because the orbits of Mercury and Venus are smaller than the Earth's, these planets can never be located very far from the Sun as seen from the Earth. As discovered by Galileo in 1610 (see Fig. 4.1), the planet Venus shows phases that look just like those of the Moon. Mercury also shows these same phases. As can be envisioned from Figure 4.1, when Mercury or Venus are on the far side of the Sun from Earth (a configuration called "superior" conjunction), these two planets are seen as "full". Note, however, that it is almost impossible to see a "full" Mercury or Venus because at this time the planet is very close to, or behind the Sun. When Mercury or Venus are closest to the Earth, a time when they pass between the Earth and the Sun (a configuration termed "inferior" conjunction), we would see a "new" phase. During their new phases, it is also very difficult to see Mercury or Venus because their illuminated hemispheres are pointed away from us, and they are again located *very* close to the Sun in the sky.

The best time to see Mercury is near the time of "greatest elongation". At the time of greatest elongation, the planet Mercury has its largest *angular* separation from the Sun as seen from the Earth. There are six or seven greatest elongations of Mercury each year. At the time of greatest elongation, Mercury can be located up to 28° from the Sun, and sets (or rises) about two hours after (or before) the Sun. In Figure 4.2, we show a diagram for the greatest elongation of Mercury that occurred on August 14, 2003. In this diagram, we

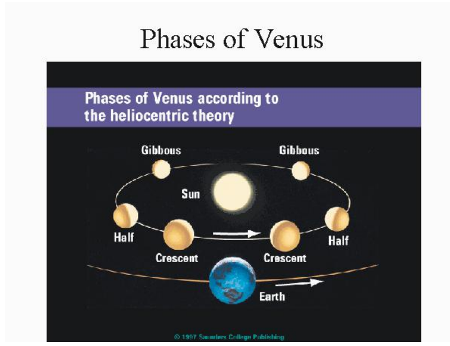


Figure 4.1: A diagram of the phases of Venus as it orbits around the Sun. The planet Mercury exhibits the same set of phases as it too is an "inferior" planet like Venus.

plot the positions of Mercury and the Sun at the time of sunset (actually just a few minutes before sunset!). As this diagram shows, if we started our observations on July 24th, Mercury would be located close to the Sun at sunset. But as the weeks passed, the angle between Mercury and the Sun would increase until it reached its maximum value on August 14th. After this date, the separation between the Sun and Mercury quickly decreases as it heads towards inferior conjunction on September 11th.

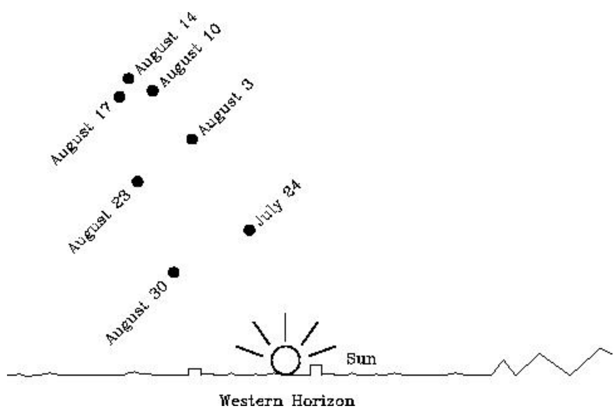


Figure 4.2: The eastern elongation of August, 2003. Mercury was at superior conjunction on July 5th, and quickly moved around its orbit increasing the angular separation between it and the Sun. By July 24th, Mercury could be seen just above the Sun shortly after sunset. As time passed, the angular separation between the Sun and Mercury increased, reaching its maximum value on August 14th, the time of greatest Eastern elongation. As Mercury continued in its orbit it comes closer to the Earth, but the angular separation between it and the Sun shrinks. Eventually, on September 11th, the time of inferior conjunction, Mercury passed directly between the Earth and the Sun.

You can see from Figure 4.2 that Mercury is following an orbit around the Sun: it was "behind" the Sun (superior conjunction) on July 5th, and quickly races around its orbit until the time of greatest elongation, and then passes between the Earth and the Sun on September 11th. If we used a telescope and made careful drawings of Mercury throughout this time, we would see the phases shown in Figure 4.3. On the first date in Figure 4.2 (July

24$^{\text{th}}$), Mercury was still on the far side of the Sun from the Earth, and almost had a full phase (which it only truly has at the time of superior conjunction). The disk of Mercury on July 24$^{\text{th}}$ is very small because the planet is far away from the Earth. As time passes, however, the apparent size of the disk of Mercury grows in size, while the illuminated portion of the disk decreases. On August 14$^{\text{th}}$, Mercury reaches greatest elongation, and the disk is half-illuminated. At this time it looks just like the first quarter Moon! As it continues to catch up with the Earth, the distance between the two planets shrinks, so the apparent size of Mercury continues to grow. As the angular separation between Mercury and the Sun shrinks, so does the amount of the illuminated hemisphere that we can see. Eventually Mercury becomes a crescent, and at inferior conjunction it becomes a "new" Mercury.

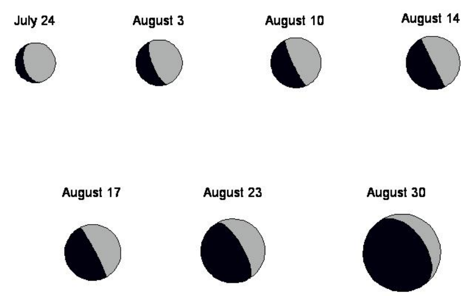


Figure 4.3: A diagram showing the actual appearance of Mercury during the August 2003 apparition. As Mercury comes around its orbit from superior conjunction (where it was "full"), it is far away from the Earth, so it appears small (as on July 24$^{\text{th}}$). As it approaches greatest elongation (August 14$^{\text{th}}$) it gets closer to the Earth, so its apparent size grows, but its phase declines to half (like a first quarter moon). Mercury continues to close its distance with the Earth so it continues to grow in size–but note that the illuminated portion of its disk shrinks, becoming a thin crescent on August 30$^{\text{th}}$. As Mercury passes between the Earth and Sun it is in its "new" phase, and is invisible.

4.1 Eastern and Western Elongations

The greatest elongation that occurred on August 14, 2003 was a "greatest Eastern elongation". Why? As you know, the Sun sets in the West each evening. When Mercury is visible *after* sunset it is located to the East of the Sun. It then sets in the West *after* the Sun has set. As you can imagine, however, the same type of geometry can occur in the morning sky. As Mercury passed through inferior conjunction on September 11$^{\text{th}}$, it moved into the morning sky. Its angular separation from the Sun increased until it reached "greatest Western elongation" on September 27$^{\text{th}}$, 2003. During this time, the phase of Mercury changed from "new" to "last quarter" (half). After September 27$^{\text{th}}$ the angular separation between the Sun and Mercury shrinks, as does the apparent size of the disk of Mercury, as it reverses the sequence shown in Figure 4.3. A diagram showing the geometry of eastern and western elongations is shown in Figure 4.4. [Another way of thinking about what each of these means, and an analogy that might come in useful when you begin plotting the orbit of Mercury, is to think about where Mercury is relative to the Sun at Noon. At Noon, the Sun is due south, and when facing the Sun, East is to the left, and West is to the right. Thus, during an Eastern elongation Mercury is to the left of the Sun, and during a Western elongation Mercury is to the right of the Sun (as seen in the Northern Hemisphere).]

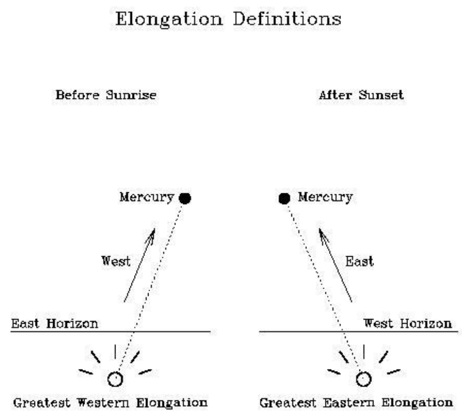


Figure 4.4: A diagram showing the geometry of greatest Western elongations (left side), and greatest Eastern elongations (right side). If you see Mercury–or any other star or planet–above the Western horizon after sunset, that object is located to the East of the Sun. The maximum angular separation between Mercury and the Sun at this time is called the greatest Eastern elongation. A greatest Western elongation occurs when Mercury is seen in the East *before* sunrise.

4.2 Why Greatest Elongations are Special

We have just spent a lot of time describing the greatest elongations of Mercury. We did this because the time of greatest elongation is very special: it is the only time when we know where an inferior planet is in its orbit (except in the rare cases where the planet "transits" across the face of the Sun!). We show why this is true in Fig 4.5. In this figure, we have represented the orbits of Mercury and the Earth as two circles (only about one fourth of the orbits are plotted). We have also plotted the positions of the Earth, the Sun, and Mercury. At the time of greatest elongation, the angle between the Earth, Mercury and the Sun is a right angle. If you were to plot Mercury at some other position in its orbit, the angle between the Earth, Mercury and the Sun would not be a right angle. Therefore, the times of greatest elongation are special, because at this time we know the exact angle between the Earth, Mercury, and the Sun. [You can also figure out from this diagram why Mercury has only one-half of its disk illuminated (a phase of "first quarter").]

Of course, plotting only one elongation is not sufficient to figure out the orbit of Mercury–you need to plot many elongations. In today's lab exercise, you will plot thirteen greatest elongations of Mercury, and trace-out its orbit. There are a lot of angles in this lab, so you need to get comfortable with using a protractor. Your TA will help you figure this out. But the most critical aspect is to not confuse eastern and western elongations. Look at Figure 4.5 again. What kind of elongation is this? Well, as seen from the Earth, Mercury is to the left of the Sun. As described earlier, if Mercury is to the left of the Sun, it is an *eastern elongation*.

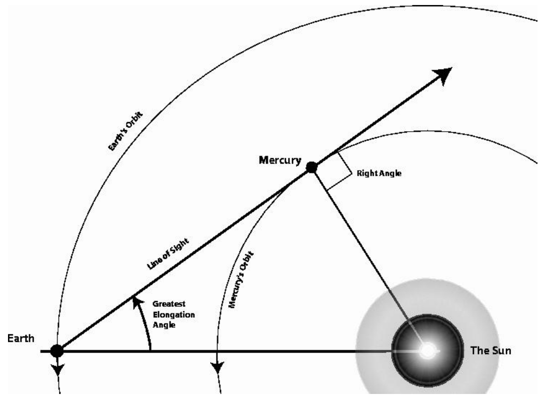


Figure 4.5: A diagram showing the orbital geometry of the Earth and Mercury during a greatest Eastern elongation. The orbits of the Earth and Mercury are the two large circles. The line of sight to Mercury at the time of greatest elongation is indicated. Note that at this time the angle between the Earth, Mercury, and the Sun is a *right* angle. The direction of motion of the two planets is shown by the arrows on the orbits.

4.3 The Orbits of Earth and Mercury

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

4.4 The Data

In Table 4.1, we have listed thirteen dates for greatest elongations of Mercury, as well as the angle of each greatest elongation. **Note that the elongations are either East or West!** In the third column, we have listed something called the Julian date. Over long time intervals, our common calendar is very hard to use to figure out how much time has elapsed. For example, how many days are their between March 13th, 2001 and December 17th 2004? Remember that 2004 is a leap year! This is difficult to do in your head. To avoid such calculations, astronomers have used a calendar that simply counts the days that have passed since some distant day #1. The system used by astronomers sets Julian date 1 to January 1st, 4713 BC (an arbitrary date chosen in the sixteenth century). Using this calendar, March 13th, 2001 has a Julian date of 2451981. While December 17th 2004 has a

Table 4.1: Elongation Data For Mercury

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

Julian date of 2453356. Taking the difference of these two numbers (2453356 − 2451981) we find that there are 1,375 days between March 13th, 2001 and December 17th 2004.

Exercise #1: Fill-in the Data Table.

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

Exercise #2: Plotting your data.

Before we describe the plotting process, review Figure 4.5. Unlike that diagram, you do not know what the orbit of Mercury looks like–this is what you are going to figure out during this lab! But we do know two things: the first is that the Earth's orbit is nearly a perfect circle, and two, that the Sun sits at the exact center of this circle. On the next page is a figure containing a large circle with a dot drawn at the center to represent the Sun. At one position on the large circle we have put a little "X" as a reference point. The large circle here is meant to represent the Earth's orbit, and the "X" is simply a good starting point.

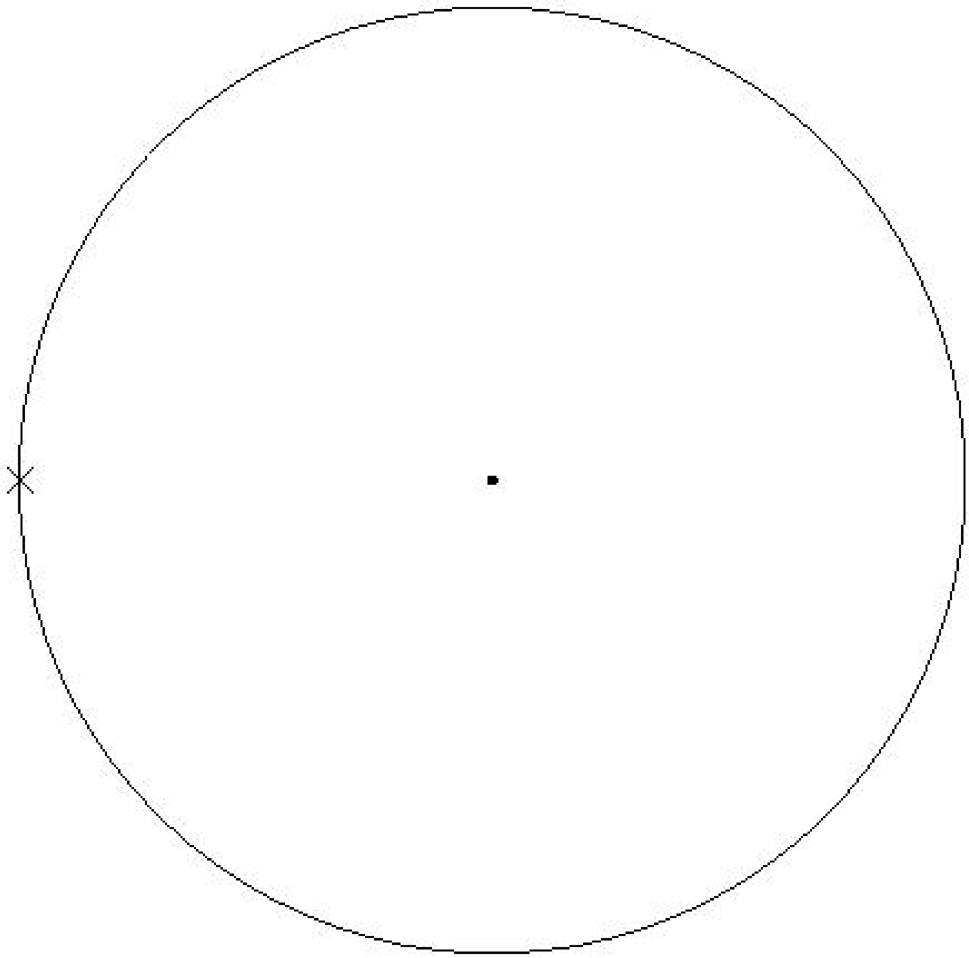
To plot the first elongation of Mercury from our data table, using a pencil, draw a line connecting the X, and the Sun using a straight edge (ruler or protractor). The first elongation in the table (September 1, 2002) is 27.2 degrees East. Using your protractor, put the "X" that marks the Earth's location at the center hole/dot on your protractor. Looking back to Figure 4.5, that elongation was also an *eastern* elongation. So, using that diagram as a guide, measure an angle of 27.2 degrees on your protractor and put a small mark on the worksheet. Now, draw a line from the Earth's location through this mark just like the "line of sight" arrow in Figure 4.5. Now, rotate your protractor so that the 90 degree mark is on this line and towards the position of the Earth, while the reference hole/dot is on the same line. Slide the protractor along the line until the 0° (or 180°) reference line intersects the center of the Sun. Mark this spot with a dark circle. This is the position of Mercury!

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

Ok, now things become slightly more difficult—the Earth moves! Looking back to Figure 4.5, note the arrows on the orbits of Earth and Mercury. This is the direction that both planets are moving in their orbits. For the second elongation, the Earth has moved 42 degrees. We have to locate where the Earth is in its orbit before we can plot the next elongation. So, now put the center hole/dot of your protractor on the Sun. Line up the 0/180 degree mark with the first line that connected the Earth and Sun. Measure an angle of 42 degrees (in the correct direction) and put a small mark. Draw a line through this mark that intersects the postion of the Sun, the mark, and the orbit of the Earth. Put an X where this line intersects the Earth's orbit. This is the spot from where you will plot the next elongation of Mercury.

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

[Hints: It is helpful to label each one of the X's you place on the Earth's orbit with the elongation number from Table 4.1. This will allow you to go back and fix any problems you might find. Note that you will have a large number of lines drawn in this plot by the time you get finished. Use a sharp pencil so that you can erase some/all/pieces of these lines to help clean-up the plot and reduce congestion. You might also find it helpful to simply put a "left" or a "right" each time you encounter East and West in Table 4.1 to insure you plot your data correctly.] **Plot all of your data (*28 points*).**



Exercise #3: Connecting the dots.

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

1) Is Mercury's orbit circular? Describe its shape. (*4 points*)

Exercise #4: Finding the *semi-major axis* of Mercury's orbit.

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

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

Divide the semi-major axis of Mercury by that of the Earth: ____________ AU. Since the semi-major axis of the Earth's orbit is defined to be "one astronomical unit", this ratio tells us the size of Mercury's semi-major axis in astronomical units (AU). (*4 points*)

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

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

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

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

Plug your values into this equation and calculate the eccentricity of Mercury's orbit. (*4 points*)

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

Exercise #5: The orbital period of Mercury.

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

Using Kepler's laws, we can estimate the orbital period of a planet (for a review of Kepler's laws, see lab #4). Kepler's third law says that the orbital period squared (P^2) is proportional to the cube of the semi-major axis (a^3): $P^2 \propto a^3$. This is a type of equation you might not remember how to solve (if you have not done so already, review Lab #1 section 1.5). But let's take it in pieces:

$a^3 = a \times a \times a =$ _______________

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

To find the period of Mercury's orbit, we now need to take the square root of the number you just calculated (see your TA if you do not know whether your calculator can perform this operation). (*4 points*)

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

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

P_{orb}(Mercury) = _______________ days.

5) How does the orbital period you just calculated using Kepler's laws compare to the one you estimated from your plot at the beginning of this exercise? (4 points)

Name: ________________________
Date: ________________________

4.5 Take Home Questions (*35 points*)

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

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

4.6 Extra Credit

In this lab you have measured three of the five quantities that completely define a planet's orbit. The other two quantities are the orbital inclination, and the longitude of perihelion. Determining the orbital inclination, the tilt of the plane of Mercury's orbit with respect to the Earth's orbit, is not possible using the data in this lab. But it is possible to determine the longitude of perihelion. Astronomers define the zero point of solar system longitude as the point in the Earth's orbit at the time of the Vernal Equinox (the beginning of Spring in the northern hemisphere). In 2004, the Vernal Equinox occurs on March 20. If you notice, one of the elongations in the table (#11) occurs close to this date. Thus, you can figure out the true location of the Vernal Equinox by moving back from position #11 by the right number of degrees. The longitude of Mercury's perihelion is just the angle measured counterclockwise from the Earth's vernal equinox. You should find that your angle is larger than 180 degrees. Subtract off 180 degrees. How does your value compare with the precise value of 77°? (*3 points*)

Name(s):________________________________
Date:____________________________________

5 Optics

5.1 Introduction

Unlike other scientists, astronomers are far away from the objects they want to examine. Therefore astronomers learn everything about an object by studying its light. 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

5.2 Discussion

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

- **n** = line which is always perpendicular to the surface; also called the *normal*

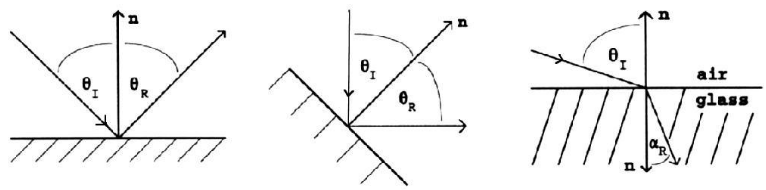


Figure 5.1: The definition of the "normal" direction **n**, and other angles found in optics.

- θ_I = angle of *incidence*; the angle between the *incoming* light ray and the normal to the surface
- θ_R = angle of *reflection*; the angle between the *outgoing* light ray and the normal to the surface
- α_R = angle of *refraction*; the angle between the *transmitted* light ray and the normal direction

5.3 Reflective Optics: Mirrors

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

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

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

Table 5.1: Data Table

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

Now experiment using different angles of incidence by rotating the Laser Straight around the edge of the protractor, always insuring the laser hits the mirror exactly at the vertex of the protractor. Note that an angle of incidence of 90^o corresponds to the "normal" defined above (see Fig. 5.1). Fill in Table 5.1 of angle of incidence vs. angle of reflection. *(3 points)*

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 subsections of flat mirrors, and make a prediction for what you will see if you put a curved mirror in the light path. You might try to make a drawing in the space below:

At the front of the classroom is in fact just such a device: A curved wooden base to which are glued a large number of flat mirrors, along with a metal stand that has three lasers mounted in it, and the "DJ5000" smoke machine. Have your TA turn on the lasers, align them onto the multi-mirror apparatus, and spew some smoke! Was your prediction correct?

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

1) Have your TA place the laser apparatus in front of the convex mirror, and spew some more smoke. **BE CAREFUL NOT TO LET THE LASER LIGHT HIT YOUR EYE.** What happens to the laser beams when they are reflected off of the convex mirror? Make a drawing of how the light is reflected [using the attached work sheet (#1)], the diagram labeled "Convex Mirror" in Figure 5.2. *(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)*:

5.4 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 5.3. Note some similarities and differences between what you have drawn in Fig. 5.2, and what you drew in Fig. 5.3 and write them in the space below. *(5 points)*

5.4.1 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)*

5.4.2 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?

5.5 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.

5.5.1 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)*

5.6 Summary

(*35 points*) Please summarize the important concepts of this lab.

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

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

5.7 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)*

5.8 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?

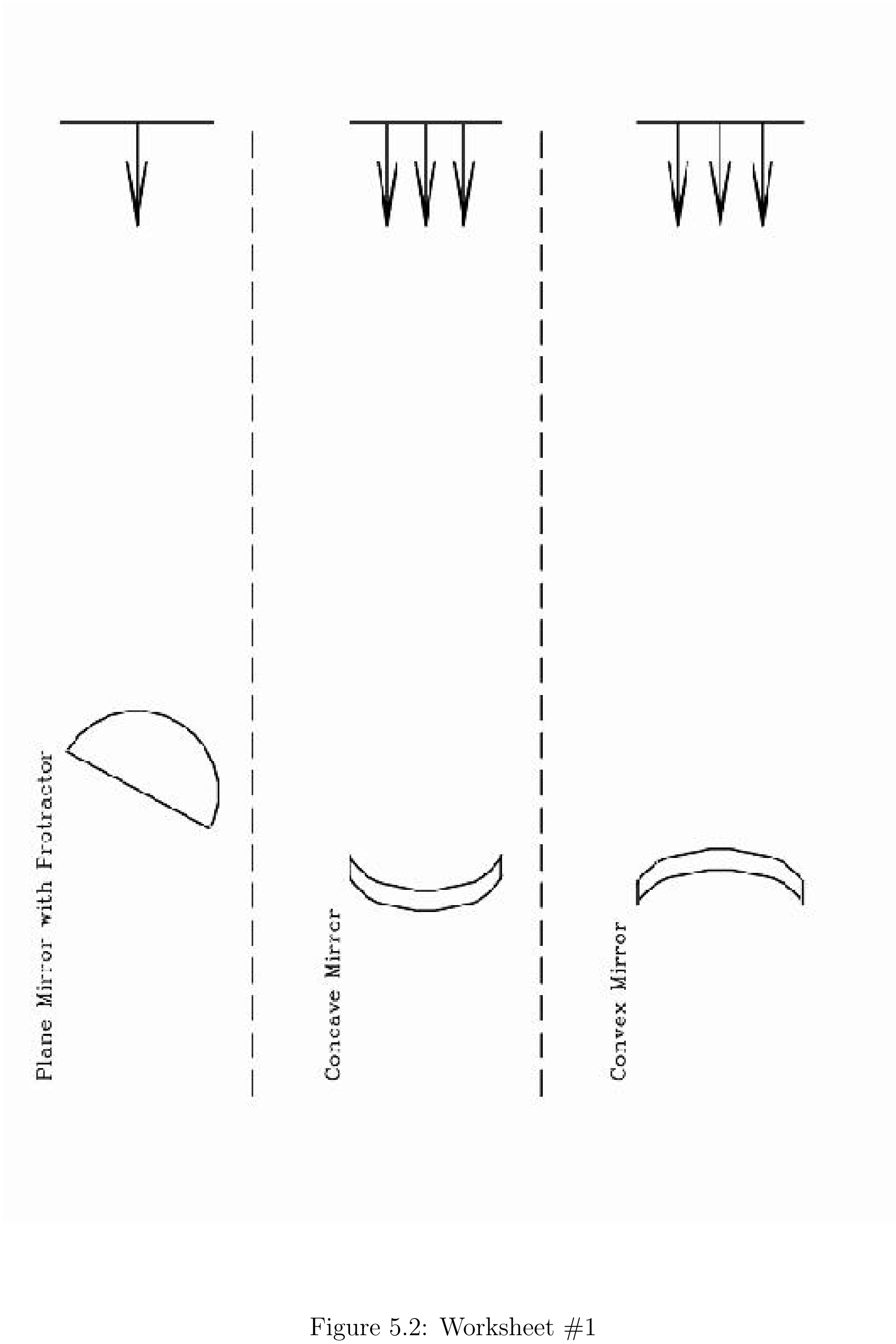


Figure 5.2: Worksheet #1

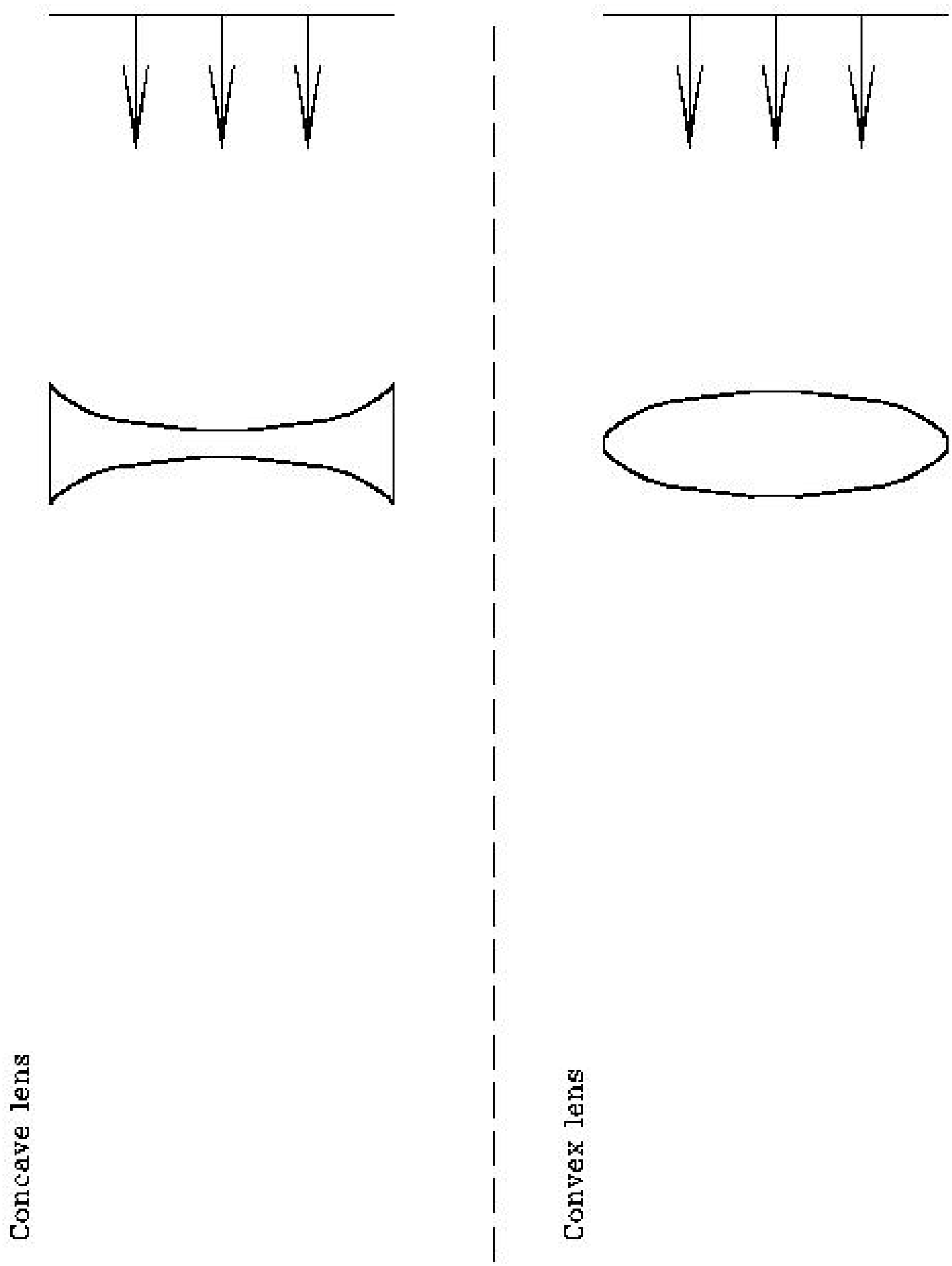


Figure 5.3: Worksheet #2

Name:______________________________
Date:______________________________

6 Scale Model of the Solar System

6.1 Introduction

The Solar System is large, at least when compared to distances we are familiar with on a day-to-day basis. Consider that for those of you who live here in Las Cruces, you travel 2 kilometers (or 1.2 miles) on average to campus each day. If you go to Albuquerque on weekends, you travel about 375 kilometers (232.5 miles), and if you travel to Disney Land for Spring Break, you travel $\sim$ 1,300 kilometers ($\sim$ 800 miles), where the '$\sim$' symbol means "approximately." These are all distances we can mentally comprehend.

Now, how large is the Earth? If you wanted to take a trip to the center of the Earth (the very hot "core"), you would travel 6,378 kilometers (3954 miles) from Las Cruces down through the Earth to its center. If you then continued going another 6,378 kilometers you would 'pop out' on the other side of the Earth in the southern part of the Indian Ocean. Thus, the total distance through the Earth, or the **diameter** of the Earth, is 12,756 kilometers ($\sim$ 7,900 miles), or 10 times the Las Cruces-to-Los Angeles distance. Obviously, such a trip is impossible–to get to the southern Indian Ocean, you would need to travel on the surface of the Earth. How far is that? Since the Earth is a sphere, you would need to travel 20,000 km to go halfway around the Earth (remember the equation Circumference = 2πR?). This is a large distance, but we'll go farther still.

Next, we'll travel to the Moon. The Moon, Earth's natural satellite, orbits the Earth at a distance of $\sim$ 400,000 kilometers ($\sim$ 240,000 miles), or about 30 times the diameter of the Earth. This means that you could fit roughly 30 Earths end-to-end between here and the Moon. This Earth-Moon distance is $\sim$ 200,000 times the distance you travel to campus each day (if you live in Las Cruces). So you can see, even though it is located very close to us, it is a long way to the Earth's nearest neighbor.

Now let's travel from the Earth to the Sun. The *average Earth-to-Sun distance*, $\sim$ 150 million kilometers ($\sim$ 93 million miles), is referred to as one **Astronomical Unit** (AU). When we look at the planets in our Solar System, we can see that the planet Mercury, which orbits nearest to the Sun, has an average distance of 0.4 AU and Pluto, the planet almost always the furthest from the Sun, has an average distance of 40 AU. Thus, the Earth's distance from the Sun is only 2.5 percent of the distance between the Sun and planet Pluto!! Pluto is very far away!

The purpose of today's lab is to allow you to develop a better appreciation for the distances between the largest objects in our solar system, and the physical sizes of these objects relative to each other. To achieve this goal, we will use the length of the football field in Aggie Memorial Stadium as our platform for developing a scale model of the Solar System. A *scale* *model* is simply a tool whereby we can use manageable distances to represent larger distances or sizes (like the road map of New Mexico used in Lab #1). We will properly distribute our planets on the football field in the same *relative* way they are distributed in the real Solar System. *The length of the football field will represent the distance between the Sun and the planet Pluto.* We will also determine what the sizes of our planets should be to appropriately fit on the same scale. Before you start, what do you think this model will look like?

Below you will proceed through a number of steps that will allow for the development of a scale model of the Solar System. For this exercise, we will use the convenient unit of the Earth-Sun distance, the Astronomical Unit (AU). Using the AU allows us to keep our numbers to manageable sizes.

SUPPLIES: a calculator, Appendix E in your textbook, the football field in Aggie Memorial Stadium, and a collection of different sized spherical-shaped objects

6.2 The Distances of the Planets From the Sun

Fill in the first and second columns of Table 2.1. In other words, list, in order of increasing distance from the Sun, the planets in our solar system and their average distances from the Sun in Astronomical Units (usually referred to as the "semi-major axis" of the planet's orbit). You can find these numbers in back of your textbook. **(21 points)**

Table 6.1: Planets' average distances from Sun.

	Average Distance From Sun	
Planet	**AU**	**Yards**
Earth	1	
Pluto	40	100

Next, we need to convert the distance in AU into the unit of a football field: the yard. This is called a "scale conversion". Determine the SCALED orbital semi-major axes of the planets, based upon the assumption that the Sun-to-Pluto average distance in Astronomical Units (which is already entered into the table, above) is represented by 100 yards, or goal-line to goal-line, on the football field. To determine similar scalings for each of the planets, you must figure out how many yards there are per AU, and use that relationship to fill in the values in the third column of Table 2.1.

6.3 Sizes of Planets

You have just determined where on the football field the planets will be located in our scaled model of the Solar System. Now it is time to determine how large (or small) the planets themselves are on the **same** scale.

We mentioned in the introduction that the diameter of the Earth is 12,756 kilometers, while the distance from the Sun to Earth (1 AU) is equal to 150,000,000 km. We have also determined that in our scale model, 1 AU is represented by 2.5 yards (= 90 inches).

We will start here by using the largest object in the solar system, the Sun, as an example for how we will determine how large the planets will be in our scale model of the solar system. The Sun has a diameter of $\sim$ 1,400,000 (1.4 million) kilometers, more than 100 times greater than the Earth's diameter! Since in our scaled model 150,000,000 kilometers (1 AU) is equivalent to 2.5 yards, how many inches will correspond to 1,4000,000 kilometers (the Sun's actual diameter)? This can be determined by the following calculation:

$$\textbf{Scaled Sun Diameter} = \textbf{Sun's true diameter (km)} \times \frac{(90 \ in.)}{(150{,}000{,}000 \ km)} = \textbf{0.84 inches}$$

So, on the scale of our football field Solar System, the *scaled Sun* has a diameter of only 0.84 inches!! Now that we have established the scaled Sun's size, let's proceed through a similar exercise for each of the nine planets, and the Moon, using the same formula:

$$\textbf{Scaled object diameter (inches)} = \textbf{actual diameter (km)} \times \frac{(90 \ in.)}{(150{,}000{,}000 \ km)}$$

Using this equation, fill in the values in Table 2.2 **(8 points)**.

Now we have all the information required to create a scaled model of the Solar System. Using any of the items listed in Table 2.3 (spheres of different diameter), select the ones that most closely approximate the sizes of your scaled planets, along with objects to represent both the Sun and the Moon.

Designate one person for each planet, one person for the Sun, and one person for the Earth's Moon. Each person should choose the model object which represents their solar system object, and then walk (or run) to that object's scaled orbital semi-major axis on the football field. The Sun will be on the goal line of the North end zone (towards the Pan Am Center) and Pluto will be on the south goal line.

Table 6.2: Planets' diameters in a football field scale model.

Object	Actual Diameter (km)	**Scaled Diameter (inches)**
Sun	$\sim$ 1,400,000	0.84
Mercury	4,878	
Venus	12,104	
Earth	12,756	0.0075
Moon	3,476	
Mars	6,794	
Jupiter	142,800	
Saturn	120,540	
Uranus	51,200	
Neptune	49,500	
Pluto	2,200	0.0013

Table 6.3: Objects that Might Be Useful to Represent Solar System Objects

Object	**Diameter (inches)**
Basketball	15
Tennis ball	2.5
Golf ball	1.625
Marble	0.5
Sesame seed	0.07
Poppy seed	0.04
Ground flour	0.001

6.4 Questions About the Football Field Model

When all of the "planets" are in place, note the relative spacing between the planets, and the size of the planets relative to these distances.

1) Is this spacing and planet size distribution what you expected when you first began thinking about this lab today? Why or why not? **(10 points)**

Answer the following questions using the information you have gained from this lab and your own intuition **(20 points)**:

2) Which planet would you expect to have the warmest surface temperature? Why?

3) Which planet would you expect to have the coolest surface temperature? Why?

4) Which planet would you expect to have the greatest mass? Why?

5) Which planet would you expect to have the longest orbital period? Why?

6) Which planet would you expect to have the shortest orbital period? Why?

Extra Credit (5 points)

Later this semester (see lab #15) we will talk about comets, objects that reside on the edge of our Solar System. Most comets are found either in the "Kuiper Belt", or in the "Oort Cloud". The Kuiper belt is the region that starts near Pluto's orbit, and extends to about 100 AU. The Oort cloud, however, is enormous: it is estimated to be 40,000 AU in radius! Using your football field scale model answer the following questions:

1) How many yards away would the edge of the Kuiper belt be from the northern goal line at Aggie Memorial Stadium?

2) How many football fields does the radius of the Oort cloud correspond to? If there are 1760 yards in a mile, how many miles away is the edge of the Oort cloud from the northern goal line at Aggie Memorial Stadium?

Possible Quiz Questions

1) What is the approximate diameter of the Earth?

2) What is the definition of an Astronomical Unit?

3) What value is a "scale model"?

6.5 Take-Home Questions

Now you will work out the numbers for a scale model of the Solar System for which the size of New Mexico along Interstate Highway 25 will be the scale.

Interstate Highway 25 begins in Las Cruces, just southeast of campus, and continues north through Albuquerque, all the way to the border with Colorado. The total distance of I-25 in New Mexico is 455 miles. Using this distance to represent the Sun to Pluto distance (40 AU), and assuming that the Sun is located at the start of I-25 here in Las Cruces and Pluto is located along the Colorado-New Mexico border, you will determine:

- the scaled locations of each of the planets in the Solar System; that is, you will determine the city along the highway (I-25) each planet will be located nearest to, and how far north or south of this city the planet will be located. If more than one planet is located within a given city, identify which street or exit the city is nearest to.
- the size of the Solar system objects (the Sun, each of the planets) on this same scale, for which 455 miles ($\sim$ 730 kilometers) corresponds to 40 AU. Determine how large each of these scaled objects will be (probably best to use feet; there are 5280 feet per mile), and suggest a real object which well represents this size. For example, if one of the scaled Solar System objects has a diameter of 1 foot, you might suggest a soccer ball as the object that best represents the relative size of this object.

If you have questions, this is a good time to ask!!!!!!

1. List the planets in our solar system and their average distances from the Sun in units of Astronomical Units (AU). Then, using a scale of 40 AU = 455 miles (1 AU = 11.375 miles), determine the scaled planet-Sun distances and the city near the location of this planet's scaled average distance from the Sun. Insert these values into Table 2.4, and draw on your map of New Mexico (on the next page) the locations of the solar system objects. **(22 points)**

2. Determine the scaled size (diameter) of objects in the Solar System for a scale in which 40 AU = 455 miles, or 1 AU = 11.375 miles). Insert these values into Table 2.5. **(19 points)**

   Scaled diameter (feet) = actual diameter (km) $\times \frac{(11.4 \ mi. \ \times \ 5280 \ ft/mile)}{150{,}000{,}000 \ km}$

Table 6.4: Planets' average distances from Sun.

Planet	Average Distance from Sun in AU	in Miles	Nearest City
Earth	1	11.375	
Pluto	40	455	3 miles north of Raton

Table 6.5: Planets' diameters in a New Mexico scale model.

Object	Actual Diameter (km)	Scaled Diameter (feet)	Object
Sun	$\sim$ 1,400,000	561.7	
Mercury	4,878		
Venus	12,104		
Earth	12,756	5.1	height of 12 year old
Moon	3,476		
Mars	6,794		
Jupiter	142,800		
Saturn	120,540		
Uranus	51,200		
Neptune	49,500		
Pluto	2,200		


COLORADO
FARMINGTON
Aztec
Bloomfield
Shiprock
Chama
Raton
Taos
Gallup
Los Alamos
SANTA FE
LAS VEGAS
Española
Grants
Milan
ALBUQUERQUE
Bernalillo
Moriarty
Santa Rosa
Belen
Socorro
Magdalena
Truth or Consequences
Silver City
Deming
Lordsburg
Hatch
LAS CRUCES
Mesilla
ALAMOGORDO
Tularosa
Ruidoso
Carrizozo
ROSWELL
Artesia
WHITE SANDS
MISSILE
RANGE
FORT BLISS
MILITARY
RESERVATION
TEXAS
GOUSHA

Name:______________________________
Date:______________________________

7 Estimating the Earth's Density

7.1 Introduction

We know, based upon a variety of measurement methods, that the density of the Earth is 5.52 grams per cubic centimeter. [This value is equal to 5520 kilograms per cubic meter. Your initial density estimate in Table 7.3 should be a value similar to this.] This density value clearly indicates that Earth is composed of a combination of rocky materials and metallic materials.

With this lab exercise, we will obtain some measurements, and use them to calculate our own estimate of the Earth's density. Our observations will be relatively easy to obtain, but they will involve contacting someone in the Boulder, Colorado area (where the University of Colorado is located) to assist with our observations. We will then do some calculations to convert our measurements into a density estimate.

As we have discussed in class, and in previous labs this semester, we can calculate the density of an object (say, for instance, a planet, or more specifically, the Earth) by knowing that object's mass and volume. It is a challenge, using equipment readily available to us, to determine the Earth's mass and its volume directly. [There is no mass balance large enough upon which we can place the Earth, and if we could what would we have available to "balance" the Earth?] But we have through the course of this semester discussed physical processes which relate to mass. One such process is the gravitational attraction (force) one object exerts upon another.

The magnitude of the gravitational force between two objects depends upon both the masses of the two objects in question, as well as the distance separating the centers of the two objects. Thus, we can use some measure of the Earth's gravitational attraction for an object upon its surface to ultimately determine the Earth's mass. However, there is another piece of information that we require, and that is the distance from the Earth's surface to its center: the Earth's radius.

We will need to determine both the MASS of the Earth and the RADIUS of the Earth. Since we will use the magnitude of Earth's gravitational attraction to determine Earth's mass, and since this magnitude depends upon the Earth's radius, well first determine Earth's circumference (which will lead us to the Earth's radius and then to the Earth's volume) and then determine the Earth's mass.

7.2 Determining Earth's Radius

Earlier this semester you read (or should have read!) in your textbook the description of Eratosthenes' method, implemented two-thousand plus years ago, to determine Earth's circumference. Since the Earth's circumference is related to its radius as:

$$\text{Circumference} = 2 \times \pi \times \text{RADIUS (with } \pi = \text{“pi”} = 3.141592)$$

and the Earth's volume is a function of its radius:

$$\text{VOLUME} = (4/3) \times \pi \times \text{RADIUS}^3$$

We will implement Eratosthenes' circumference measurement method and end up with an estimate of the Earth's radius.

Now, what measurements did Eratosthenes use to estimate Earth's circumference? Eratosthenes, knowing that Earth is spherical in shape, realized that the length of an object's shadow would depend upon how far in latitude (north-or-south) the object was from being directly beneath the Sun. He measured the length of a shadow cast by a vertical post in Egypt at local noon on the day of the northern hemisphere summer solstice (June 20 or so). He made a measurement at the point directly beneath the Sun (23.5 degrees North, at the Egyptian city Syene), and at a second location further north (Alexandria, Egypt). The two shadow lengths were not identical, and it is that difference in shadow length plus the knowledge of how far apart the the two posts were from each other (a few hundred kilometers), that permitted Eratosthenes to calculate his estimate of Earth's circumference.

As we conduct this lab exercise we are not in Egypt, nor is today the seasonal date of the northern hemisphere summer solstice (which occurs in June), nor is it locally Noon (since our lab times do not overlap with Noon). But, nonetheless, we will forge ahead and estimate the Earth's circumference, and from this we will estimate the Earth's radius.

TASKS:

- Take a post outside, into the sunlight, and measure the length of the post with the tape measure.
- Place one end of the post on the ground, and hold the post as vertical as possible.
- Using the tape measure provided, measure to the nearest 1/2 centimeter the length of the shadow cast by the post; this shadow length should be measured three times, by three separate individuals; record these shadow lengths in Table 7.1.
- You will be provided with the length of a post and its shadow measured simultaneously today in Boulder, Colorado.
- Proceed through the calculations described after Table 7.1, and write your answers in the appropriate locations in Table 7.1. **(15 points)**

7.3 ANGLE DETERMINATION:

With a bit of trigonometry we can transform the height and shadow length you measured into an angle. As shown in Figure 7.1 there is a relationship between the length (of your shadow in this situation) and the height (of the shadow-casting pole in this situation), where:

Table 7.1: **Angle Data**

Location	Post Height (cm)	Shadow Length (cm)	Angle (Degrees)
Las Cruces Shadow #1			
Las Cruces Shadow #2			
Las Cruces Shadow #3			
Average Las Cruces Angle:			
Boulder, Colorado			

TANGENT of the ANGLE = far-side length/ near-side length

Since you know the length of the post (the near-side length, which you have measured) and the length of the shadow (the far-side length, which you have also measured, three separate times), you can determine the shadow angle from your measurements, using the ATAN, or TAN^{-1} capability on your calculator (these functions will give you an angle if you provide the ratio of the height to length):

$$\text{ANGLE} = \text{ATAN (shadow length / post length)}$$
or
$$\text{ANGLE} = \text{TAN}^{-1}\text{(shadow length / post length)}$$

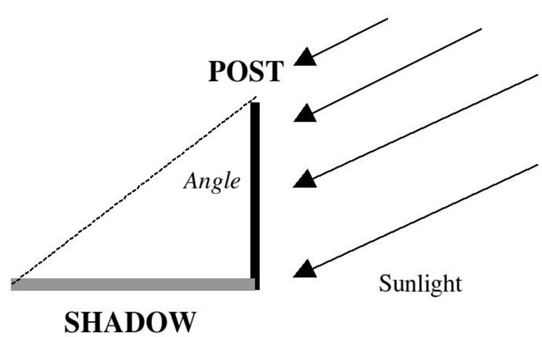


Figure 7.1: The geometry of a vertical post sitting in sunlight.

Calculate the shadow angle for each of your three shadow-length measurements, and also for the Boulder, Colorado shadow-length measurement. Write these angle values in the appropriate locations in Table 7.1. Then calculate the average of the three Las Cruces shadow angles, and write the value on the "Average Las Cruces Angle" line.

The angles you have determined are: 1) an estimate of the angle (latitude) difference between Las Cruces and the latitude at which the Sun appears to be directly overhead (which is currently $\sim$ 12 degrees south of the equator since we are experiencing early northern autumn), *and* 2) the angle (latitude) difference between Boulder, Colorado and the latitude at which the Sun appears to be directly overhead. The difference (Boulder angle minus Las Cruces angle) between these two angles is the angular (latitude) separation between Las Cruces and Boulder, Colorado.

We will now use this information and our knowledge of the actual distance (in kilometers) between Las Cruces' latitude and Boulder's latitude. This distance is:

857 kilometers north-south distance between Las Cruces and Boulder, Colorado

In the same way that Eratosthenes used his measurements (just like those you have made today), we can now determine an estimate of the Earth's circumference from:

EARTH CIRCUMFERENCE (kilometers) =

857 kilometers × (360°)/(Boulder angle —Avg LC Angle) =

857 × [360°/(________ − ________)] = ________________ km (5 points)

Using your calculated Boulder Shadow Angle and your Average Las Cruces Shadow Angle values, calculate the corresponding EARTH CIRCUMFERENCE value, and write it below:

AVERAGE EARTH CIRCUMFERENCE = ________________ kilometers (5 points)

The CIRCUMFERENCE value you have just calculated is related to the RADIUS via the equation:

$$\text{EARTH CIRCUMFERENCE} = 2 \times \pi \times \text{EARTH RADIUS}$$

which can be converted to RADIUS using:

$$\text{EARTH RADIUS} = \text{R}_\text{E} = \text{EARTH CIRCUMFERENCE} \ / \ (2 \times \pi)$$

For your calculated CIRCUMFERENCE, calculate that value of the Radius (in units of kilometers) in the appropriate location below:

AVERAGE EARTH RADIUS VALUE = $\mathbf{R_E}$ = ____________________ kilometers (5 points)

Convert this radius ($\mathbf{R_E}$) from kilometers to meters, and enter that value in Table 7.3. (Note we will use the radius in meters the rest of the lab.)

You have now obtained one important piece of information (the radius of the Earth) needed for determining the density of Earth. We will, in a bit, use this radius value to calculate the Earth's volume. Next, we will determine Earth's mass, since we need to know both the Earth's volume and its mass in order to be able to calculate the Earth's density.

7.4 Determining the Earth's Mass

The gravitational acceleration (increase of speed with increase of time) that a dropped object experiences here at the Earth's surface has a magnitude defined by the Equation (thanks to Sir Isaac Newton for working out this relationship!) shown below:

$$\textbf{Acceleration (meters per second per second)} = \mathbf{G} \times \mathbf{M_E}/\mathbf{R_E}^2$$

Where $\mathbf{M_E}$ is the mass of the Earth in *kilograms*, $\mathbf{R_E}$ is the radius of the Earth in units of *meters*, and the Gravitational Constant, $\mathbf{G} = 6.67 \text{ x } 10^{-11}$ meters^3/(kg-seconds^2). You have obtained several estimates, and calculated an average value of R_E, above. However, you currently have no estimate for M_E. You can estimate the Earth's mass from the measured acceleration of an object dropped here at the surface of Earth; you will now conduct such an exercise.

A falling object, as shown in Figure 7.2, increases its downward speed at the constant rate **"X"** (in units of meters per second per second). Thus, as you hold an object in your hand, its downward speed is zero meters per second. One second after you release the object, its downward speed has increased to **X** meters per second. After two seconds of falling, the dropped object has a speed of **2X** meter per second, after 3 seconds its downward speed is **3X** meters per second, and so on. So, if we could measure the speed of a falling object at some point in time after it is dropped, we could determine the object's acceleration rate, and from this determine the Earth's mass (since we know the Earth's radius). However, it is difficult to measure the instantaneous speed of a dropped object.

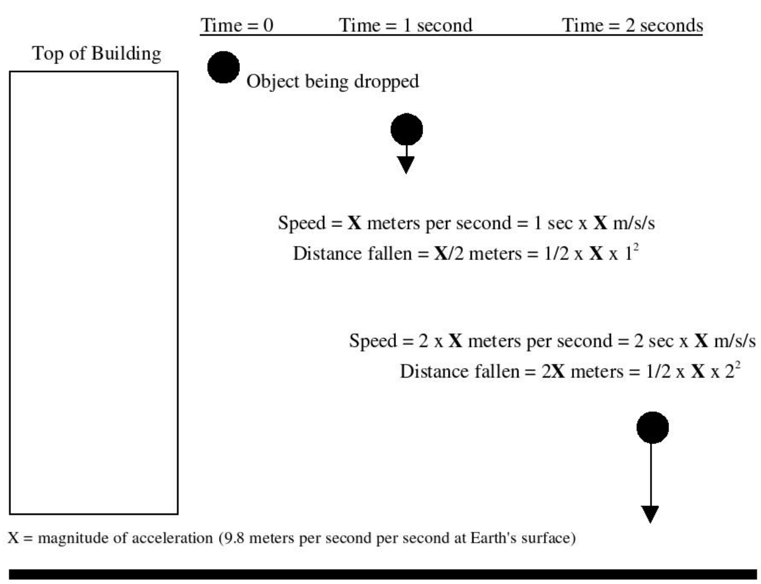


Figure 7.2: The distance a dropped object will fall during a time interval t is proportional to t^2. A dropped object speeds up as it falls, so it travels faster and faster and falls a greater distance as t increases.

We can, however, make a different measurement from which we can derive the dropped object's acceleration, which will then permit us to calculate the Earth's mass. As was pointed out above, before being dropped the object's downward speed is zero meters per second. One second after being dropped, the object's downward speed is X meters per second. During this one-second interval, what was the object's AVERAGE downward speed? Well, if it was zero to begin with, and X meters per second after falling for one second, **its average fall speed during the one-second interval is:**

Average Fall speed during first second = (Zero + X) / 2 = X/2 meters per second, which is just the average of the initial (zero) and final (X) speeds.

At an average speed of X/2 meters per second during the first second, the distance traveled during that one second will be:

$$\mathbf{(X/2)\ (meters\ per\ second) \times 1\ second = (X/2)\ meters,}$$

since:

$$\mathbf{DISTANCE = AVERAGE\ SPEED \times TIME = 1/2 \times ACCELERATION\ x\ TIME^2}$$

So, if we measure the length of time required for a dropped object to fall a certain distance, we can calculate the object's acceleration.

Tasks:

- Using a stopwatch, measure the amount of time required for a dropped object (from the top of the Astronomy Building) to fall 9.0 meters (28.66 feet). Different members of your group should take turns making the fall-time measurements; write these fall time values for two "drops" in the appropriate location in Table 7.2. **(10 points for a completed table)**
- Use the equation: Acceleration = [2.0 x Fall Distance] / [(Time to fall)^2]

  and your measured Time to Fall values and the measured distance (9.0 meters) of Fall to determine the gravitational acceleration due to the Earth; write these acceleration values (in units of meters per second per second) in the proper locations in Table 7.2.
- Now, knowing the magnitude of the average acceleration that Earth's gravity imposes upon a dropped object, we will now use the "Gravity" equation to get M_E:

  Gravitational acceleration = G $\times$ M_E/R_E^2 (where R_E must be in meters!)

By rearranging the Gravity equation to solve for M_E, we can now make an estimate of the Earth's mass:

$\mathbf{M_E}$ **= Average Acceleration $\times$ [1000 $\times$ $\mathbf{R_E}$]^2 / G = ________________________ (5 points)**

[The factor of 1000 here converts your Average Radius determined in the previous section in units of kilometers to a radius in units of meters.]

Write the value of M_E (in kilograms) in Table 7.3 below.

Table 7.2: **Time of Fall Data**

	Time to Fall	Fall Distance	Acceleration
Object Drop #1		9 meters	
Object Drop #2		9 meters	
Average =			

7.5 Determining the Earth's Density

Now that we have estimates for the mass (M_E) and radius (R_E) of the Earth, we can easily calculate the density: Density = Mass/Volume. You will do this below.

Tasks:

- Calculate the volume (V_E) of the Earth given your determination of its radius (in meters!):

$$\mathbf{V_E = (4/3)} \times \pi \times \mathbf{R_E}^3$$

  and write this value in the appropriate location in Table 7.3 below.

- Divide your value of M_E (that you entered in Table 7.3) by your estimate of V_E that you just calculated (also written in Table 7.3): the result will be your estimate of the Average Earth Density in units of kilograms per cubic meter. Write this value in the appropriate location in Table 7.3.

- Divide your AVERAGE ESTIMATE OF EARTH'S DENSITY value that you just calculated by the number 1000.0; the result will be your estimated Earth density value in units of grams per cubic centimeter (the unit in which most densities are tabulated). Write this value in the appropriate location in Table 7.3.

Table 7.3: **Data for the Earth**

Estimate of Earth's Radius:	____________________	m (7 points)
Estimate of Earth's Mass:	____________________	kg (7 points)
Estimate of Earth's Volume:	____________________	m^3 (7 points)
Estimate of Earth's Density:	____________________	kg/m^3 (7 points)
Density of the Earth:	____________________	gm/cm^3 (7 points)

7.6 IN-LAB QUESTIONS:

1. Is your calculated value of the Earth's density GREATER THAN, or LESS THAN, or EQUAL TO the actual value (see the Introduction) of the Earth's density? If your calculated density value is not identical to the known Earth density value, calculate the "percent error" of your calculated density value compared to the actual density value **(5 points)**:

   PERCENT ERROR =

$$\frac{100\% \times (\text{CALCULATED DENSITY} - \text{ ACTUAL DENSITY})}{\text{ACTUAL DENSITY}} = \underline{\hspace{3cm}} \tag{9}$$

2. You used the AVERAGE Las Cruces shadow angle in calculating your estimate of the Earth's density (which you wrote down in Table 7.3). If you had used the LARGEST of the three measured Las Cruces shadow angles shown in Table 7.1, would the Earth density value that you would calculate with the LARGEST Las Cruces shadow angle be larger than or smaller than the Earth density value you wrote in Table 7.3? Think before writing your answer! Explain your answer. **(7.5 points)**

3. If the Las Cruces to Boulder, Colorado distance was actually 2000 km in length, but your measured fall times did not change from what you measured, would you have calculated a larger or smaller Earth density value? Explain the reasoning for your answer. **(7.5 points)**

4. If we had conducted this experiment on the Moon rather than here on the Earth, would your measured values (fall time, angles and angle difference between two locations separated

north-south by 857 kilometers) be the same as here on Earth, or different? Clearly explain your reasoning. [It might help if you draw a circle representing Earth and then draw a circle with $1/4^{\text{th}}$ of the radius of the Earth's circle to represent the Moon.]

Name: ________________________________

Earth Density Lab
Ast 105
Take-Home Questions (35 points)

1. Using the post-height (length) and post and shadow lengths your Lab TA will provide to you at the end of the lab meeting, fill in the Table 7.4 below.

Table 7.4: **Angle Data**

Location	Post Height (cm)	Shadow Length (cm)	Angle (Degrees)
Las Cruces Angle:			
Boulder, Colorado Angle			

Now re-calculate the following numbers:

Earth Circumferance = ____________________ kilometers

Earth Radius = ____________________ kilometers

Answer Questions #2, #3, and #4 below in typed form on a separate sheet of paper, and then type your response to item #5. These will be handed in with the remainder of your lab materials.

2. List in an appropriate order the steps involved in determining the Earth's density in this lab (this includes both measurements and calculations).

3. Using the "Earth Radius" value you calculated using the provided-by-your-TA Las Cruces and Boulder post and shadow lengths (see Table 7.4 above):

   Calculate a new estimate of Earth's density using these values as your starting point. How does your answer compare to your AVERAGE DENSITY OF EARTH value in Table 7.3 of the lab?

   Do you believe this new density value is a worse, or better estimate than you calculated using the values measured during your lab? Why?

4. TYPE a 1.5-2 page LAB REPORT in which you will address the following topics:

   a) the estimated density value you arrived at was likely different from the actual Earth density value of 5.52 grams per cubic centimeter; describe 2 or 3 potential errors in your measurements that could possibly play a role in generating your incorrect estimated density value

   b) describe 2-3 ways in which you could improve the measurement techniques used in lab; keep in mind that NMSU is a state-supported school and thus we do not have infinite resources to purchase expensive sophisticated equipment, so your suggestions should not be too expensive

c) describe what you have learned from this lab, what aspects of the lab surprised you, what aspects of the lab worked just as you thought they would, etc.

Name:______________________________

Date:______________________________

8 Surface of the Moon

8.1 Introduction

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

The type of orbit our Moon makes around the Earth is called a synchronous orbit. This phenomenon is shown graphically in Figure 8.1 below. If we imagine that there is one large mountain on the hemisphere facing the Earth (denoted by the small triangle on the Moon), then this mountain is always visible to us no matter where the Moon is in its orbit. As the Moon orbits around the Earth, it turns slightly so we always see the same hemisphere.

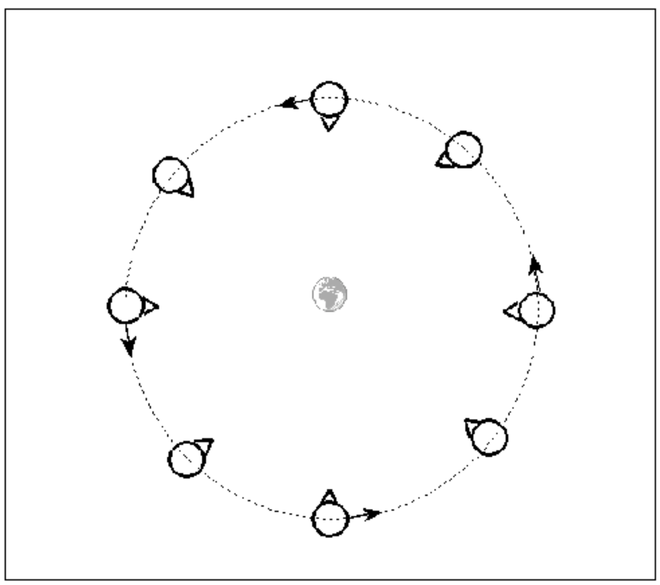


Figure 8.1: The Moon's synchronous orbit. (Not drawn to scale.)

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.

- Lab 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

8.2 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 8.2, 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 8.2 also shows that the rock beneath the crater becomes fractured (full of cracks).

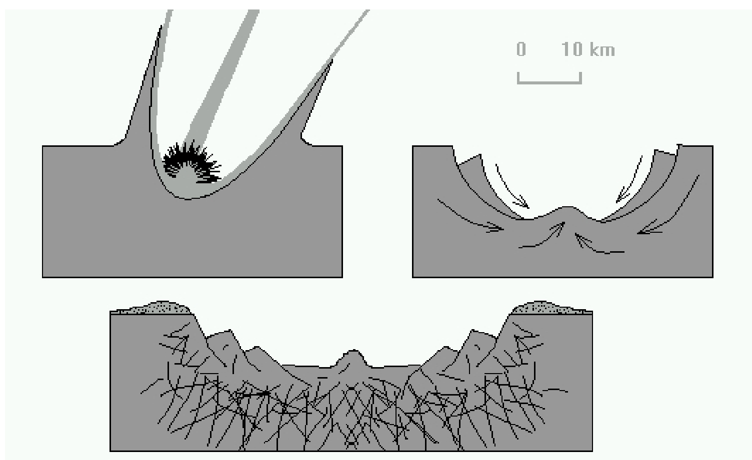


Figure 8.2: Formation of an impact crater.

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

8.3 Relative Ages on the Moon

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

8.4 Lab Stations

In this lab you will "visit" several stations that have several black and white images of the Moon (or Earth) and a few questions. At some stations we present data comparing the Moon to the Earth or Mars. Using your understanding of simple physical processes here on Earth and information from the class lecture and your reading, you will make observations and draw logical conclusions in much the same way that a planetary geologist would.

You should work in groups of 2–4 people, with one binder for each group. The binders contain separate sections, or "stations," with the photographs and/or images for each specific exercise. Each group must go through all the stations, and consider and discuss each question and come to a conclusion. **Remember to back up your answers with reasonable explanations, and be sure to answer *all* of the questions.** While you should discuss the questions as a group, be sure to write down one group answer for each question. The take-home questions must be done on your own. **Answers for the take-home questions that are exact duplicates of those of other members of your group will not be acceptable.**

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.

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. (**5 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.

2. Using the diameters for the large craters noted above, and a ruler, what is the approximate diameters of the smallest craters you can clearly see 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. (**5 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.

3. Roughly how much area (in km^2) does Mons Piton cover? Compare it to the Organ Mountains (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?] (**5 points**)

Station 2: Now let's move to the "highlands". In **Image #6** (which is identical to image #2), the crater Clavius can be seen on the bottom edge—it is the bottom-most labeled feature on this map. **Image #7** shows 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.

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).

4. 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 7.3 of the introduction.] (**5 points**)

Station 3: Comparing Apollo landing sites. **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.

5. 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.

6. 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). **Image #20** is a close-up of Plato.

7. 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° latitude is the equator, just like on the Earth. Like the Earth, the North pole of the Moon has a latitude of +90°, and the south pole is at −90°. On the x-axis is the *longitude* of the Moon. Longitude runs from 0° to 360°. The point at 0° 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° N, and its longitude is 351°. You can clearly see the outline of Plato if you look closely.

8. Is Plato located in a high region, or a low region? Is Plato lower than Mare Imbrium (centered at 32°N, 344°)? [Remember that Plato is on the Northern edge of Mare Imbrium.](**5 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°, passing through 0°, and going all the way to 90° (remember, 0 is located at the center of the

Moon as seen from Earth). **Image #23** is a more conventional topographical map of the Moon, showing the two hemispheres: near side, and far side.

9. Compare the average elevation of the near-side of the Moon to that of the far-side. Are they different? Explain. Can you make out the maria? Compare the number of maria on the far side to the number on the near side. (**5 points**)

[Why the far side of the Moon is so different from the near side remains a mystery!]

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 fewer craters than the surface of the Moon? Discuss two differences between the Earth and the Moon that could explain this. **(5 points)**

8.5 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 as with water, denser objects in molten rock sink to the bottom more quickly than less dense 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. Image #24 is a map of the amount of iron on the surface of the Moon ("hotter" colors mean more iron than cooler colors). Image #25 is the same type of map, but for titanium.

10. 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? (**5 points**)

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

The structure of the Earth is shown in the Figure 8.3. 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. As you may recall from the Density lab, the density of a material is simply its mass (in grams or kilograms) divided by its volume (in cubic centimeters or meters). Water has a density of 1 gm/cm^3. The density of the Earth's crust is about 3 gm/cm^3, while the mantle has a density of 4.5 gm/cm^3. The core is very dense: 14 gm/cm^3 (this is partly due to its composition, and partly due to the great pressure exerted by the mass located above the core). The core of the Earth is almost pure iron, while the mantle is a mixture of magnesium, silicon, iron and oxygen. The average density of the Earth is 5.5 gm/cm^3.

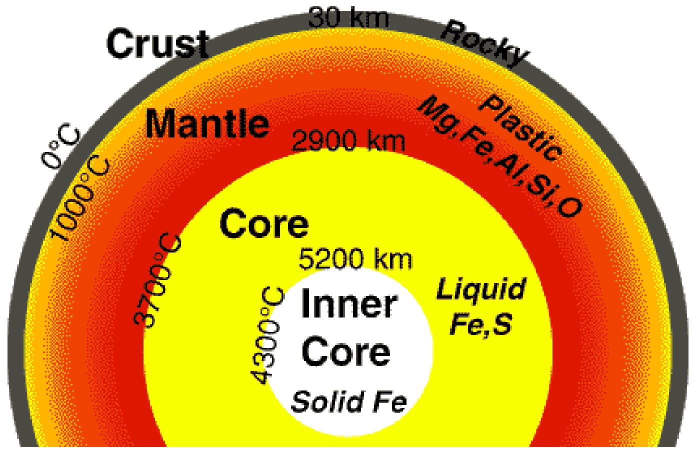


Figure 8.3: The internal structure of the Earth, showing the dimensions of the crust, mantle and core, as well as their composition and temperatures.

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 8.1, we present a comparison of the compositions of the Moon and the Earth. The data for the Moon comes from analysis of the rocks brought back by the Apollo astronauts.

Table 8.1: 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%

12. Is the Moon composed of the same proportion 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? (**5 points**)

As you will learn in lecture, the terrestrial planets in our solar system (Mercury, Venus, Earth and Mars) have higher densities than the jovian planets (Jupiter, Saturn, Uranus and Neptune). One theory for the formation of the Moon is that it formed 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.

13. Given this information, do you think it is likely that the Moon formed out near Mars? Why? (**5 points**)

The currently accepted theory for the formation of the Moon is called the "Giant Impact" theory. In this model, a large body (about the size of 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. Table 8.2 shows the composition of the Earth's crust and mantle compared to that of the Moon.

Table 8.2: Chemical Composition of the Earth (crust and mantle) 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%

14. Given the data in Table 8.2, present an argument for why the giant impact theory probably 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**)

Name:______________________________

Date:______________________________

8.6 Take-Home Questions

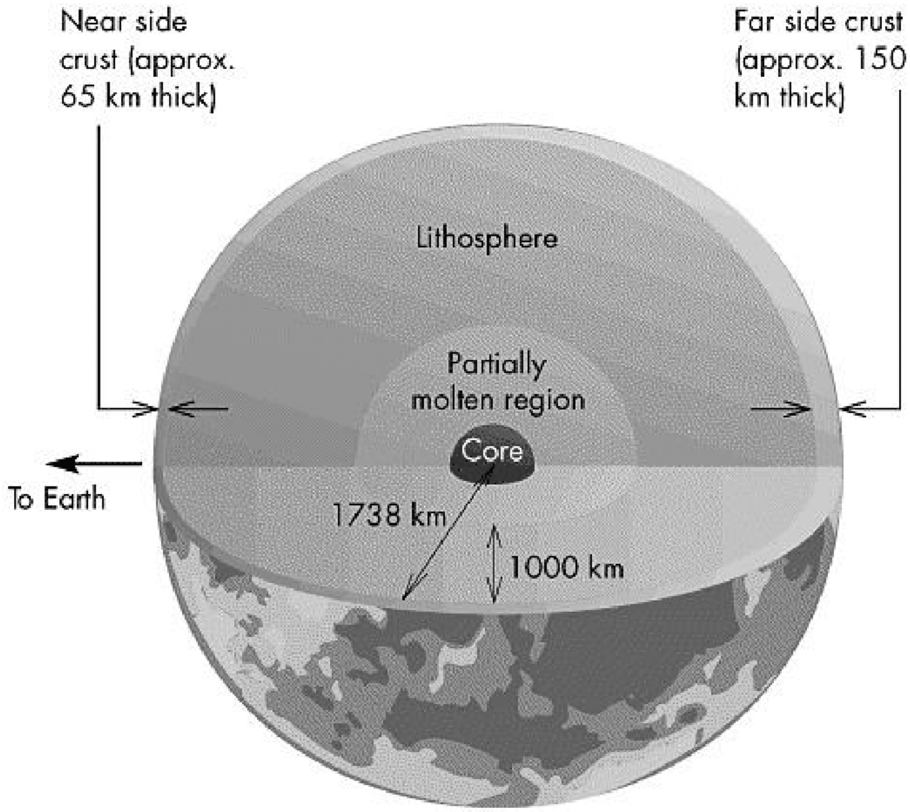
15. What are the maria, and how were they formed? (**5 points**)

16. Explain how you would assign relative ("this is older than that") ages to features on the Moon or on any other surface in the solar system. (**5 points**)

17. How can the Earth be older than the Moon, as suggested by the Giant Impact Theory of the Moon's formation, but the Moon's surface is older than the Earth's surface? What do we mean by 'old' in this context? (**5 points**)

18. The maria are present on the Earthward-facing portion of the Moon and not on the Moon's far side. Since there is no reason to suspect that the impact history of the

near side of the Moon is substantially different from that experienced by the far side, suggest another possible reason why the maria are present on the Earth-facing side only, using the below figure as a guide. **(10 points)**



Name:______________________________
Date:________________________________

9 Introduction to the Geology of the Terrestrial Planets

9.1 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 9.1 summarizes the main properties of the planets in our solar system (Pluto is an oddball planet that does not fall into either categories, sharing many properties with the "Kuiper belt" objects discussed in the "Comet Lab").

Table 9.1: The Properties of the Planets

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

It is clear from Table 9.1 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 9.2.

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

Table 9.2: 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

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.

9.2 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 9.1, 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 9.2. 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.

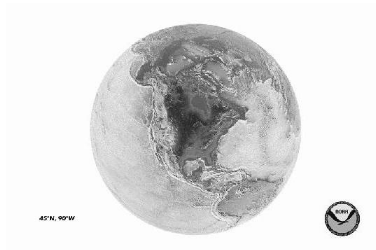


Figure 9.1: A topographic map showing one hemisphere of Earth centered on North America. In this 3D representation the continents are correctly rendered.

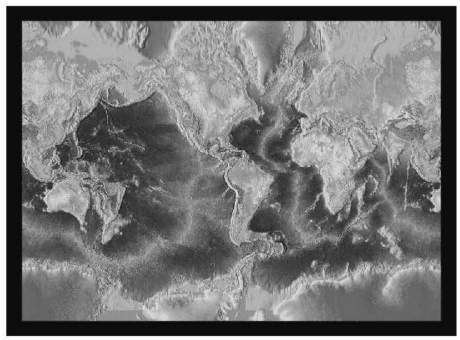


Figure 9.2: A topographic map showing the entire surface of the Earth. In this 2D representation, the continents are incorrectly rendered. Note that Antartica (the land mass that spans the bottom border of this map) is 50% smaller than North America, but here appears massive. You might also be able to compare the size of Greenland on this map, to that of the previous map.

9.3 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!

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)*

9.4 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, there is a discussion on how impact craters form (in case you have not done that lab, read that discussion). 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)*

9.5 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)*

9.6 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 9.3, 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. 9.4), 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.

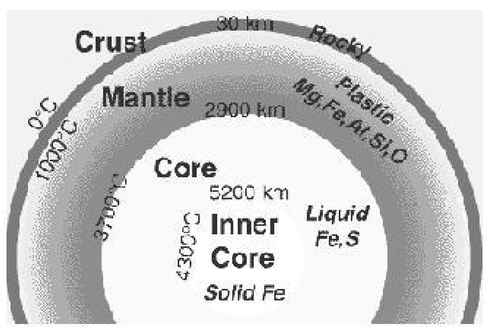


Figure 9.3: A cutaway diagram of the structure of the Earth showing the hot core, the mantle, and the crust. The core of the Earth is very hot, and is composed of both liquid and solid iron. The mantle is a zone where the rocks are partially melted ("plastic-like"). The crust is the cold, outer skin of the Earth, and is very thin.

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.

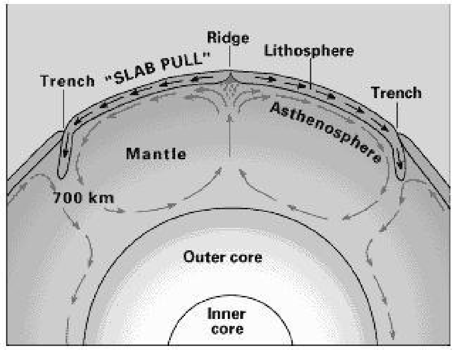


Figure 9.4: The escape of the heat from the Earth's core sets-up a boiling motion in the mantle. Where material rises to the surface it pushes apart the plates and volcanoes, and mountain chains are common. Where the material is cooling, it flows downwards (subsides) back into the mantle pulling down on the plates ("slab-pull'). This is how the large crustal plates move around on the Earth's surface.

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)*

9.7 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?

9.8 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)*

9.9 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:________________________________
Date:_________________________________

10 Surface Water Flow Features on Mars

10.1 Introduction

In this lab you will be making measurements of some valleys and channels on Mars. The main goal of this lab is to be able to distinguish the different surface features left by small, slow flowing streams and large, rapid outflows. You will calculate the volumes of water required to carve these features, and consider how this volume compares with other bodies of water. Be sure to write down and turn in all of your measurements and work. **Write your name on all transparencies and staple them to your lab.**

10.2 Warrego Valles

The first three questions refer to the two images of Warrego Valles. One image is a close-up, the other a wider view. First, look at the close-up view and find the valley system. Look at the impact craters and determine which direction the sunlight is coming from. Warrego Valles is located in Mars' southern hemisphere; its location is identified on the Mars globe and map we have available for you to look at.

1. By looking at the morphology, or shape, of the valley, geologists can tell how the valley was formed. **Does this valley system have a dendritic pattern (like the veins in a leaf) or an anastomosing pattern (like an intertwined rope)? (2 points)**

2. Overlay a transparency film onto the close-up image and tape or paperclip the photo and transparency together so that the transparency does not shift. Trace the valley pattern onto the transparency (be sure to attach your transparency to your lab). **Does the shape of this valley point to slow formation over time or to fast formation from a localized water source? Why do you say this? (3 points)**

3. **Now, trace the boundary between the uplands and plains on your close-up overlay (the transparency sheet) and label the UPLANDS and the PLAINS.** (Again, be sure to attach your transparency.) **Is Warrego located in the uplands or on the plains? (5 points)**

4. Which terrain is older? Recall that we can use crater counting to help determine the age of a surface, so let's do some crater counting. *Attach a transparency sheet to the wide-view image.* Pick out two square regions on the wide view image, each 3 cm $\times$ 3 cm. One region should cover the smooth plains and the other should cover the cratered region. Draw these two squares on the transparency sheet. **Count all the impact craters greater than 1 millimeter in diameter within each of the two squares you have outlined. Write these numbers below, with identification. Which region is older? What does this exercise tell you about approximately (or relatively) when Warrego formed? (5 points)**

5. To figure out how much water was required to form this valley, we first need to estimate its volume. The volume of a rectangular solid (like a shoebox) is equal to $\ell \times w \times h$, where ℓ is the length of the box, h is the height of the box, and w is the width. We will approximate the shape of the valley as one long shoebox and focus only on the main valley system. Use the close-up image for this purpose.

   First, we need to add up the total length of all the branches of the valley. Measure the length, in millimeters, of each branch and the main trunk. Be careful not to count the same length twice. Sometimes it is hard to tell where each branch ends. You need to use your own judgment and be consistent in the way you measure each branch. Now add up all your measurements and convert the sum to kilometers. In this image 1 mm = 2 km. **What is the total length ℓ of the valley system in kilometers? Show your work. (5 points)**

Second, we need to find the average width of the valley. Carefully measure the width of the valley (in millimeters) in several places. **What is the average width? Convert this to kilometers.** Again, **show all of your work. (5 points)**

Finally, we need to know the depth. It is hard to measure depths from photographs, so we will just guess. From other evidence that we will not discuss here, the depth of typical Martian valleys is about 200 meters. **Convert this to kilometers. (5 points)**

Now find the total valley volume in km^3, using the relation $V = \ell \times w \times h$. This is the amount of sediment and rocks that was removed by water erosion to form this valley. We do not know for sure how much water was required to remove each cubic kilometer, but we can guess. Let's assume that $100\,\text{km}^3$ of water was required to erode $1\,\text{km}^3$ of Mars. **How much water was required to form Warrego Valles? (5 points)**

10.3 Ares and Tiu Valles

The remaining questions refer to Ares and Tiu Valles. On the wide scale image, Ares is on the right and Tiu is on the left (your instructor will show you which way to hold the images). The Mars Pathfinder *spacecraft landed in the top left region of this image in 1997. Can you guess why that particular spot was chosen? Again, look at the impact craters to get an idea of where the Sun is.*

6. First, which way did the water flow that carved these channels? The way to tell is to look at streamlined islands, like those on the second print. When flowing water erodes an island, it leaves a shape that has the smallest amount of drag possible. This same shape is used in things like cars and airplane wings. Think about these every-day shapes. **In the close-up photo, did water flow south-to-north or north-to-south? (5 points)**

   Find these same two islands in the large scale print (they are close to the top, left of center). Find other islands with the same shape elsewhere in the channel. *Tape or clip a transparency to your photo and make a sketch of the pattern of these channels.* **Now add arrows to show the path and direction the flowing water took.** Look at pattern of these channels. **Are they dendritic or anastomosing? (5 points)**

   Can you identify locations where the ground seems to have collapsed and the ground water poured out? These are called "chaos" regions because the ground surface appears to be a chaotic jumble. **Label these regions on your sketch and attach it to your work. (5 points)**

7. Now we want to get an idea of the volume of water required to form Ares (the right hand) Valles. Measure the length of the channel from near the Pathfinder landing site to the bottom right corner of the image. Also, measure the length of any tributaries that you see. In this image, 1 mm = 10 km. **How long is the channel in km? (5 points)**

   Measure the channel width in several places and find the average width. **On average, how wide is the channel in km? (5 points)**

   The average depth is about 700 m. **How much is that in km? (5 points)**

Now multiply your answers (in units of km) to find the volume of the channel in km^3. *Use the same ratio of water volume to channel volume that we used in Question 3 to find the volume of water required to form the channel.* **How does the volume of water required to form Ares Valles compare to the volume of water required to form Warrego Valles? (5 points)**

8. You have now studied Warrego and Ares Valles up close. **Compare and contrast the two different varieties of fluvial (water-carved) landforms in as many ways as you can think of (at least three!). Do you think they formed the same way? (10 points)**

Name:______________________________
Date:_______________________________

10.4 Take-Home Question

Answer the following question on a separate sheet of paper, and turn it in with the rest of your lab.

9. What happened to all of the water that carved these valley systems? We do not see any water on the surface of Mars when we look at present-day images of the planet, but if our interpretation of these features is correct, and your calculated water volumes are correct (which they probably are), then where has all of the water gone? Discuss two possible (probable?) fates that the water might have experienced. Think about discussions we have had in class about planets' atmospheres and what their fates have been. Also think about how Earth compares to Mars and how the water abundances on the two planets now differ. **If you have questions, please ask! (20 points)**

Name:____________________________________
Date:_____________________________________

11 Heat Loss from Io

11.1 Introduction

With this lab, we will explore two concepts we have discussed in class. Jupiter's moon Io is the most volcanically active body in the Solar System, due to the intense tidal 'stretching' it experiences because of its proximity to Jupiter and its orbital characteristics related to the orbits of Europa and Ganymede. The regions of the surface where molten lava from the interior comes up from below are very hot, but in general the surface is quite cold since Io is 5.2 AU from the Sun. These regions of different surface temperatures emit different amounts of thermal (blackbody) radiation, since the quantity of energy emitted is proportional to the temperature raised to the 4th power (T^4). We will use observations, obtained with the Voyager spacecraft in the late 1970's, of the quantity of energy emitted by various locations on Io's surface to determine the temperatures of these surfaces. This is the reverse of what we have generally discussed this semester, where we know the temperature and determine something about how much radiation is emitted. By knowing the temperature of the lava/molten material, we can make a good guess as to the composition of the lava.

Supplies:

1. One wide-angle view and one close-up image of Io's surface obtained with the Voyager 1 spacecraft in 1979
2. A map of Io's western hemisphere with various features identified by name
3. A transparency sheet with circles of different diameters drawn on it

11.2 Blackbody Radiation Review

Io's surface is covered with volcanoes and the deposits erupted by these volcanoes. The white regions on Io's surface show spectral absorption features (visible wavelengths at which Io does not reflect much sunlight) of sulfur dioxide (SO_2). Sulfur dioxide is white when solid, and when heated enough it changes to gas (just like water, though the freezing/evaporating temperatures for SO_2 will be different than for water).

The surface colors on Io are consistent with sulfur volcanism. When sulfur is heated, it changes from pale yellow to orange to brown to black as the temperature increases. Laboratory studies indicate that the blackest structures on Io should be hottest, assuming they are sulfur. We will test this prediction today.

For this lab, we are going to look at data returned by an instrument on the *Voyager* spacecraft, which flew by Jupiter and its moons in 1979. The Infrared Spectrometer and Radiometer (IRIS) was mounted on the same part of the spacecraft (the instrument platform) as the visible light camera. This means that both instruments had the same view of Io's surface at any given time. While the camera took images using the sunlight **reflected** by the surface (just like when you take a snapshot), the IRIS measured the thermal infrared radiation **emitted** by the surface. We will use this information to learn about the temperature of the surface of Io.

First, we need to review the properties of **blackbody radiation**. A blackbody is an object that exactly satisfies the Stefan-Boltzmann law and Wien's law. While generally real objects do not exactly satisfy these laws, many objects come very close and in general we assume that most solar system objects (including Io's surface) are blackbodies. Answer the following questions to re-familiarize yourself with these laws.

1. How does the total amount of radiant energy (or flux) emitted by a blackbody depend on its temperature ? How does the wavelength at which most of the energy is emitted depend on its temperature? (**5 points**)

   One rule that was briefly discussed in class is that **the flux of energy at all wavelengths emitted by a black body at temperature T is proportional to the fourth power of its temperature**, which can be written as:

$$F \propto T^4. \tag{1}$$

   Here F (flux) is the energy emitted by each square meter of the object each second. Using equation (1), let's compare the flux emitted by each square meter of the surface of two different objects, A and B. We will construct the ratio:

$$\frac{Flux_A}{Flux_B} = \frac{T_A^4}{T_B^4} = \left(\frac{T_A}{T_B}\right)^4 \tag{2}$$

2. Assume that T_A, the surface temperature of Object A, is 200 K, and T_B, the surface temperature of Object B, is 100 K. How many times greater is the flux from A compared to the flux from B? (**5 points**)

3. Now, assume that we receive 81 times more flux from Object X than from Object Y. How many times hotter is the surface of X compared to the surface of Y? (**5 points**)

11.3 Temperature of Io's Volcanoes

As indicated above, we can suitably approximate the surface of a planet or a moon as a blackbody. Using the above equations and temperature determination techniques, and IRIS observations, we can determine the temperatures of some of the volcanoes on Io's surface. You will be filling **Table 11.1** as you go along.

Within your lab package you will find two *Voyager* camera images of a region on Io's surface. One of these images is a wide-angle view (covers a large area) in which you can see several dark regions, and the other image is a close-up in which you can see two features, one dark and one bright, that are readily apparent in the wide-angle image.

4. Determine the location, in the wide-angle view image, of the two features you can see in the close-up view. [You should have the GREEN corner of each image in the lower left as you look at them]. The black feature in the close-up image is called *Mihr Patera* (Patera means pancake). Find Mihr Patera on the map provided along with the images and write down its latitude and longitude on Io. (**5 points**)

As Voyager's visible camera was taking the images you have in front of you, its infrared-sensitive instrument, IRIS, was also looking at the same location on Io's surface. However, IRIS had much lower spatial resolution than the imaging camera. It only measured the total amount of energy emitted from a large circular region each second.

Overlay your transparency sheet on the wide-angle image. Match the green edges on your wide-view photo and on your transparency, and point the arrow upwards, to determine which circular Areas (A, B, C, D, E) correspond to the various features on the wide-angle image. The circles on the transparency show the IRIS field of view ("footprints") over the same area as the photograph.

Now, let's determine how hot the surfaces are within these circular areas. We assume that area A is completely covered with ice composed of sulfur, and that all regions within this circular area are at the same temperature. The amount of emitted energy received from Area A by IRIS corresponds to a surface temperature of $\sim$ 125 Kelvin. [If we calculate a surface temperature for Io based upon the reflectivity of the ice, distance from the Sun, etc., we arrive at a temperature of $\sim$ 125 K, so the IRIS measurements are very reasonable.]

5. Looking at just the Energy values in Column 2 of Table 11.1, which areas do you conclude contain warmer surface temperatures than the surface temperatures within Area A? Why do you conclude this? What distinguishes these areas, at visible wavelengths, from their neighbors in the wide-angle image? (**10 points**)

To determine the temperatures of these regions, we will make the following assumption: *for those regions that contain both bright and dark regions, we will assume all the emitted energy IRIS received came from the dark regions.* We can safely make this assumption because of the T^4 dependence of energy emission, and since through our knowledge of the surface composition (sulfur), we are quite confident that darker regions will be warmer than brighter regions.

We now want to determine how much (maybe all?) of the area within a circular field-of-view is producing the flux received by IRIS. We will do this by counting squares (picture elements, or pixels). For circular regions containing both bright and dark pixels, count up the number of dark pixels. For regions of uniform brightness (*e.g.,* Area E), assume the entire circular area produces the flux measured and count the total number of pixels contained within the circle.

Thus, for Area B, we will count the number of pixels that the dark circular feature covers. For Area C, count the pixels that cover the large dark feature, for Area D count the pixels covering the dark portions, and for Area E assume that the surface is equally bright everywhere. Write the number of pixels you count for each area in Column 3 of Table 11.1. (**6 points**)

Now we know i) the relative amount of energy coming from each circular area, and ii) how many pixels of area generated the flux that was measured.

We can now calculate temperatures (finally). We know that the amount of energy emitted is proportional to T^4. We will use the following equation:

$$\left(\frac{T_x}{T_A}\right)^4 = \left(\frac{E_x}{E_A}\right) \times \left(\frac{Pixels_A}{Pixels_x}\right) \tag{3}$$

Here E_A is the energy measured at site A, $Pixels_A$ is the number of pixels that cover site A, and T_A is the temperature measured at site A. The 'x' subscript corresponds to areas B, C, D, or E.

- Use Equation (3) and the values in Columns 2 and 3 from Table 11.1 to calculate the ratio (raised to the 4th power) of the surface temperature in the area of interest to the surface temperature in Area A. Place these values in Column 4 of Table 11.1. (**8 points**)

- Take the square root TWICE of the values you just place in Column 4 to obtain the ratio of the surface temperature of the area of interest to the surface temperature within Area A. Place these values in Column 5 of Table 11.1. (**8 points**)

- Multiply the values you just placed in Column 5 by the temperature of Area A, and you will have determined the surface temperature within the areas of interest. Place these values in Column 6 of Table 11.1. (**8 points**)

- To put these temperatures into units that you are more familiar with, convert the temperatures you just calculated from Kelvins to degrees Fahrenheit using the following formula, where F the temperature in Fahrenheit and K is the temperature in Kelvins:
$$F = ((K - 273.15) \times 1.8) + 32 \tag{4}$$
Place these new temperature values in Column 7 of Table 11.1. (**5 points**)

Additional workspace – SHOW ALL OF YOUR WORK HERE:

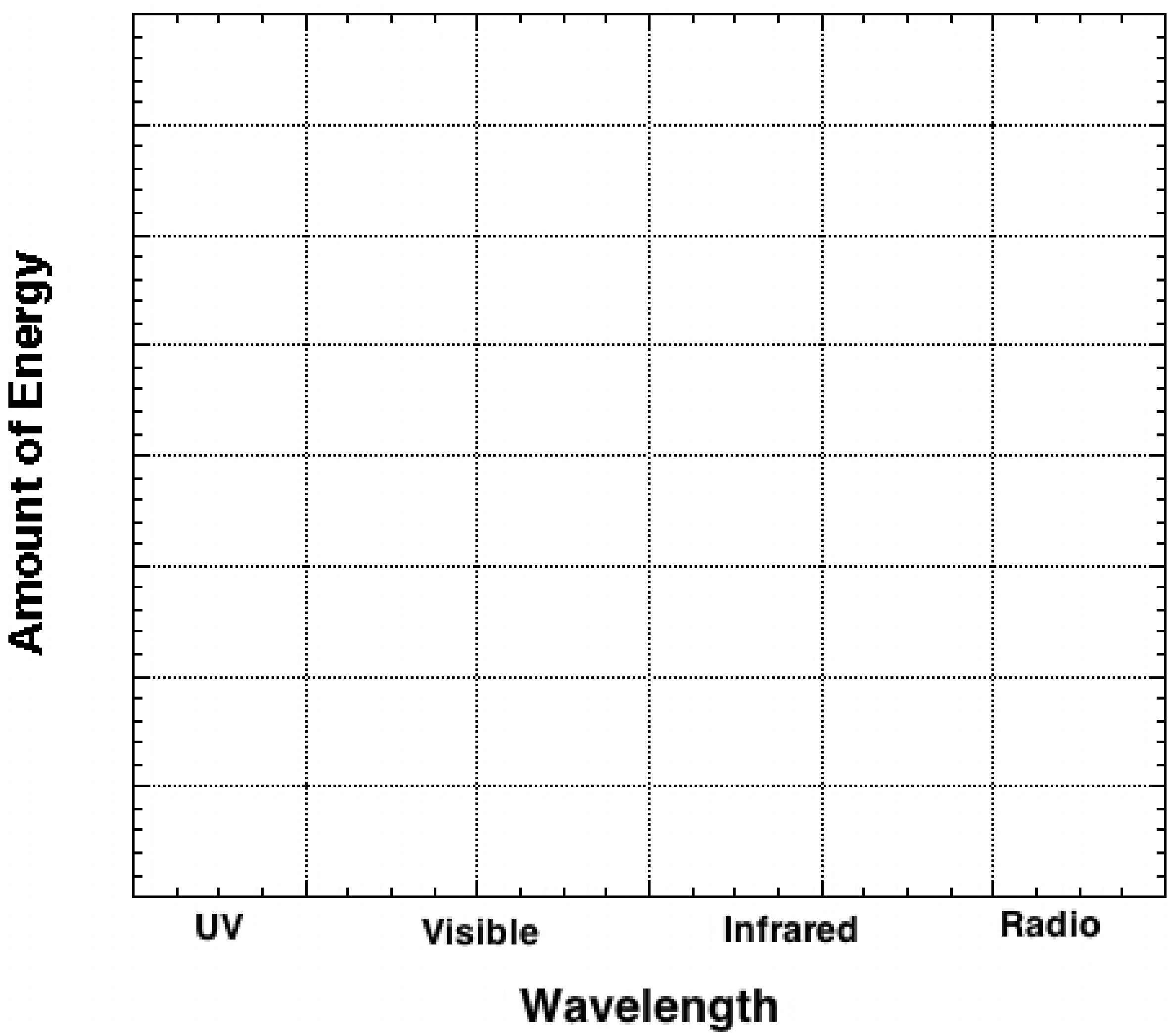
Area	Energy	Area (# pixels)	$(T_x/T_A)^4$	T_x/T_A	T_x (K)	T_x (°F)
A	1.000	132	1.000	1.000	125	
B	4.833	33				
C	4.523					
D	3.560					
E	0.983					

Table 11.1: Energy Emitted and Temperature of Io's Surface.

Name:______________________________
Date:_______________________________

11.4 Take-Home Questions

6. On the graph axes below, draw two curves indicating the blackbody curves (energy as a function of wavelength) emitted by i) a hot area, and ii) a cool area. You will be graded on the *relative positions* of these two curves with respect to one another (in other words, which one – "i" or "ii" – is hotter vs. cooler, and which one has more vs. less energy at the peak). **Be sure to label both curves! (10 points)**



7. If Jupiter's average distance from the Sun was 10 AU instead of its actual value of 5.2 AU, and if Europa, Ganymede, and Callisto were farther from Jupiter, would you still expect Io to experience volcanism? Explain. (**5 points**)

8. The volcanic features we have studied in this lab involve the chemical element sulfur. It is not expected that molten sulfur gets any hotter than ~ 350 Kelvin or so on Io's surface. However, some spots on Io's surface have been determined to possess temperatures as hot as 1800 Kelvin. It is believed that such regions consist of molten rock (like lava here on Earth) and not molten sulfur.

   a) How many times greater would the flux from such a rock-lava region be compared to the flux emitted by Area A in this lab? [Remember area "A" has a temperature of 125 K.](**5 points**)

   b) Which type of region would you expect you would have a better chance of seeing at visible wavelengths on the night side of Io (not illuminated by the Sun) if you were orbiting overhead? Explain. (**5 points**)

9. How would you change the orbit of the Moon to have it experience tidal heating similar to the kind Io experiences? Explain your reasoning. (**5 points**)

10. Jupiter has several moons that are much smaller than Io and that are closer to Jupiter than Io is. Give a brief explanation of why you think these moons do NOT show

evidence of volcanism. (**5 points**)

Name:________________________________
Date:_________________________________

12 Building a Comet

12.1 Introduction

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 are also beautiful objects to observe in the night sky, unlike their darker and less spectacular cousins, asteroids, and therefore capture the attention of the public. The objective of this lab is to teach you more about these fascinating objects.

- *Goals:* to discuss the composition, components, and types of comets; to build a comet and test its strength and reaction to light
- *Materials:* ziplock bag, bucket, spoon, towel, mallet, light source, water, sand, ammonia, potting soil, dry ice, gloves

12.2 Composition and Components of a Comet

Comets are composed of ices (water ice and other kinds of ices), gases (water, carbon dioxide, carbon monoxide, hydrogen, hydroxyl, oxygen, carbon, silicon, and so on), and dust particles. 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 tail. The shape of the gas tail is influenced by the magnetic field in the solar wind. Gas tails are pointed in the direction 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 opposite the comet's direction of motion, and can also extend 10^8 km from the nucleus.

12.3 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 comets entering the inner solar system from all different directions. These comets are thought to originate in the **Oort cloud**, a spherical cloud of icy bodies that extends from ∼ 20,000 – 150,000 AU from the Sun. 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.

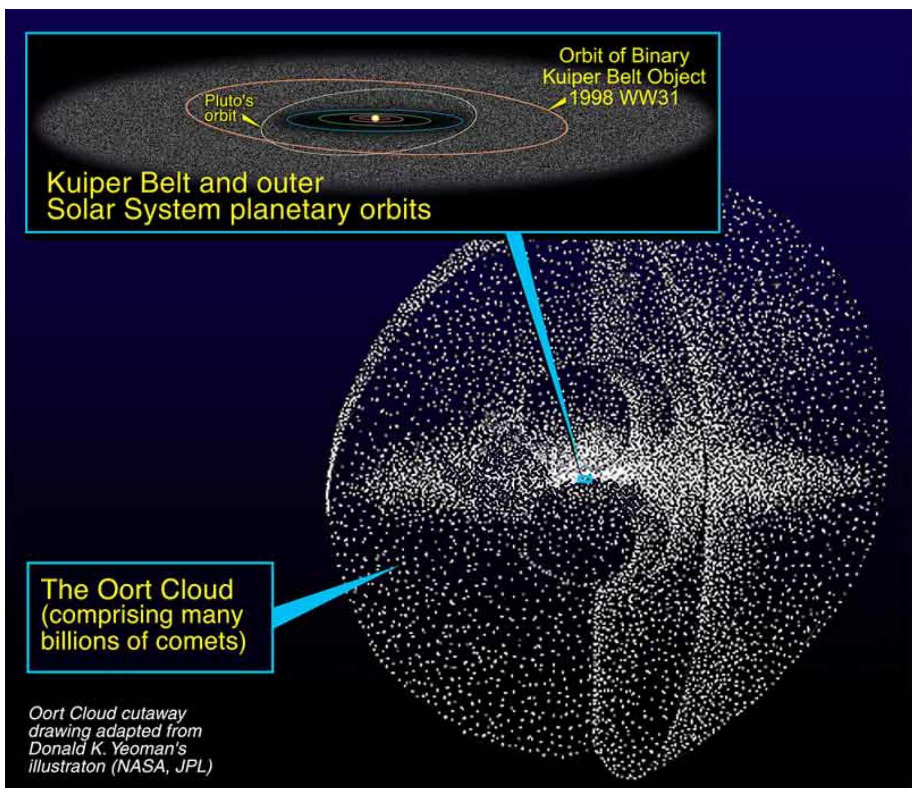


Figure 12.1: Different origins for long and short period comets. Image courtesy of NASA.

12.4 Exercises

12.4.1 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:

1. Put the ziplock bag in your bucket.
2. Place 1 cup of water in the bucket.
3. Add 2 spoonfuls of sand, mix well. (**NOTE:** Do not stir so hard that you rip the bag!!)
4. Add a dash of ammonia.
5. Add a dash of organic material (potting soil). Stir until well-mixed.
6. The TA will place a block or chunk of dry ice inside a towel and crush the block with the mallet.
7. Add 1 cup of crushed dry ice to the bucket, while stirring vigorously. (**NOTE:** Do not stir so hard that you rip the 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.
10. Add water slowly, and as needed, to get the mixture frozen into a ball.
11. Unwrap the comet once it is frozen enough to hold its shape.

12.4.2 Comets and Light

Observe the comet as it is sitting on a desk. Make note of some of its physical characteristics, for example: (**5 points**)

- shape:
- color:
- smell:

Now bring the comet over to the light source (overhead projector) and place it on top. Observe and record what happens to the comet. (**5 points**)

12.4.3 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 that case, 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.

After everyone in your group has carefully examined your comet, it is time to say good-bye. Take a sample rock and your comet, go outside, and drop them both on the sidewalk. What happened to each object? (**5 points**)

12.5 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. (**10 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? (**10 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.). (**15 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? (**10 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? (**10 points**)

6. Do you think comets ("dirty snowballs") 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?] (**10 points**)

Name:______________________________
Date:_______________________________

12.6 Take-Home Summary

Summarize the important ideas covered in this lab. Questions you may want to consider are:

- Why are comets important to planetary astronomers, and 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?

Type this summary. Use complete sentences, and proofread your summary before handing in the lab. **(30 points)**

12.7 Extra Credit

Use the internet to look up one (or more) of the following current or planned spacecraft missions to comets and briefly describe the mission, its scientific objectives, and the significance of these objectives. **DO NOT copy the information from the web sites; put it into your own words! (3 points each)**

- Stardust (`http://stardust.jpl.nasa.gov/`)
- Deep Impact (`http://deepimpact.umd.edu/home/index.html`)
- Rosetta (`http://sci.esa.int/science-e/www/area/index.cfm?fareaid=13`)
- CONTOUR (`http://discovery.nasa.gov/contour.html`)

Name:________________________________

Date:_________________________________

13 The Sun

13.1 Introduction

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

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

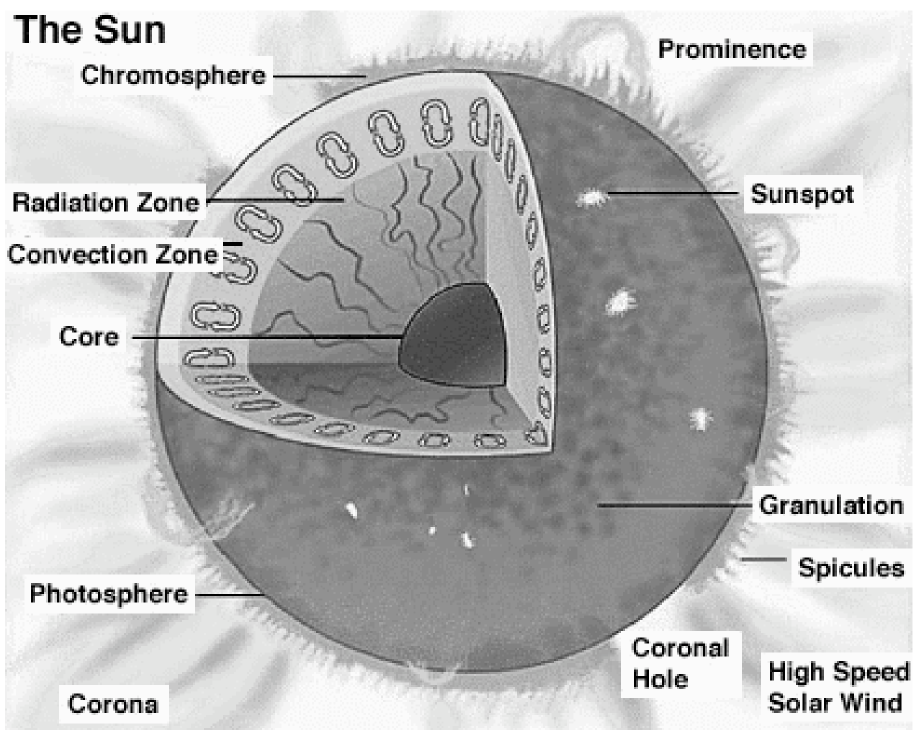


Figure 13.1: A diagram of the various layers/components of the Sun, as well as the appearance and location of other prominent solar features.

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

13.2 Layers of the Sun

One of the things we know best about the Sun is its overall structure. Figure 13.1 is a schematic of the layers of the Sun's interior and atmosphere. The interior of the Sun is made up of three distinct regions: the core, the radiative zone, and the convective zone. The *core* of the Sun is very hot and dense. This is the only place in the Sun where the temperature and pressure are high enough to support nuclear reactions. The *radiative zone* is the region of the sun where the energy is transported through the process of radiation. Basically, the photons generated by the core are absorbed and emitted by the atoms found in the radiative zone like cars in stop and go traffic. This is a very slow process. The *convective zone* is the region of the Sun where energy is transported by rising "bubbles" of material. This is the same phenomenon that takes place when you boil a pot of water. The hot bubbles rise to the top, cool, and fall back down. This gives the the surface of the Sun a granular look. Granules are bright regions surrounded by darker narrow regions. These granules cover the entire surface of the Sun.

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

13.3 Sunspots

Sunspots appear as dark spots on the photoshere (surface) of the Sun (see Figure 13.2). They last from a few days to over a month. Their average size is about the size of the Earth, although they have been observed to be over twice the size of the Earth! Sunspots are commonly found in pairs. How do these spots form?

The formation of sunspots is attributed to the Sun's *differential rotation*. The Sun is a ball of gas, and therefore does not rotate like the Earth or any other solid object. The Sun's equator rotates faster than its poles. It takes roughly 25 days for something to travel once around the equator, but about 35 days for it to travel once around the north or south pole. This differential rotation acts to twist up the magnetic field lines inside the Sun. At times, the lines can get so twisted that they pop out of the photosphere. Figure 13.3 illustrates this concept. When a magnetic field loop pops out, the places where it leaves and re-enters the

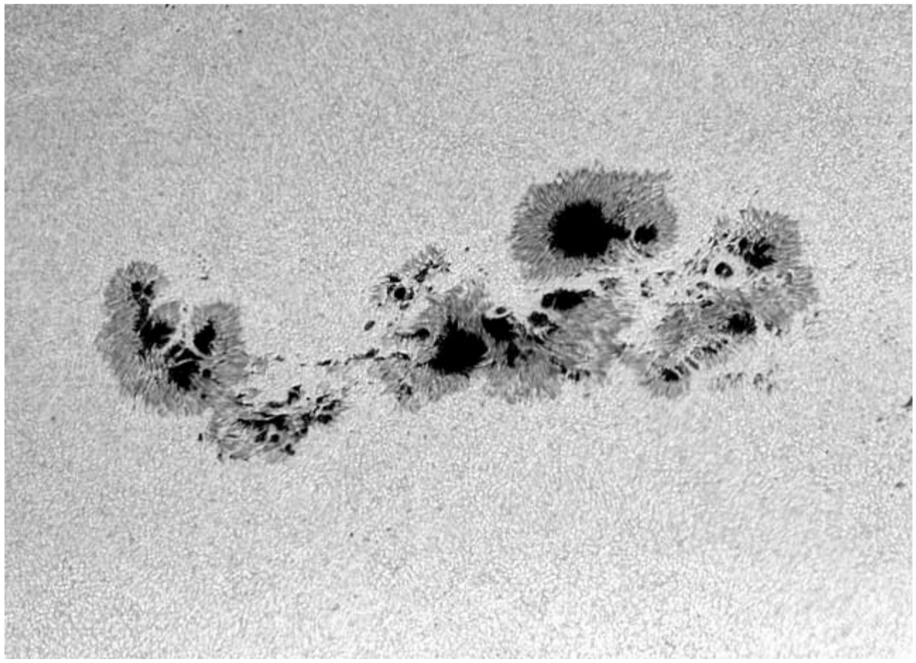


Figure 13.2: A large, complex group of sunspots.

photosphere are cooler than the rest of the Sun's surface. These cool places appear darker, and therefore are called "sunspots."

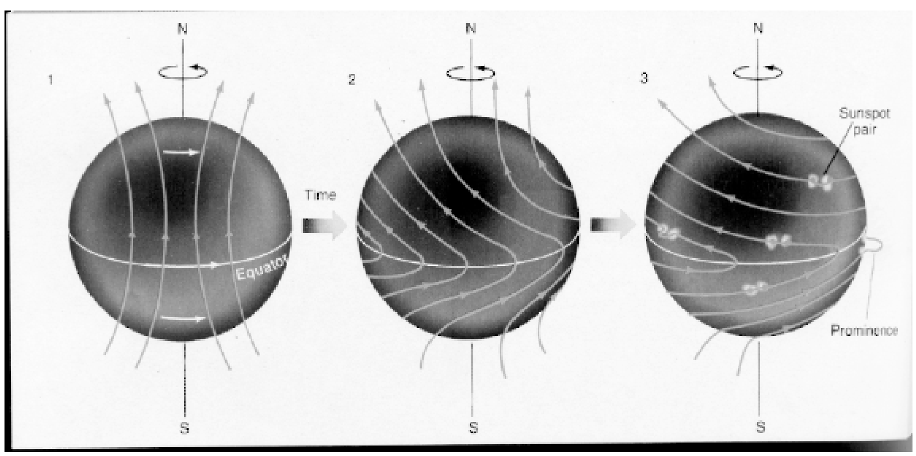


Figure 13.3: Sunspots are a result of the Sun's differential rotation.

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

13.4 Solar Phenomenon

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

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

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

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

13.5 Lab Exercises

There are two main exercises in this lab. The first part consists of a series of "stations" in a three ring binder where you examine some pictures of the Sun and answer some questions about the images that you see. In the second exercise you will actually look at the Sun using a special telescope to see some of the phenomena that were detailed in the images in the first exercise of this lab. During this lab you will use your own insight and knowledge of basic physics and astronomy to obtain important information about the phenomena that we see on the Sun, just as solar astronomers do. If there is not sufficient room to write in your answers into this lab, do not hesitate to use additional sheets of paper. Do not try to squeeze your answers into the tiny blank spaces in this lab description if you need more space then provided! Don't forget to **SHOW ALL OF YOUR WORK**.

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

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

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

- The first image in this station is a simple "white light" picture of the Sun as it would appear to you if you were to look at it in a telescope that was designed for viewing the

Sun. Note the dark spots on the surface of the Sun. These are "sunspots," and are dark because they are cooler than the rest of the photosphere.

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

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

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

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

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

- Determine the precise time difference between the images. Use this information plus the fact that the Sun has turned by 90 degrees in that time to determine the rotation rate of the Sun. If the Sun turns by 90 degrees in time t, it would complete one revolution of 360 degrees in how much time? **(5 points)**

- Does this match the rotation rate given in your textbook or in lecture? Show your work. **(5 points)**

In the second set of photographs at this station are two different images of the Sun: the first one on is a photo of the Sun taken in normal light, and the second one on the right is a "magnetogram" (a picture of the magnetic field distribution on the surface of the Sun) taken at about the same time. (Note that black and white areas represent regions with different *polarities*, like the north and south poles of a bar magnet.)

- What do you notice about the location of *sunspots* in the photo and the location of the *strongest magnetic fields*, shown by the brightest or darkest colors in the magnetogram? **(5 points)**

- Based on this answer, what do you think causes sunspots to form? Why do you think they are dark? **(5 points)**

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

- Determine the diameter of the Sun, then measure the minimum extent of the corona (diagonally from upper left to lower right). **(3 points)**

- If the photospheric diameter of the Sun is 1.4 million kilometers (1.4×10^6 km), how big is the corona? (HINT: use unit conversion!) **(7 points)**

- How many times larger than the Earth is the corona? (Earth diameter=12,500 km) **(5 points)**

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

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

- Convert these values into real distances based on the linear scale of the images. The diameter of the Sun is 1.4×10^6 kilometers. **(7 points)**

- The velocity of an object is the distance it travels in a certain amount of time (velocity=distance/time). Find the velocity of the prominence by subtracting the two distances and dividing the answer by the amount of time between the two images. **(5 points)**

- In the most severe of solar storms, those that cause flares, and "coronal mass ejections" (and can disrupt communications on Earth), the material ejected in the prominence (or flare) can reach velocities of 2,000 kilometers per second. If the Earth is 150×10^6 kilometers from the Sun, how long (hours or days) would it take for this ejected material to reach the Earth? **(5 points)**

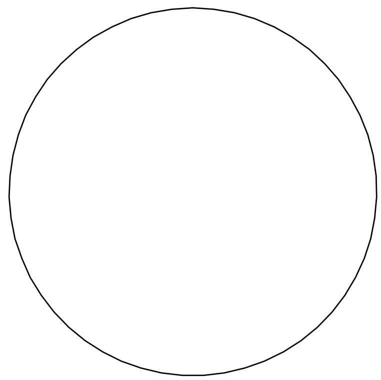
Station 5: This is a plot of where sunspots tend to occur on the Sun as a function of *latitude* (top plot) and time (bottom plot). What do you notice about the distribution sunspots? How long does it take the pattern to repeat? What does this length of time correspond to? **(5 points)**

13.5.2 Exercise #2: Looking at the Sun

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

- In the "Solar Observation Worksheet" below, draw what you see on and near the Sun as seen through the special solar telescope. **(10 points)**

Solar Observation Worksheet



Name: ______________________ Lab Sec.: ___________

Date: ______________________ TA: _________________

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

Name:________________________________
Date:__________________________________

13.6 Summary

(**30 points**) Summarize the important concepts discussed in this lab.

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

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

Name:
Date:
Object:
Telescope:

Draw the object as it looks to you through the telescope

Name:
Date:
Object:
Telescope:

Draw the object as it looks to you through the telescope