# ASTR 105G Lab Manual

# Astronomy Department
# New Mexico State University

# 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 hundredth) |
| milli | m | 0.001 (one thousandth) |
| micro | $\mu$ | 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?

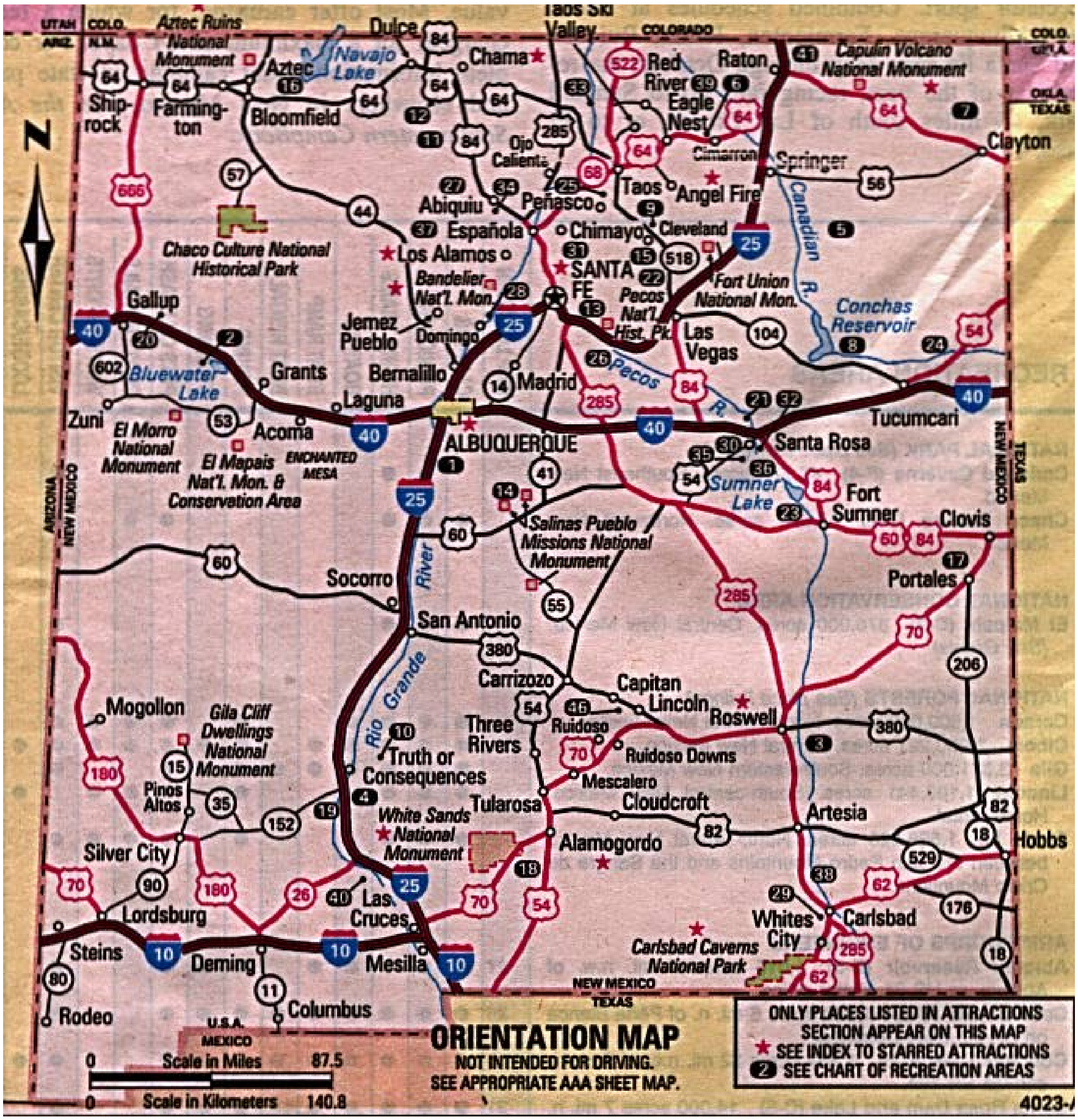



Figure 1.1: Map of New Mexico.

## 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 "$\surd$ ", 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 $1.0 \times 10^2$. 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 $1.346 \times 10^{12}$.

**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 $1 \times 10^{-1}$. 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 $2.37 \times 10^1$, or 0.5 as $5.0 \times 10^{-1}$. 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 $3.3 \times 10^{-3}$ meter. But telling someone the answer is 215 kg, is much easier than saying $2.15 \times 10^2$ 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 $8.778046 \times 10^{11}$. Similarly, 1.4672E-05 is equivalent to $1.4672 \times 10^{-5}$.

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 $6.589 \times 10^7$, you may need to type 6.589 "E" 7.

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

- $7.99921 \times 10^{21}$
- $2.2951324 \times 10^{-6}$

### 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.

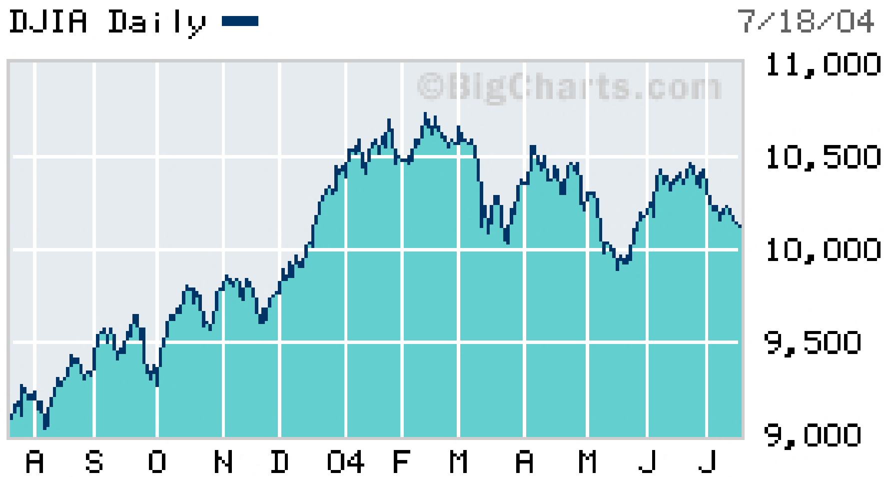



Figure 1.2: The change in the Dow Jones stock index over one year (from April 2003 to July 2004).

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.

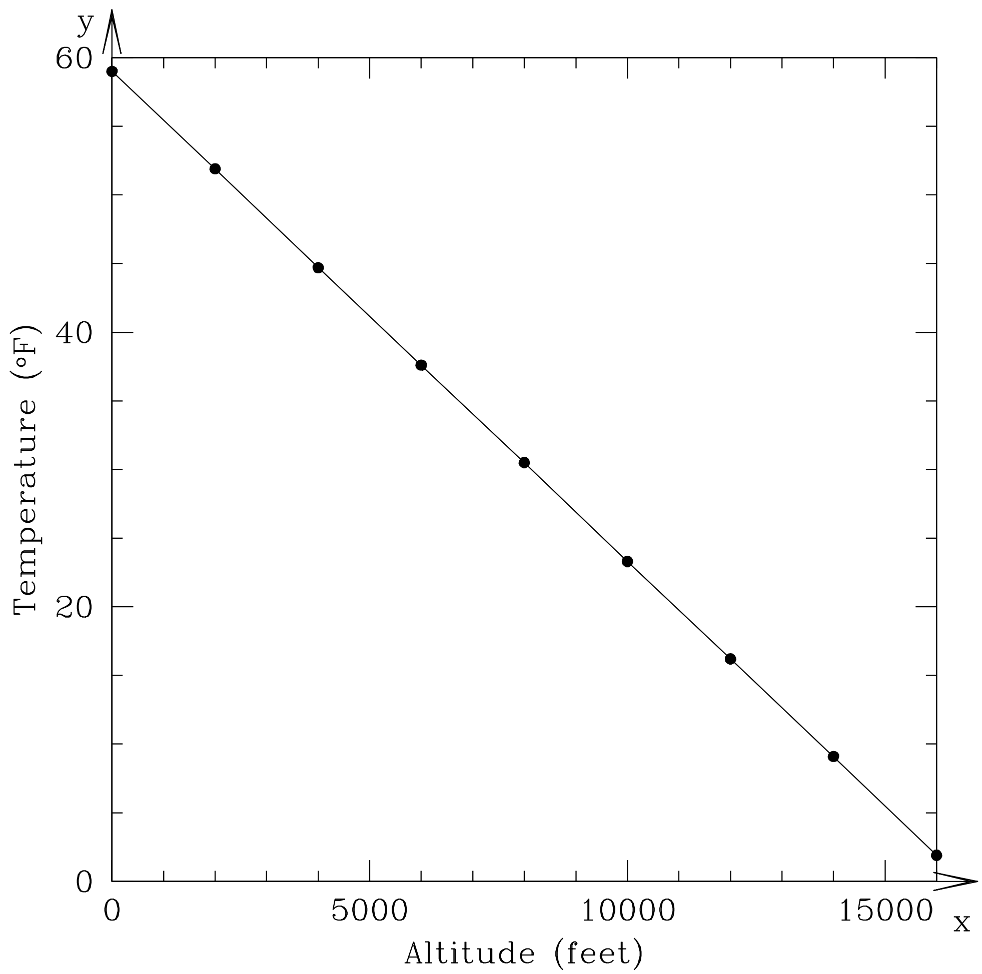



Figure 1.3: The change in temperature as you climb in altitude with the data from Table 1.2. At sea level (0 ft altitude) the surface temperature is 59°F. As you go higher in altitude, the temperature goes down.

### 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. (**10 points**)

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

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

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. (**5 points each**)

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

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

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

## 1.10 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? (**10 points**)

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

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

Name(s):______________________________
Date:____________________________________

# 2 The Origin of the Seasons

## 2.1 Introduction

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

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

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

## 2.2 The Seasons

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

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

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

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

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

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

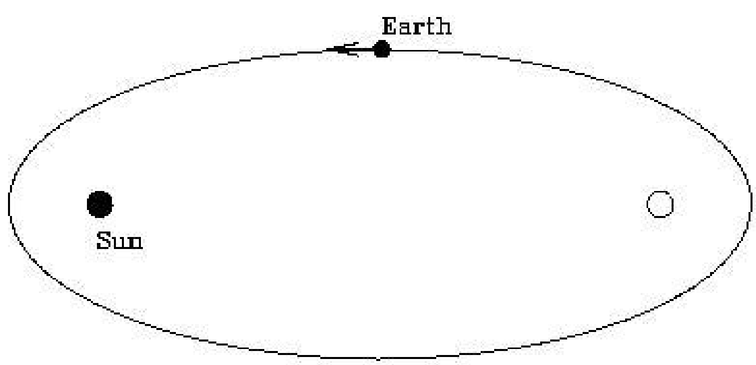



Figure 2.1: An ellipse with the two "foci" identified. The Sun sits at one focus, while the other focus is empty. The Earth follows an elliptical orbit around the Sun, but not nearly as exaggerated as that shown here!

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

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

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

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

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

Sun diameter in January image = ____________ mm.

Sun diameter in July image = ____________ mm.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## 2.3 The Spinning, Revolving Earth

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

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

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

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


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

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

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

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

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

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

Table 2.2: Total Arc Length

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

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

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

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

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

Table 2.3: Position #1: Equinox Data Table

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

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

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

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

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

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

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

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

Table 2.5: Position #2: Solstice Data Table

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

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

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

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

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

Table 2.7: Position #3: Solstice Data Table

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

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

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

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

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

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

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

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

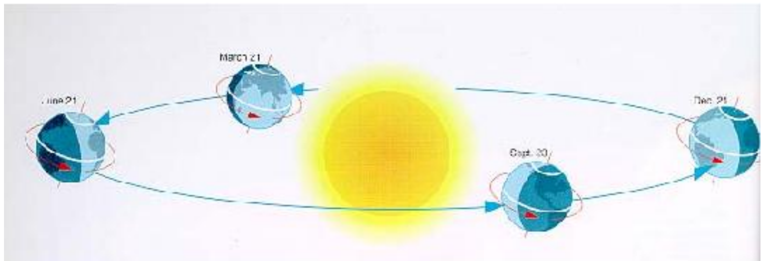



Figure 2.4: The Earth's spin axis always points to one spot in the sky, *and* it is tilted by 23.5° to its orbit. Thus, as the Earth orbits the Sun, the illumination changes with latitude: sometimes the North Pole is bathed in 24 hours of daylight, and sometimes in 24 hours of night. The exact opposite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

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

## 2.4 Elevation Angle and the Concentration of Sunlight

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

The Sun is highest in the sky at noon everyday. But how high is it? This, of course, depends on both your latitude and the time of year. For Las Cruces, the Sun has an altitude of 81° on June 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).

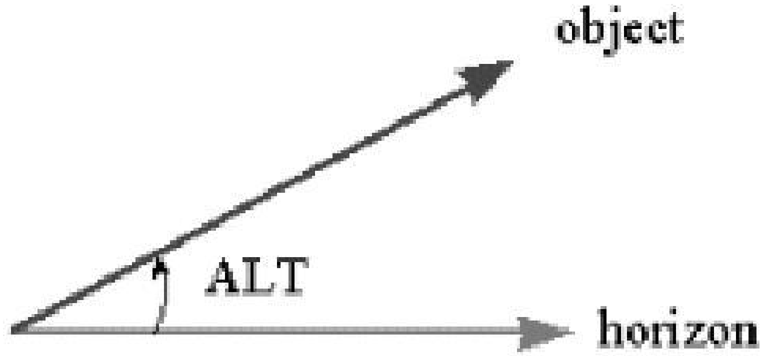



Figure 2.5: Altitude ("Alt") is simply the angle between the horizon, and an object in the sky. The smallest this angle can be is 0°, and the maximum altitude angle is 90°. Altitude is interchangeably known as elevation.

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

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

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

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

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

The radius of the illuminated circle is __________________ cm.

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

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

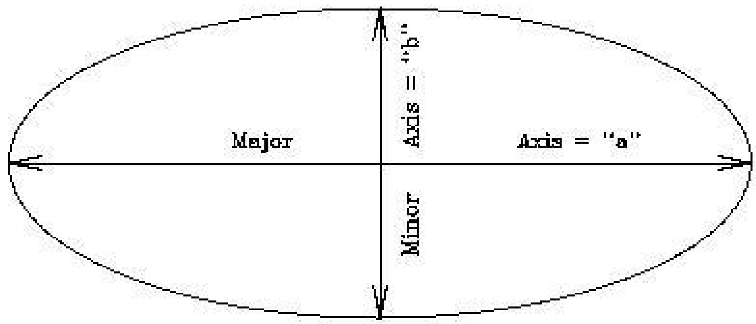



Figure 2.6: An ellipse with the major and minor axes defined.

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

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

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

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

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

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

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

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

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

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

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

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

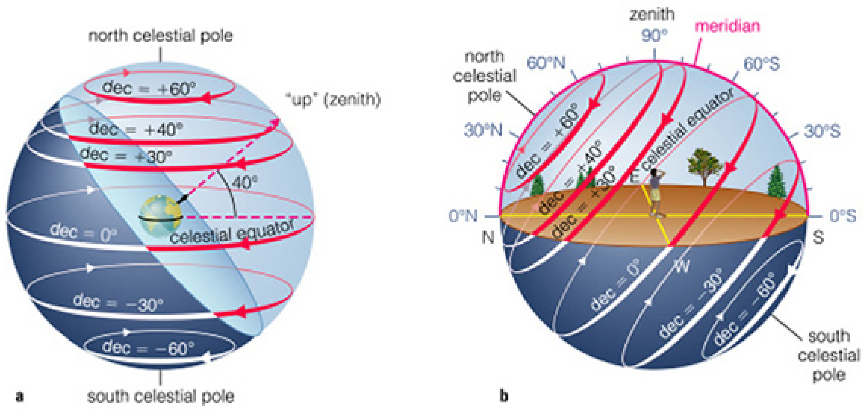



Figure 2.7: The Celestial Equator is the circle in the sky that is straight overhead ("the zenith") of the Earth's equator. In addition, there is a "North Celestial" pole that is the projection of the Earth's North Pole into space (that almost points to Polaris). But the Earth's spin axis is tilted by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

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

Name:____________________________________
Date:_____________________________________

## 2.5 Take Home Exercise (35 total points)

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

1. Why does the Earth have seasons?

2. What is the origin of the term "Equinox"?

3. What is the origin of the term "Solstice"?

4. Most people in the United States think the seasons are caused by the changing distance between the Earth and the Sun. Why do you think this is?

5. What type of seasons would the Earth have if its spin axis was *exactly* perpendicular to its orbital plane? Make a diagram like Fig. 2.4.

6. What type of seasons would the Earth have if its spin axis was *in* the plane of its orbit? (Note that this is similar to the situation for the planet Uranus.)

7. What do you think would happen if the Earth's spin axis wobbled randomly around on a monthly basis? Describe how we might detect this.

## 2.6 Possible Quiz Questions

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

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

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

Name:________________________________

Date:_________________________________

# 3 Scale Model of the Solar System

## 3.1 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 = $2\pi$R?). 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

## 3.2 The Distances of the Planets From the Sun

Fill in the first and second columns of Table 6.1. 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 3.1: 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 6.1.

## 3.3 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 1,400,000 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 6.2 **(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 6.3 (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.

**Observations:**

On Earth, we see the Sun as a disk. Even though the Sun is far away, it is physically so large, we can actually see that it is a round object with our naked eyes (unlike the planets,

Table 3.2: 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 3.3: Objects that Might Be Useful to Represent Solar System Objects

| **Object** | **Diameter (inches)** |
|---|---|
| Basketball | 15 |
| Tennis ball | 2.5 |
| Golf ball | 1.625 |
| Nickel | 0.84 |
| Marble | 0.5 |
| Peppercorn | 0.08 |
| Sesame seed | 0.07 |
| Poppy seed | 0.04 |
| Sugar grain | 0.02 |
| Salt grain | 0.01 |
| Ground flour | 0.001 |

where we need a telescope to see their tiny disks). Let's see what the Sun looks like from the other planets! Ask each of the "planets" whether they can tell that the Sun is a round object from their "orbit". What were their answers? List your results here: (**5 points**):

Note that because you have made a "scale model", the results you just found would be exactly what you would see if you were standing on one of those planets!

## 3.4 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. Answer the following questions using the information you have gained from this lab and your own intuition:

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**)

2) Given that there is very little material between the planets (some dust, and small bits of rock), what do you conclude about the nature of our solar system? (**5 points**)

3) Which planet would you expect to have the warmest surface temperature? Why? (**2 points**)

4) Which planet would you expect to have the coolest surface temperature? Why? (**2 points**)

5) Which planet would you expect to have the greatest mass? Why? (**3 points**)

6) Which planet would you expect to have the longest orbital period? Why? (**2 points**)

7) Which planet would you expect to have the shortest orbital period? Why? (**2 points**)

8) The Sun is a normal sized star. As you will find out at the end of the semester, it will one day run out of fuel (this will happen in about 5 billion years). When this occurs, the Sun will undergo dramatic changes: it will turn into something called a "red giant", a cool star that has a radius that may be $100\times$ that of its current value! When this happens, some of the innermost planets in our solar system will be "swallowed-up" by the Sun. Calculate which planets will be swallowed-up by the Sun (**5 points**).

## 3.5 Take Home Exercise (35 points total)

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 6.4, and draw on your map of New Mexico (on the next page) the locations of the solar system objects. **(20 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 6.5. **(15 points)**

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

Table 3.4: Planets' average distances from Sun.

| **Planet** | **Average Distance from Sun** | | **Nearest City** |
|---|---|---|---|
| | **in AU** | **in Miles** | |
| | | | |
| | | | |
| Earth | 1 | 11.375 | |
| | | | |
| Jupiter | 5.2 | | |
| | | | |
| Uranus | 19.2 | | |
| | | | |
| Pluto | 40 | 455 | 3 miles north of Raton |

Table 3.5: 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 |
| Mars | 6,794 | | |
| Jupiter | 142,800 | | |
| Saturn | 120,540 | | |
| Uranus | 51,200 | | |
| Neptune | 49,500 | | |
| Pluto | 2,200 | 0.87 | soccer ball |


COLORADO
FARMINGTON
Aztec
Bloomfield
Shiprock
NAVAJO
Chama
Raton
Taos
Newcomb
INDIAN
RESERVATION
Gallina
Los Alamos
Española
White Rock
SANTA FE
LAS VEGAS
Wagon Mound
Cuba
GALLUP
Fort Wingate
Milan
Grants
ALBUQUERQUE
Bernalillo
Moriarty
Santa Rosa
Isleta
Los Lunas
Belen
Estancia
Mountainair
Quemado
Magdalena
Socorro
Datil
Corona
Carrizozo
Ruidoso
ROSWELL
Truth or Consequences
Hillsboro
Tularosa
ALAMOGORDO
Silver City
Hurley
Hatch
Lordsburg
Deming
LAS CRUCES
Mesilla
Artesia
WHITE SANDS
MISSILE
RANGE
FORT BLISS
MILITARY
RESERVATION
TEXAS
GOUSHA

## 3.6 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"?

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

Later this semester 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?

Name(s):____________________
Date:____________________

# 4 Phases of the Moon

## 4.1 Introduction

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

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

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

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

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

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

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

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

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

**Materials**

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

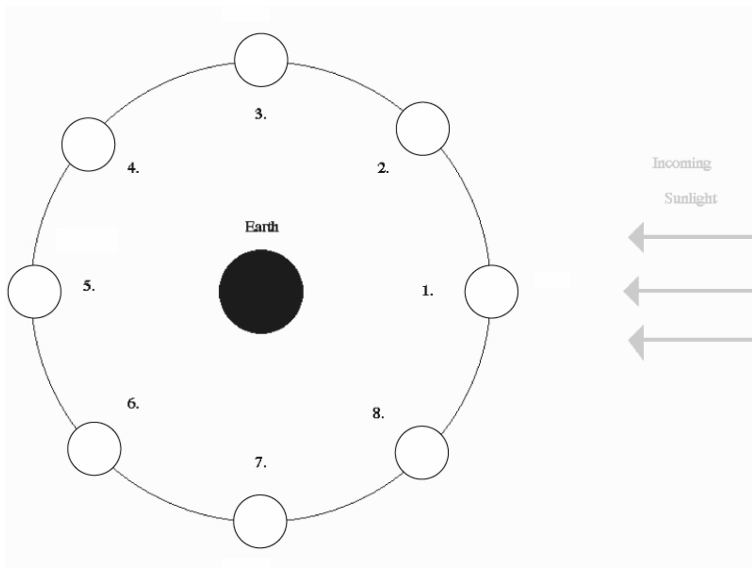
You will use the colored sphere and flashlight as props for this demonstration. Carefully read and thoroughly answer the questions associated with each of the five Exercises on the following pages. [Don't be concerned about eclipses as you answer the questions in these Exercises]. Using the dual-colored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

Note that there are additional questions at the end.

## Work in Groups of Three People!

## 4.2 Exercise 1 (10 points)

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




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

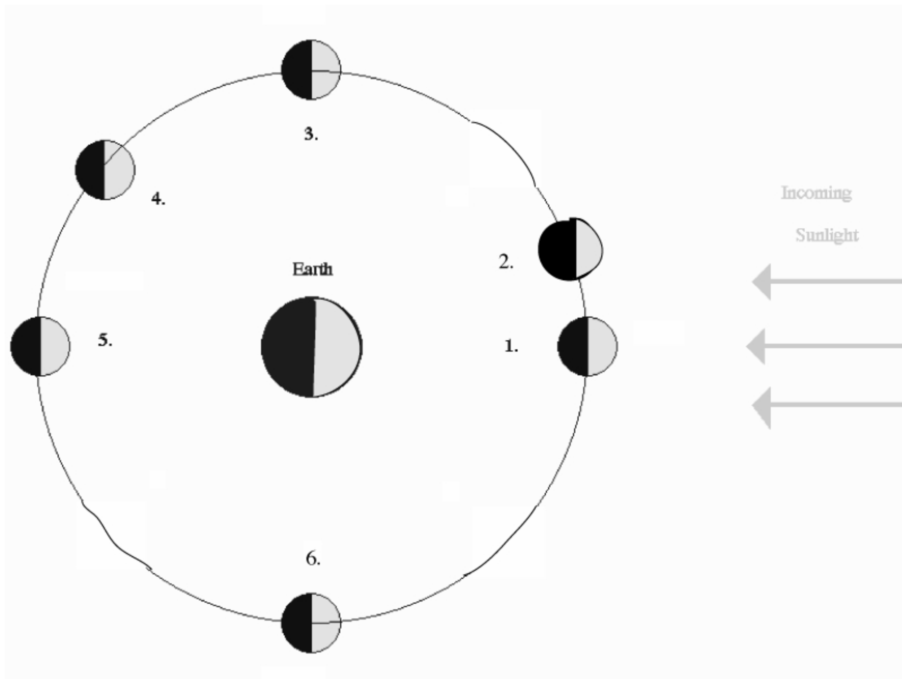
**Ranking Order:** Greatest A ____B ____C ____D ____E ____F ____G ____H ____Least

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

**Carefully explain** the reasoning for your result:

## 4.3 Exercise 2 (10 points)

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




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

**Ranking Order:** Greatest A ______B ______C ______D ______E ______F ______Least

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

**Carefully explain** the reasoning for your result:

## 4.4 Exercise 3 (10 points)

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

A B C D E

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

**Ranking Order:**

1) Waxing Gibbous

2) ____________________

3) ____________________

4) ____________________

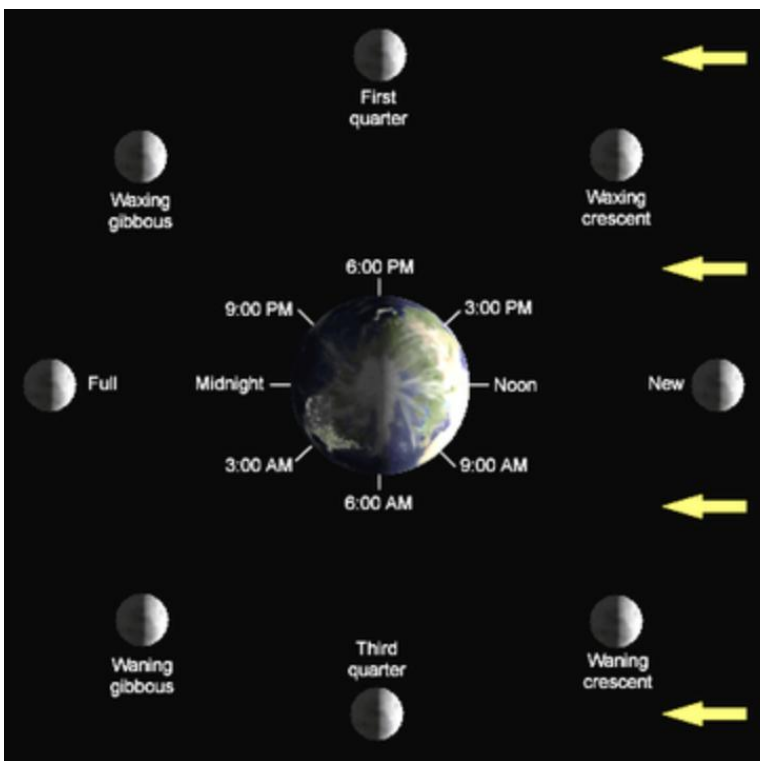
5) ____________________

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

## 4.5 Lunar Phases, and When They Are Observable

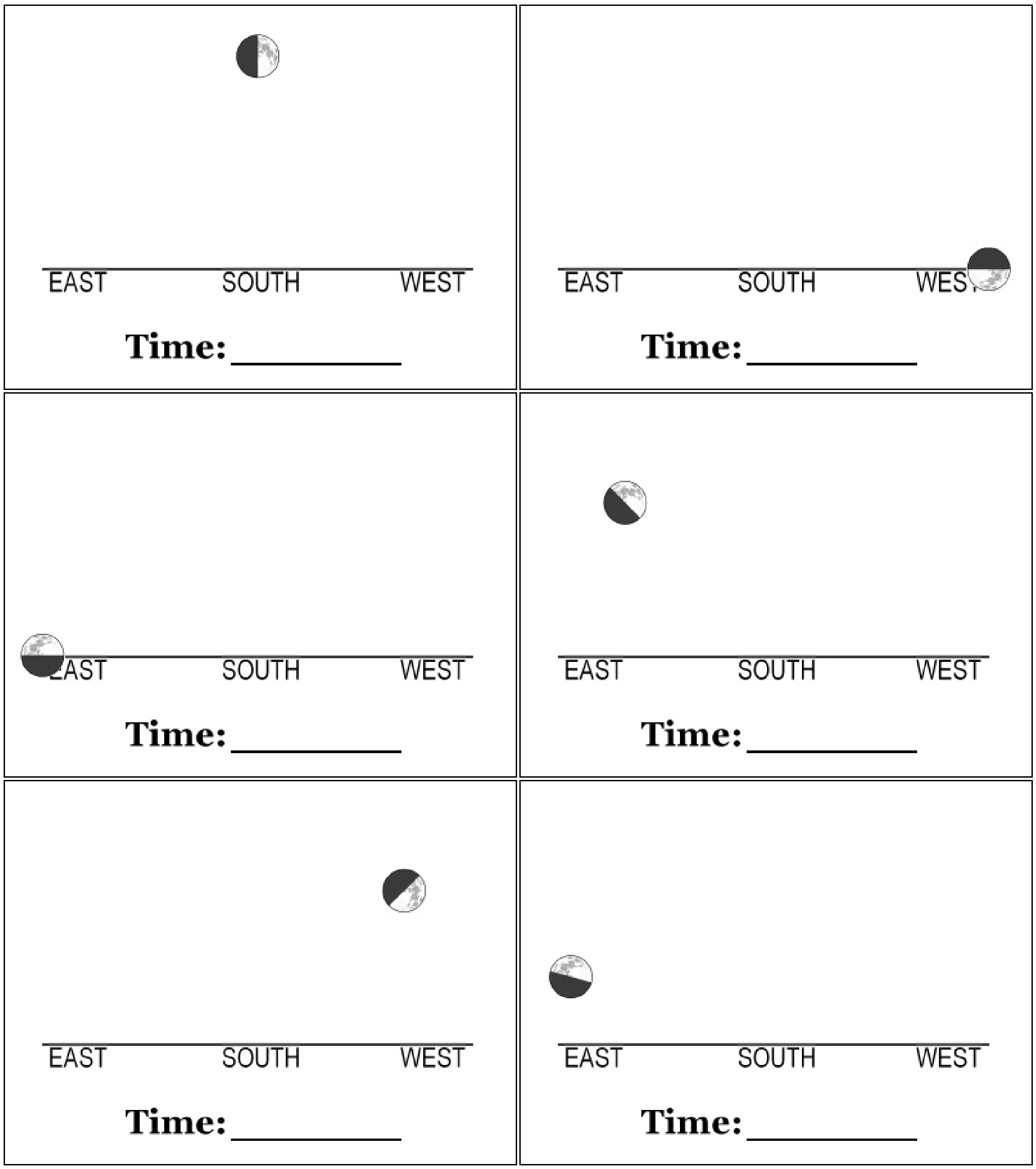
The next three exercises involve determining when certain lunar phases can be observed. Or, alternatively, determining the approximate time of day or night using the position and phase of the Moon in the sky.

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



## 4.6 Exercise 4 (6 points)

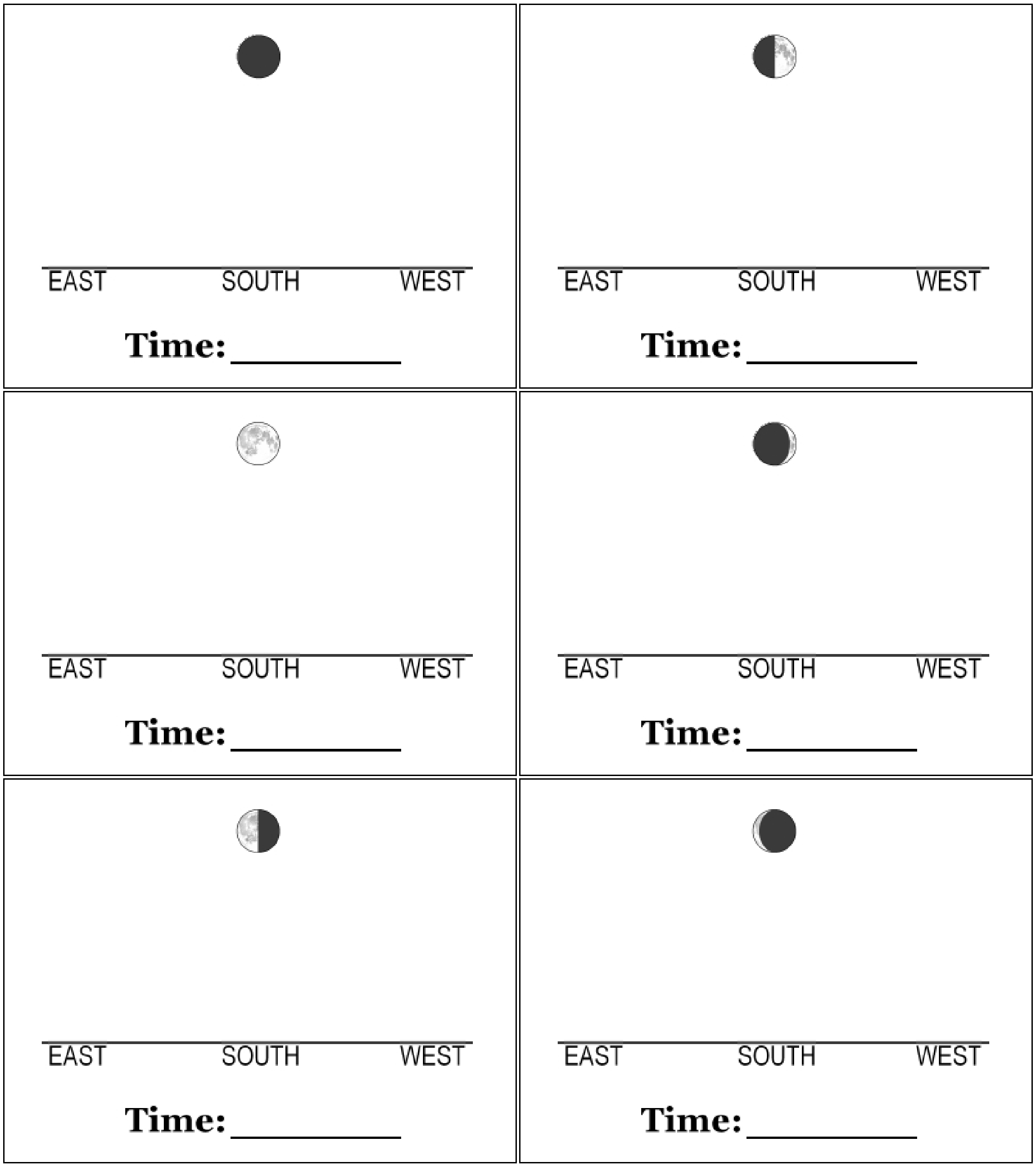
In the set of figures below, the Moon is shown in the first quarter phase at different times of the day (or night). Assume that sunset occurs at 6 p.m. and that sunrise occurs at 6 a.m.




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

## 4.7 Exercise 5 (6 points)

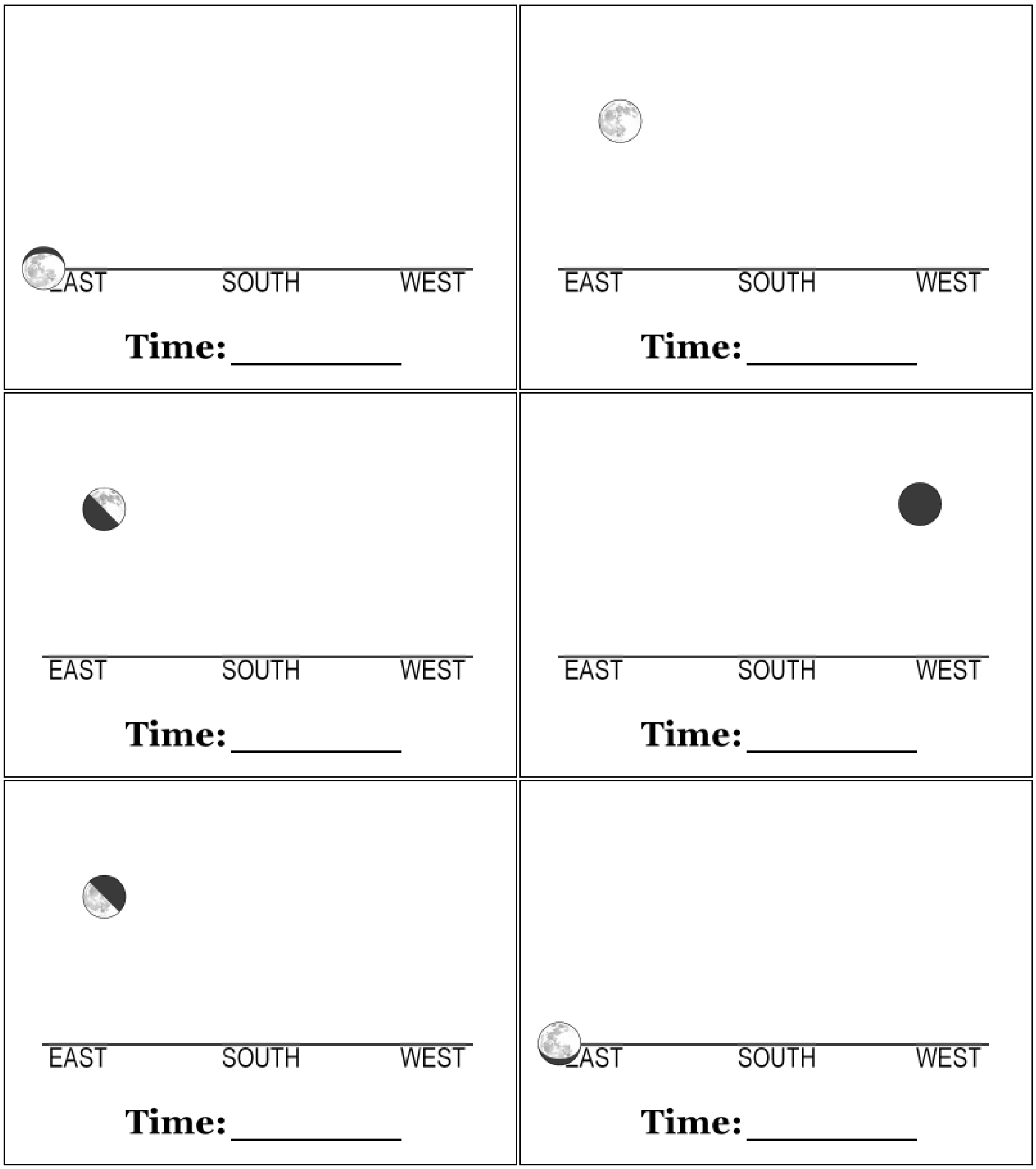
In the set of figures below, the Moon is shown overhead, at its highest point in the sky, but in different phases. Assume that sunset occurs at 6 p.m. and that sunrise occurs at 6 a.m.




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

## 4.8 Exercise 6 (6 points)

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




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

## 4.9 Demonstrating Your Understanding of Lunar Phases

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

Name:__________________________________
Date:___________________________________

## 4.10 Take-Home Exercise (35 points total)

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

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

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

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

## 4.11 Possible Quiz Questions

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

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

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

Name:______________________________

Date:______________________________

# 5 Surface of the Moon

## 5.1 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 5.1 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.

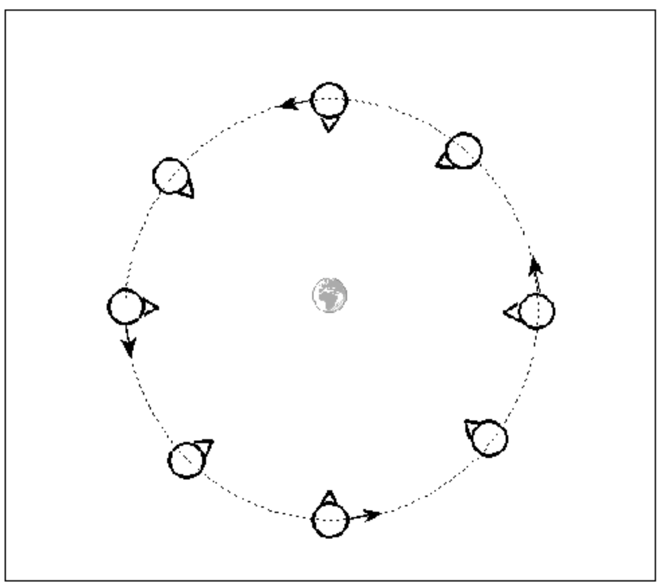


Figure 5.1: The Moon's synchronous orbit. (Not drawn to scale.)

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

## 5.2 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 5.2, 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 5.2 also shows that the rock beneath the crater becomes fractured (full of cracks).

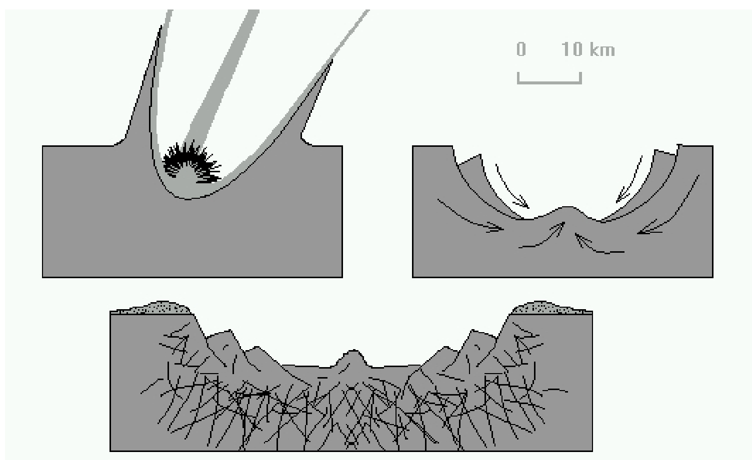



Figure 5.2: Formation of an impact crater.

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.

## 5.3 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.

## 5.4 Lab Stations

In this lab you will be using a three-ring binder that contains images of the Moon divided into separate sections, or "stations". At some stations we present data comparing the Moon to the Earth. 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. (**3 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. (**3 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. Estimate the coverage of the Organ Mountains that are located to the east of Las

Cruces. Estimate a width and a length, and assuming a rectangle, what is the approximate area of the Organs? (**2 points**)

4. Roughly how much area (in $km^2$) does Mons Piton cover? Compare it to the Organ Mountains. 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?] (**2 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 telescope (this is similar to what you would see at the campus observatory). Clavius is one of the largest craters on the Moon, with a diameter of 225 km. In the upper right hand corner is one of the best known craters on the Moon, "Tycho." In image #1 you can identify Tycho by the large number of bright "rays" that emanate from this crater. Tycho is a very young crater, and the ejecta blasted out of the lunar surface spread very far from the impact site.

**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).

5. Compare the region around Clavius to Mare Imbrium. Scientists now know that the lunar highlands are older than the maria. What evidence do you have (using these

photographs) that supports this idea? [Hint: review section 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! Recently, a new mission to map the Moon with better resolution called the "Lunar Reconnaissance Orbiter" (LRO) sent back images of the Apollo 11 landing site (**image 11B**). In this image LM is the base of the lunar module, LRRR and PSEP are two science experiments. You can even see the (faintly) disturbed soil where the astronauts walked!

**Images #12 and #13** show the landing site of the last Apollo mission, #17. Apollo 17 landed on the Moon on December 11th, 1972. In **image 13B** is an LRO image of the landing site. Note that during Apollo 17 they had a "rover" (identified with the notation LRV) to drive around with. Compare the two landing sites.

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

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

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

**Station 4:** On the northern-most edge of Mare Imbrium sits the crater Plato (labeled in images #2 and #6). **Image #20** is a close-up of Plato.

8. 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. (**4 points**)

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

Image #22 is a topographical map for the Moon, showing the highlands (orange, red, and pink areas), and the lowlands (green, blue, and purple). [Grey and black areas have no data.] The scale is shown at the top. The lowest points on the Moon are 10 km below sea level, while the highest points are about 10 km above sea level. On the left hand edge (the "y-axis") is a scale showing the latitude. 0° 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.

9. 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.](**4 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.

10. 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. (**4 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)**

## 5.5 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.

11. Compare the distribution of iron and titanium to the surface features of the Moon (using images #1, #2 or #6, or the topographical map in image #23). Where are the highest concentrations of iron and titanium found? (**5 points**)

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

A cut-away diagram of the Earth is shown in the Figure 5.3. 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$^3$.

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 5.1,

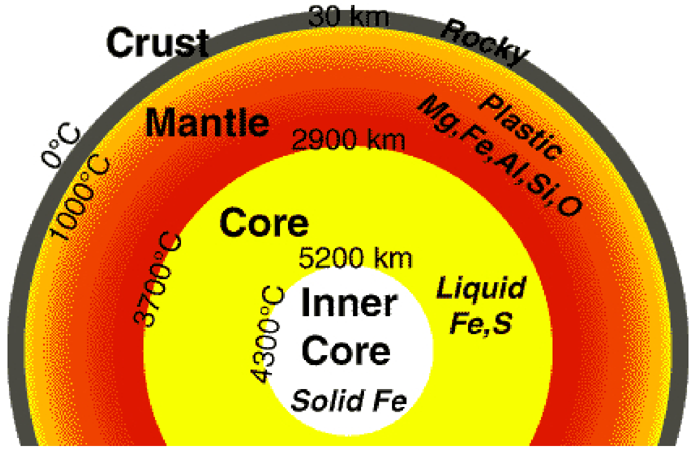



Figure 5.3: The internal structure of the Earth, showing the dimensions of the crust, mantle and core, as well as their composition and temperatures.

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 5.1: 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% |

13. 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.

14. 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 5.2 shows the composition of the Earth's crust and mantle compared to that of the Moon.

Table 5.2: 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% |

15. Given the data in Table 5.2, 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? (**3 points**)

Name:______________________________

Date:_______________________________

## 5.6 Take Home Exercise (35 points total)

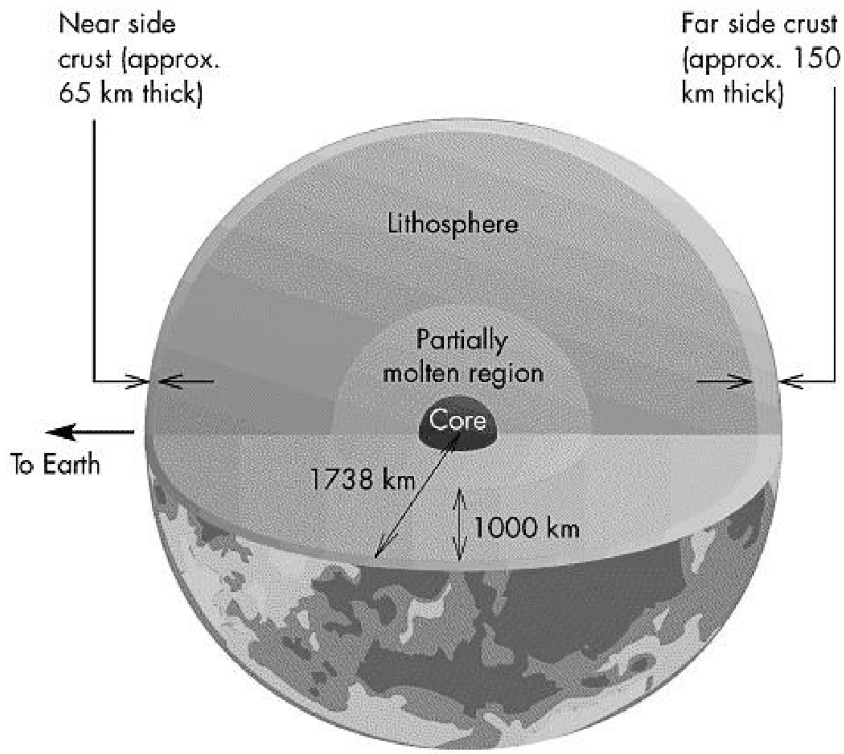
Answer the following questions in the space provided:

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

2. 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**)

3. 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? (**10 points**)

4. 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. **(15 points)**



## 5.7 Possible Quiz Questions

1. What is an impact crater?
2. What are the Maria?
3. What is the difference between the words Mare and Maria?
4. Explain what a synchronous orbit is.
5. What is a topographical map?

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

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

Name:____________________________________
Date:_____________________________________

# 6 Introduction to the Geology of the Terrestrial Planets

## 6.1 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 6.1 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 6.1: 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 6.1 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 6.2.

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

Table 6.2: 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 |

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

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

## 6.2 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 6.1, 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 6.2. 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.

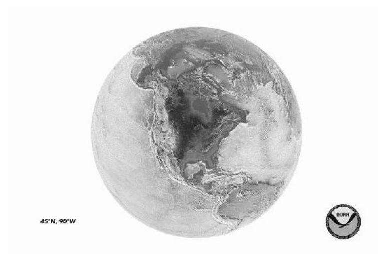


Figure 6.1: A topographic map showing one hemisphere of Earth centered on North America. In this 3D representation the continents are correctly rendered.

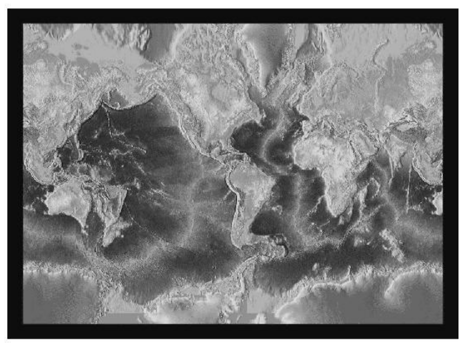


Figure 6.2: A topographic map showing the entire surface of the Earth. In this 2D representation, the continents are incorrectly rendered. Note that Antarctica (the land mass that spans the bottom border of this map) is 50% smaller than North America, but here appears massive. You might also be able to compare the size of Greenland on this map, to that of the previous map.

## 6.3 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 recently been visited by the Messenger spacecraft. Much new data has recently become available, but we do not yet have the same type of plots for Mercury as we do for the other planets.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## 6.4 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**)

## 6.5 Erosion Processes and Evidence for Water

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

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

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

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

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

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

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

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

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

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

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

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

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

## 6.6 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 6.3, 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. 6.4), 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.

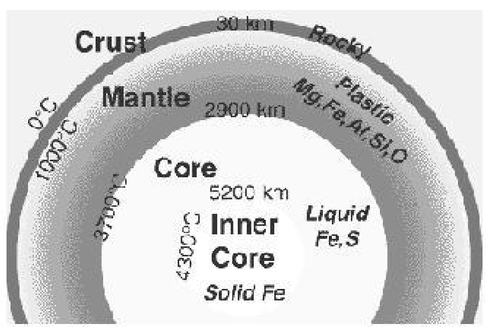



Figure 6.3: A cut away diagram of the structure of the Earth showing the hot core, the mantle, and the crust. The core of the Earth is very hot, and is composed of both liquid and solid iron. The mantle is a zone where the rocks are partially melted ("plastic-like"). The crust is the cold, outer skin of the Earth, and is very thin.

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

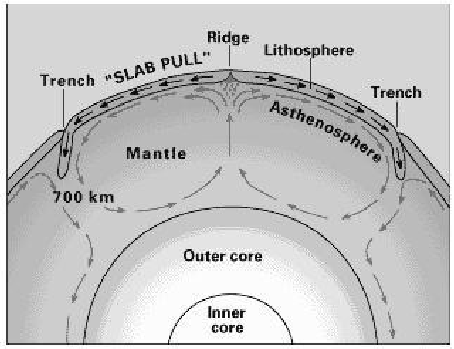



Figure 6.4: The escape of the heat from the Earth's core sets-up a boiling motion in the mantle. Where material rises to the surface it pushes apart the plates and volcanoes, and mountain chains are common. Where the material is cooling, it flows downwards (subsides) back into the mantle pulling down 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 exaggerated by a factor of ten!* It might be hard to tell, but Venus is also dominated by one main type of Volcano, what is it? (**5 points**)

Name:_________________________________
Date:__________________________________

## 6.7 Take Home Exercise (35 points total)

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. On a separate sheet of paper, write a report answering the following questions:

- 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?

## 6.8 Possible Quiz Questions

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

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

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

Name:________________________________
Date:_________________________________

# 7 Density

## 7.1 Introduction

As we explore the objects in our Solar System, we quickly find out that these objects come in all kinds of shapes and sizes. The Sun is the largest object in the Solar System and is so big that more than 1.3 million Earths could fit inside. But the mass of the Sun is only 333,000 times that of the Earth. If the Sun were made of the same stuff as the Earth, it should have a mass that is 1.3 million times the mass of the Earth—obviously, the Sun and the Earth are not composed of the same stuff! What we have just done is a direct comparison of the *densities* of the Sun and Earth. Density is extremely useful for examining what an object is made of, especially in astronomy, where nearly all of the objects of interest are very far away.

In today's lab we will learn about density, both how to measure it, and how to use it to gain insight into the composition of objects. The average or "mean" density is defined as the *mass* of the object divided by its *volume*. We will use grams (g) for mass and cubic centimeters ($cm^3$) for volume. The *mass* of an object is a measure of how many protons and neutrons (the "building blocks" of atoms) the object contains. Denser elements, such as gold, possess many more protons and neutrons within a cubic centimeter than do less dense materials such as water.

## 7.2 Mass versus Weight

Before we go any further, we need to talk about *mass* versus *weight*. The *weight* of an object is a measure of the *force* exerted upon that object by the gravitational attraction of a large, nearby body. An object here on the Earth's surface with a *mass* of 454 grams (grams and kilograms are a measure of the mass of an object) has a weight of one pound. If we do not remove or add any protons or neutrons to this object, its mass and density will not change if we move the object around. However, if we move this object to some other location in the Solar System, where the gravitational attraction is different then what it is at the Earth's surface, than the *weight* of this object will be different. For example, if you weigh 150 lbs on Earth, you will only weigh 25 lbs on the Moon, but would weigh 355 lbs on Jupiter. Thus, weight is not a useful measurement when talking about the bulk properties of an object—we need to use a quantity that does not depend on *where* an object is located. One such property is *mass*. So, even though you often see conversions between pounds (unit of weight) and kilograms (unit of mass), those conversions are only valid on the Earth's surface (the astronauts floating around inside the International Space Station obviously still have mass, even though they are "weightless").

## 7.3 Volume

Now that we have discussed mass, we need to talk about the other quantity in our equation for density, and that is volume. Volume is pretty easy to calculate for objects with regular shapes. For example, you probably know how to calculate the volume of a cube: V = $s \times s \times s = s^3$, where $s$ is the length of a side of the cube. Let us generalize this to any rectangular solid. In Figure 7.1 we show a drawing for a box that has sides labeled with "length," "width," and "height." What is its volume? Its volume is V = length $\times$ width $\times$ height. If we told you that the length = 10 cm, the height = 5 cm, and the depth = 5 cm, what is the box's volume? V = 10 cm $\times$ 5 cm $\times$ 5 cm = 250 cubic cm = 250 $cm^3$. Do you now see why volume is measured in $cm^3$? This where that comes from—everyday objects are "three dimensional" in that they *have* volume ($cm^3$, $m^3$, $km^3$, $inches^3$, $miles^3$).

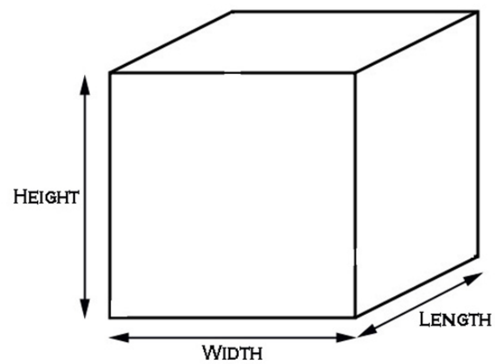



Figure 7.1: A rectangular solid has sides of length, width, and height.

Now that we understand how volume is calculated, how do we do it for objects that have more complicated shapes, like a coke bottle, a car engine, or a human being? You may have heard the story of Archimedes. Archimedes was asked by the King of Syracuse (in ancient Greece) to find out if the dentist making a gold crown for one of his teeth had embezzled some of the gold the king had given him to make this crown (by adding lead, or another cheaper metal to the crown while keeping some of the gold for himself). Archimedes pondered the problem for a while and hit on the solution while taking a bath. Archimedes became so excited he ran out into the street naked shouting "Eureka!" What Archimedes realized was that you can use water to figure out a solid object's volume. For example, you could fill a teacup to the brim with water and drop an object in the teacup. The amount of water that overflows and collects in the saucer has the same volume as that object. All you need to know to figure out the object's volume is the conversion from the amount of liquid water to its volume in $cm^3$. An example of the process is shown in Fig. 7.2.

In the metric system a gram was defined to be equal to one cubic cm of water, and one cubic cm of water is identical to 1 ml (where "ml" stands for milliliter, i.e., one thousandth of a liter). Today we will measure the water displacement for a variety of objects, and use this conversion directly: 1 ml = 1 $cm^3$.

In this lab you will first determine the densities of ten different natural substances, and then we will show you how astronomers use density to give us insight into the nature of various objects in our Solar System.

**Exercise #1:** Measuring Masses, Volumes and Densities

First, we measure the masses of objects using a triple beam balance. At your table, your TA has given you a plastic box with a number of compartments containing ten different substances, a triple beam balance, several graduated cylinders, digital calipers, and a container of water. Our first task is to measure the masses of all ten of the objects using the triple beam balance. Note: these balances are very sensitive, and quite expensive, so treat them with care. The first thing you should do is make sure all of the weights[1] are moved to their leftmost positions so that their pointers are all on *zero*. The two larger weights will sit in detents, the smaller one just needs to be lined up with the zero mark. When this is done, and there is no mass on the steel "pan," the lines on the right hand part of the scale should line-up with each other **exactly**. The scale must be balanced before you begin, and the TA, or their helper, has already done this for you. If the two lines do not line-up, ask your TA for help.

To measure the mass of one of the objects, put it on the pan and slide the weights over to the right. Note that for this lab, none of our objects require movement of the largest weight, just the two smaller weights. You should attempt to read the mass of the object to two significant figures—it is possible, but quite unlikely, that an object will have a mass of exactly 10.0 or 20.0 g. If the sliding weight on the "10 g" beam falls between units, estimate exactly where it is so that you get more precise numbers like 22.15 g (all of your masses should be measured to two places beyond the decimal!).

**Task #1:** Fill in column #2 ("Mass") of Table 7.1 by measuring the masses of your ten objects. **(10 points)**

Now we are going to measure the volumes of these ten objects using the method of Archimedes. Pour some water into the graduated cylinder and make a note of the initial volume. Drop the first object into the graduated cylinder, and read off the volume again. The increase in volume is due to the object displacing the water. Record the change in volume in the table. Repeat the process for all of your objects. Note that the smaller the object, the smaller the graduated cylinder you should use (just make sure you don't get the object stuck). Using a big cylinder with a small object will lead to errors, as the big cylinders

[1] This is the historical name for these sliding masses, as the first scales like these were used to measure weight.

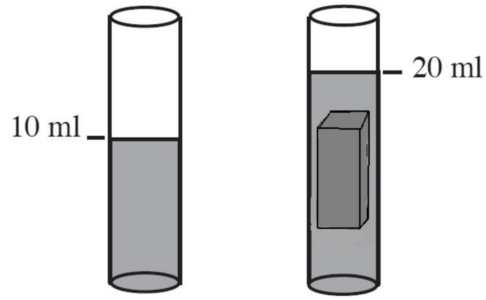



Figure 7.2: The rectangular object displaces 10 ml of water. Therefore, it has a volume of 10 ml = 10 $cm^3$.

are harder to read to high precision. Ask your TA about how to "read the miniscus" if you do not know what that means.

**Task #2:** Fill in columns 3 and 4 (again, remember for column #4, that 1 ml = 1 $cm^3$). **(10 points)**

**Task #3:** Fill in the Density column in Table 7.1. **(5 points)**

**Question # 1:** Think about the process you used to determine the volume. How accurate do you think it is? Why? How could we improve this technique? **(5 points)**

We chose to supply you with several rectangular solids so that we could check on how well you measured the volume using the Archimedes method. Now we want you to actually measure the volume of the five metal "cubes" (do not assume they are perfect cubes!) using

Table 7.1: The Masses, Volumes, and Densities of the Different Objects.

| **Object**<br><br>**Column #1** | **Mass (g)**<br><br>**#2** | Volume of Water (ml)<br>**#3** | **Volume** $cm^3$<br>**#4** | **Density** $g/cm^3$<br>**#5** |
|---|---|---|---|---|
| Obsidian | | | | |
| Gabbro | | | | |
| Pumice[2] | | | | |
| Silicon | | | | |
| Magnesium | | | | |
| Copper | | | | |
| Iron (Steel) | | | | |
| Zinc | | | | |
| Mystery | | | | |
| Aluminum | | | | |

[2]It is tricky to measure the volume of Pumice, but find a way to *submerge* the entire stone.

the digital caliper. You will measure the lengths of their sides in mm, but remember to convert to cm (1 cm = 10 mm). The digital caliper is easy to operate, but requires two actions: 1) there is a button that switches between inches and millimeters, we want mm, and 2) they must be "zeroed". To zero the caliper, use the thumbwheel to insure the jaws are closed, and then hit the "zero" button. Open the caliper slowly to the width necessary to measure the cube, and then close them tight. Read off the number. It is not a bad idea to zero the caliper before each object, as repeated motion can cause small errors to creep-in.

**Task #4:** Fill in Table 7.2. Copy the mass measurements from Table 7.1 for the five metal "cubes". Calculate the volumes of these "cubes" using the caliper. **(5 points)**

Table 7.2: The Masses, Volumes, and Densities of the Metal Cubes.

| **Object** | **Mass (g)** | $l \times \ w \times \ h \quad =$ | **Volume** $cm^3$ | **Density** $g/cm^3$ |
|---|---|---|---|---|
| Copper | | | | |
| Iron (Steel) | | | | |
| Zinc | | | | |
| Mystery | | | | |
| Aluminum | | | | |

**Question #2:** Compare the two sets of densities you found for each of the five metal cubes. How close are they? Assuming the second method was better, which substance had the biggest error? Why do you think that happened? **(5 points)**

**Question #3:** One of the objects in our table was labeled as a "mystery" metal. This particular substance is composed of two metals, called an "alloy." You have already measured the density of the two metals that compose this alloy. We now want you to figure out which of these two metals are in this alloy. Note that this particular alloy is a 50-50 mixture! So its mean density is (Metal A + Metal B)/2.0. What are these two metals? Did its color help you decide? **(3 points)**

You have just used density to attempt to figure out the composition of an unknown object. Obviously, we had to tell you additional information to allow you to derive this answer. Scientists are not so lucky, they have to figure out the compositions of objects without such hints (though they have additional techniques besides density to determine what something is made of–you will learn about some of these this semester).

**Exercise #2:** Using Density to Understand the Composition of Planets.

We now want to show you how density is used in astronomy to figure out the compositions of the planets, and other astronomical bodies. As part of Exercise #1, you measured the density of three rocks: Obsidian, Gabbro, and Pumice. All three of these rocks are the result of volcanic eruptions. Even though they are volcanic in origin ("igneous rocks"), both Obsidian and Gabbro have densities similar to most of the rocks on the Earth's surface. So, what elements are found in Obsidian and Gabbro? Their chemistries are quite similar. Obsidian is 75% Silicon dioxide ($SiO_2$), with a little bit (25%) of Magnesium (Mg) and Iron (Fe) oxides (MgO, and $Fe_3O_4$). Gabbro has the same elements, but less Silicon dioxide ($\sim$ 50%), and more Magnesium and Iron.

**Question #4:** You measured the densities of (pure) silicon, iron and magnesium in Exercise #1. Compare the density of Gabbro and Obsidian to that of pure silicon. Can you tell that there must be some iron and/or magnesium in these minerals? How? Which of these two elements *must* dominate? Were your density measurements good enough to demonstrate that Gabbro has less silicon than Obsidian? **(4 points)**

Now let's compare the densities of these rocks to two familiar objects: the Earth and the Moon. We have listed the mean densities of the Earth and Moon in Table 7.3, along with the density of the Earth's crust. As you can see, the mean density of the Earth's crust is similar to the value you determined for Gabbro and/or Obsidian–it better be, as these rocks *are from the Earth's crust*!

Table 7.3: Densities of the Earth and Moon

| Object | Density g/cm$^3$ |
|---|---|
| Earth | 5.5 |
| Moon | 3.3 |
| Earth's Crust | 3.0 |

**Question #5:** Compare the mean densities of the Earth's crust and the Moon. The leading theory for the formation of the Moon is that a small planet crashed into the Earth 4.3 billion years ago, and blasted off part of the Earth's crust. This material went into orbit around the Earth, and condensed to form the Moon. Do the densities of the Earth's crust and the Moon support this idea? How? **(4 points)**

**Question #6:** If you were asked "What are the main elements that make-up the Moon?", what would your answer be? Why? **(2 points)**

It is clear from Table 7.3, that the mean density of the whole Earth is much higher than the density of its crust. There must be denser material below the crust, deep inside the Earth.

**Question #7:** Given that the mean density of the Earth's crust is 3.0 $g/cm^3$, and the mean density of the whole Earth is 5.5 $g/cm^3$, what (common) element do you suppose is partially responsible for the higher mean density of the whole Earth? If we guess, and say that the Earth is a 50-50 mixture of this element, and the crust material, what density do you calculate? Does the resulting density compare with that for the whole Earth? **(4 points)**

Now let's return to the rocks in our set of objects. We included Pumice into this set to show you that nature can sometimes surprise you—have you ever seen a rock that floats?

Would it surprise you to find out that Pumice has almost the same composition as Gabbro and Obsidian? It is mostly $SiO_2$! So how can this rock float?! Let's try to answer this.

**Question #8:** If Pumice has the same basic composition as Gabbro, how might it have such a low density? [Hint: think about a boat. As you have found out, cubes of pure metals do not float. But then how does a boat made of iron (steel) or aluminum actually float? What is found in the boat that fills most of its volume?] **(2 points)**

**Question #9:** Dry air has a density of 0.0012 g/cm$^3$, let's make an estimate for how much air must be inside Pumice to give it the density you measured. Note: this is like the alloy problem you worked on above, but the densities of one of the two components in the alloy is essentially zero. **(6 points)**

You measured the volume of the piece of Pumice along with its mass, and then calculated its density. We stated that density = mass/volume. But you could re-arrange this equation to read volume = mass/density. **Assume that the density of the material that comprises the solid parts of Pumice is the same as that for Gabbro.**

a) What would be the volume of a piece of Gabbro that has the same mass as your piece of Pumice?

$$\text{Volume(Gabbro)} = \text{Mass(Pumice)/Density(Gabbro)} = \underline{\hspace{3cm}} \text{ cm}^3$$

b) Now take the value of the volume you just calculated and divide it by the volume of the Pumice stone that you measured:

$$r = \text{Volume(Gabbro)/Volume(Pumice)} = \underline{\hspace{3cm}} \%$$

This ratio, "r", shows you how much of the volume of Pumice is occupied by **rocky material**. The volume of Pumice occupied by "air" is:

$$1 - r = \underline{\hspace{3cm}} \%$$

Pumice is formed when lava is explosively ejected from a volcano. Deep in the volcano the liquid rock is under high pressure and mixed with gas. When this material is explosively ejected, it is shot into a low pressure environment (air!) and quickly expands. Gas bubbles get trapped inside the rock, and this leads to its unusually low density.

Name:______________________________
Date:_______________________________

## 7.4 Take Home Exercise (35 points total)

For the take-home part of this lab, we are going to explore the densities and compositions of other objects in the Solar System.

1. Use your textbook, class notes, or other sources to fill in the following table **(10 points)**:

| **Object** | **Average Density (g/cm$^3$)** |
|---|---|
| Sun | |
| Mercury | |
| Venus | |
| Mars | |
| Ceres (largest asteroid) | 2.0 |
| Jupiter | |
| Saturn | |
| Titan (Saturn's largest moon) | |
| Uranus | |
| Neptune | |
| Pluto | |
| Comet Halley (nucleus) | 0.1 |

2. Mercury, Venus, Earth, and Mars are classified as Terrestrial planets ("Terrestrial" means Earth-like). Do they have similar densities? Do you think they have similar compositions? Why/Why not? **(3 points)**

3. Jupiter, Saturn, Uranus and Neptune are classified as Jovian planets ("Jovian" means Jupiter-like). Why do you think that is? Compare the densities of the Jovian planets to that of the Sun. Do you think they are made of similar materials? Why/why not? **(6 points)**

4. Saturn has an unusual density. What would happen if you could put Saturn into a huge pool/body of water?? (Remember water has a density of 1 g/cm$^3$, and recall the density and *behavior* of Pumice.) **(2 points)**

5. The densities of Ceres, Titan and Pluto are very similar. Most astronomers believe that these three bodies contain large quantities of water ice. If we assume roughly half of the volume of these bodies is due to water (density = 1 g/cm$^3$) and half from some other material, what is the approximate mean density of this other material? Hint: this is identical to the alloy problem you worked-on in lab:

$$\text{Density(Ceres)} = (1.0 \text{ g/cm}^3 + \text{X g/cm}^3)/2.0$$

   Just solve for "X" (if this hard for you, see the section "Solving for X" in Appendix A at the end of this manual). What material have we been dealing with in this lab that has a density with a value *similar* to "X"? What do you conclude about the composition of Ceres, Titan and Pluto? **(8 points)**

6. The nucleus of comet Halley has a very low density. We know that comets are mostly composed of water and other ices, but those other ices still have a higher density than that measured for Halley's comet. So, how can we possibly explain this low density? [Hint: Look back at Question #9. Why is Pumice so light, even though it is a silicate rock?] What does this imply for the nucleus of comet Halley?!!] **(6 points)**

## 7.5 Possible Quiz Questions

1. What is the difference between mass and weight?
2. How do you calculate density?
3. What are the physical units on density?
4. How do astronomers use density to study planets?
5. Does the shape of an object affect its density?

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

Look up some information about the element Mercury (chemical symbol "Hg"). Note that at room temperature, Mercury is a liquid. You found out above that, depending on density, some objects will float in water (like pumice). What is the density of Mercury? So, if you had a beaker full of Mercury, which of the metals you experimented with in this lab do you think would float in Mercury? In Question # 7, we discussed that the core of the Earth is much more dense than its crust, and concluded that there must be a lot of iron at the center of the Earth. Given what you have just found out about rather dense materials floating in Mercury, apply this knowledge to discuss why the Earth's core is made of molten (=liquid) iron, while the crust is made of silicates.

Name:________________________________
Date:_________________________________

# 8 Estimating the Earth's Density

## 8.1 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 8.3 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, we'll 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.

## 8.2 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:

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

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 8.1.
- You will be provided with the length of a post and its shadow measured simultaneously today in Boulder, Colorado.

1. Proceed through the calculations described after Table 8.1, and write your answers in the appropriate locations in Table 8.1. **(10 points)**

Table 8.1: **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 | | | |

## 8.3 Angle Determination:

With a bit of trigonometry we can transform the height and shadow length you measured into an angle. As shown in Figure 8.1 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:

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 $\mathrm{TAN}^{-1}$ capability on your calculator (these functions will give you an angle if you provide the ratio of the height to length):

ANGLE = ATAN (shadow length / post length)

or

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

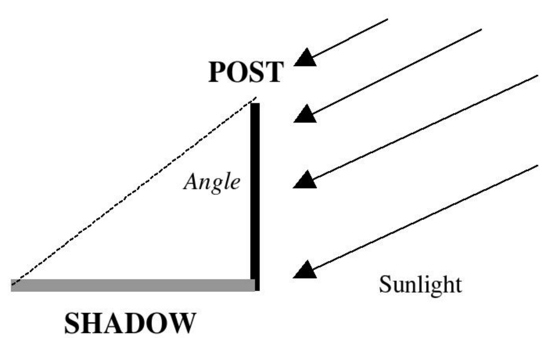



Figure 8.1: The geometry of a vertical post sitting in sunlight.

2. **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 8.1. 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.

3. 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) =**

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

   **857 × [360°/(________ − ________)] = ________________ km (2 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:

   $$\text{EARTH RADIUS} = R_E = \text{EARTH CIRCUMFERENCE} / (2 \times \pi)$$

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

**AVERAGE EARTH RADIUS VALUE = $R_E$ = ____________________ kilometers (3 points)**

5. **Convert this radius ($R_E$) from kilometers to meters, and enter that value in Table 8.3.** *(Note we will use the radius in meters the rest of this 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.

## 8.4 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:

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

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 8.2, 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

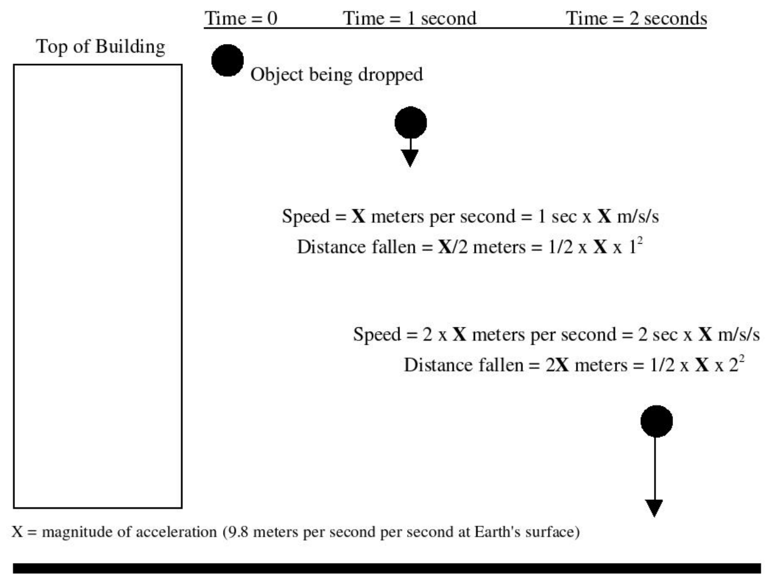



Figure 8.2: The distance a dropped object will fall during a time interval $t$ is proportional to $t^2$. A dropped object speeds up as it falls, so it travels faster and faster and falls a greater distance as $t$ increases.

dropped object.

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 8.2. **(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 8.2.

- 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!)

Table 8.2: **Time of Fall Data**

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

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

   **$M_E$ = Average Acceleration $\times$ $(R_E)^2$ / G =** ______________________ **(5 points)**

   Write the value of $M_E$ (in kilograms) in Table 8.3 below.

## 8.5 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 8.3 below.

- *Divide your value of $M_E$ (that you entered in Table 8.3) by your estimate of $V_E$ that you just calculated (also written in Table 8.3):* 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 8.3.

- *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 8.3.

Table 8.3: **Data for the Earth**

| | | |
|---|---|---|
| Estimate of Earth's Radius: | ______________________ **m** | (4 points) |
| Estimate of Earth's Mass: | ______________________ **kg** | (4 points) |
| Estimate of Earth's Volume: | ______________________ $\mathbf{m^3}$ | (4 points) |
| Estimate of Earth's Density: | ____________________ $\mathbf{kg/m^3}$ | (4 points) |
| Converted Density of the Earth: | __________________ $\mathbf{gm/cm^3}$ | (4 points) |

## 8.6 In-Lab Questions:

1. Is your calculated value of the (Converted) 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 **(2 points)**:

   PERCENT ERROR =

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

2. You used the AVERAGE Las Cruces shadow angle in calculating your estimate of the Earth's density (which you wrote down in Table 8.3). If you had used the LARGEST of the three measured Las Cruces shadow angles shown in Table 8.1, 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 8.3? Think before writing your answer! Explain your answer. **(5 points)**

3. If the Las Cruces to Boulder, Colorado distance was actually 200 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. **(3 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.] **(5 points)**

Name:______________________________

Date:______________________________

## 8.7 Take Home Exercise (35 points total)

1. 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.

## 8.8 Possible Quiz Questions

1. What is meant by the "radius" of a circle? (Drawing ok)
2. What does the term "circumference of a circle" mean?
3. How do you calculate the circumference of a circle if given the radius?
4. What is "pi" (or $\pi$)? What is the value of pi?
5. What is the volume of a sphere?
6. What does the term "density" mean?

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

Astronomers use density to segregate the planets into categories, such as "Terrestrial" and "Jovian". Using your book, or another reference, look up the density of the Sun and Jupiter (or, if you have completed the previous lab, use the data table you constructed for Take-Home portion of that lab). Compare the densities of the Sun and Jupiter. Do you think they are composed of same elements? Why/why not? What are the two main elements in the periodic table that dominate the composition of the Sun? If the material that formed the Sun (and the Sun *has* 99.8% of the mass of the solar system) was the original "stuff" from which all of the planets were formed, how did planets like Earth end up with such high densities? What do you think might have happened in the distant past to the lighter elements? (Hint: think of a helium balloon, or a glass of water thrown out onto a Las Cruces parking lot in the summer!).

Name:____________________________________
Date:____________________________________

# 9 Building a Comet

During this semester we have explored the surfaces of the Moon, terrestrial planets and other bodies in the solar system, and found that they often are riddled with craters. In Lab 12 there is a discussion on how these impact craters form. Note that every large body in the solar system has been bombarded by smaller bodies throughout all of history. In fact, this is one mechanism by which planets grow in size: they collect smaller bodies that come close enough to be captured by the planet's gravity. If a planet or moon has a rocky surface, the surface can still show the scars of these impact events–even if they occurred many billions of years ago! On planets with atmospheres, like our Earth, weather can erode these impact craters away, making them difficult to identify. On planets that are essentially large balls of gas (the "Jovian" planets), there is no solid surface to record impacts. Many of the smaller bodies in the solar system, such as the Moon, the planet Mercury, or the satellites of the Jovian planets, do not have atmospheres, and hence, faithfully record the impact history of the solar system. Astronomers have found that when the solar system was very young, there were large numbers of small bodies floating around the solar system impacting the young planets and their satellites. Over time, the number of small bodies in the solar system has decreased. Today we will investigate how impact craters form, and examine how they appear under different lighting conditions. During this lab we will discuss both asteroids and comets, and you will create your own impact craters as well as construct a "comet".

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

## 9.1 Asteroids and Comets

There are two main types of objects in the solar system that represent left over material from its formation: asteroids and comets. In fact, both objects are quite similar, their differences arise from the fact that comets are formed from material located in the most distant parts of our solar system, where it is very cold, and thus they have large quantities of frozen water and other frozen liquids and gases. Asteroids formed closer-in than comets, and are denser, being made-up of the same types of rocks and minerals as the terrestrial planets (Mercury, Venus, Earth, and Mars). Asteroids are generally just large rocks, as shown in Fig. 9.1 shown below.

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

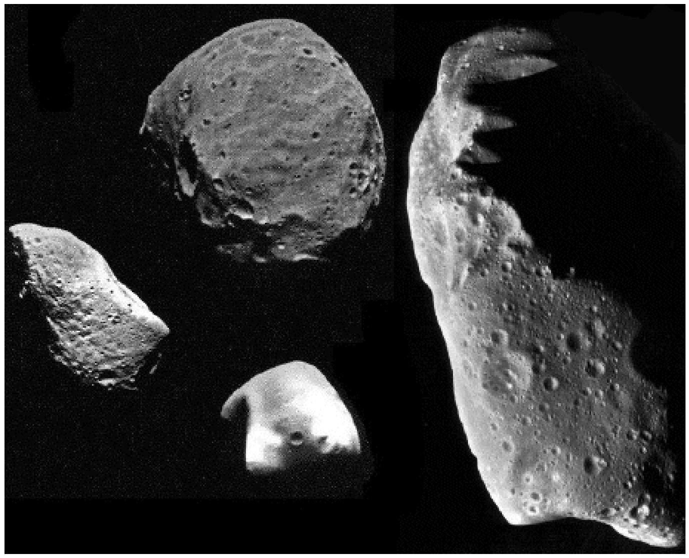


Figure 9.1: Four large asteroids. Note that these asteroids have craters from the impacts of even smaller asteroids!

in orbits between those of Mars and Jupiter (the so-called “asteroid belt”, see Figure 9.2). Some asteroids, however, are in orbits that take them inside that of the Earth, and could

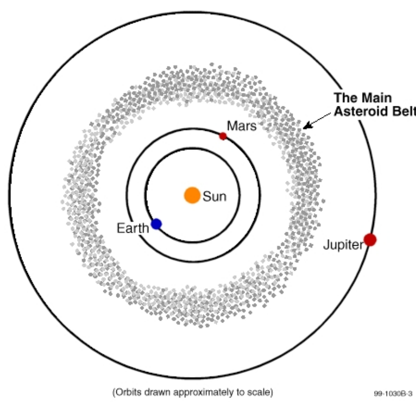



Figure 9.2: The Asteroid Belt.

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

## 9.2 Comets

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

## 9.3 Composition and Components of a Comet

Comets are composed of ices (water ice and other kinds of ices), gases (carbon dioxide, carbon monoxide, hydrogen, hydroxyl, oxygen, and so on), and dust particles (carbon and silicon). The dust particles are smaller than the particles in cigarette smoke. In general, the model for a comet's composition is that of a "dirty snowball." 9.3

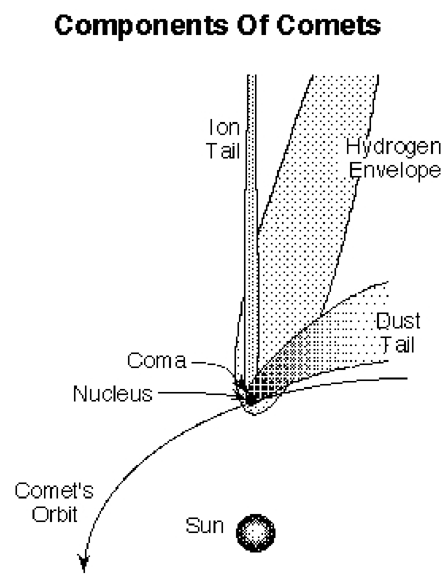



Figure 9.3: The main components of a comet.

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

- *nucleus*: made of ice and rock, roughly 5-10 km across
- *coma*: the "head" of a comet, a large cloud of gas and dust, roughly 100,000 km in diameter
- *gas tail*: straight and wispy; gas in the coma becomes ionized by sunlight, and gets carried away by the solar wind to form a straight blueish "ion" tail. The shape of the gas tail is influenced by the magnetic field in the solar wind. Gas tails are pointed in the direction directly opposite the sun, and can extend $10^8$ km.
- *dust tail*: dust is pushed outward by the pressure of sunlight and forms a long, curving tail that has a much more uniform appearance than the gas tail. The dust tail is

pointed in the direction directly opposite the comet's direction of motion, and can also extend $10^8$ km from the nucleus.

These various components of a comet are shown in the diagram, above (Fig. 9.3).

## 9.4 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 *more* than 200 years. Their orbits are random in shape and inclination, with long-period comets entering the inner solar system from all different directions. These comets are thought to originate in the **Oort cloud**, a spherical cloud of icy bodies that extends from ~20,000 to 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. Quite a few large Kuiper Belt objects have now been discovered, including one (Eris) that is about the same size as Pluto.

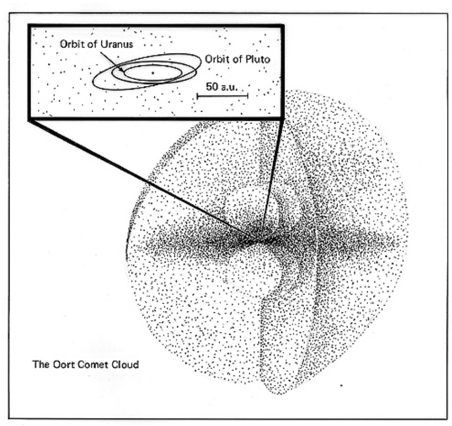



Figure 9.4: The Oort cloud.

## 9.5 The Impacts of Asteroids and Comets

Objects orbiting the Sun in our solar system do so at a variety of speeds that directly depends on how far they are from the Sun. For example, the Earth's orbital velocity is 30

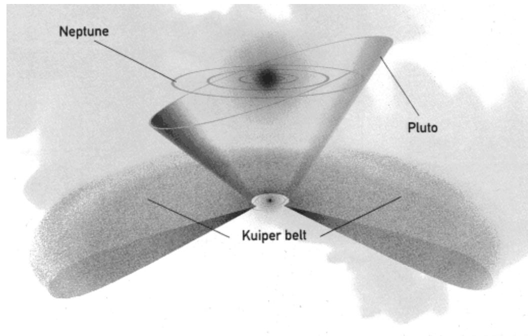



Figure 9.5: The Kuiper belt.

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

## 9.6 Exercise #1: Creating Impact Craters

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

1. Have one member of your lab group take the meter stick, while another takes the smaller ball bearing.
2. Take the plastic tub that is filled with flour, and place it on the floor.
3. Make sure the flour is uniformly level (shake or comb the flour smooth)
4. Carefully hold the meter stick so that it is just touching the top surface of the flour.

5. The person with the ball bearing now holds the ball bearing so that it is located exactly one half meter (50 cm) above the surface of the flour.

6. Drop the ball bearing into the center of the flour-filled tub.

7. Use the magnet to carefully extract the ball bearing from the flour so as to cause the least disturbance.

8. Carefully measure the diameter of the crater caused by this impact, and place it in the data table, below.

9. Repeat the experiment for heights of 1 meter and 2 meters using the smaller ball bearing (note that someone with good balance might have to *carefully* stand on a chair to get to a height of two meters!).

10. Now repeat the entire experiment using the larger ball bearing. Record all of the data in the data table.

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

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

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

1. Now plot the data you have just collected on graph paper. Put the impact velocity on the *x axis*, and the crater diameter on the $y$ axis. (**10 points**)

### 9.6.1 Impact crater questions

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

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

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

## 9.7 Crater Illumination

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

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

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

**points**)

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

## 9.8 Exercise #2: Building a Comet

In this portion of the lab, you will actually build a comet out of household materials. These include water, ammonia, potting soil, and dry ice ($CO_2$ ice). Be sure to distribute the work evenly among all members of your group. Follow these directions: (**10 points**)

1. Use a freezer bag to line the bottom of your bucket.
2. Place a little less than 1 cup of water (this is a little less than 1/2 of a "Solo" cup!) in the bag/bucket.
3. Add 3 spoonfuls of sand, stirring well. (**NOTE:** Do not stir so hard that you rip the freezer bag lining!!)
4. Add 1 capful of ammonia.
5. Add 1 spoon of organic material (potting soil). Stir until well-mixed.
6. Your TA will place a block or chunk of dry ice inside a towel and crush the block with the mallet and give you some crushed dry ice.
7. Add about 1 cup of crushed dry ice to the bucket, while stirring vigorously. (**NOTE:** Do not stir so hard that you rip the freezer bag!!)
8. Continue stirring until mixture is almost frozen.
9. Lift the comet out of the bucket using the plastic liner and shape it for a few seconds as if you were building a snowball (use gloves!).
10. If not a solid mass, add small amounts of water and keep working the "snowball" until the mixture is completely frozen.

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

### 9.8.1 Comets and Light

1. Observe the comet as it is sitting on a desk. Make some notes about its physical characteristics, for example: shape, color, smell (**5 points**):

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

### 9.8.2 Comet Strength

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

**Exercise:** After everyone in your group has carefully examined your comet (make sure to note its appearance, shape, smell, weight), it is time to say goodbye. Take a sample rock and your comet, go outside, and drop them both on the sidewalk. What happened to each

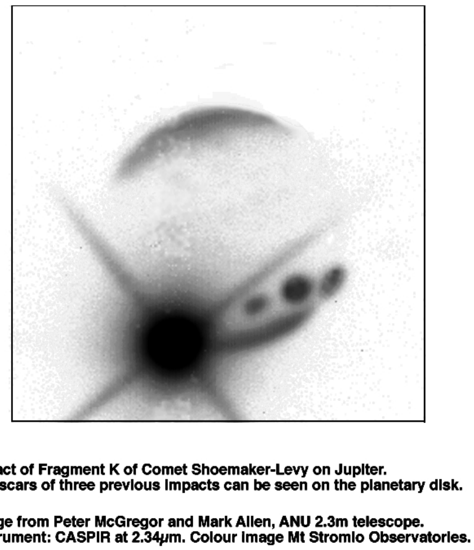



Figure 9.6: The Impact of "Fragment K" of Comet Shoemaker-Levy/9 with Jupiter. Note the dark spots where earlier impacts occurred.

object? (**2 points**)

### 9.8.3 Comet Questions

1. Draw a comet and label all of its components. Be sure to indicate the direction the Sun is in, and the comet's direction of motion. (**5 points**)

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

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

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

4. Do you think comets have more or less internal strength than asteroids, which are composed primarily of rock? [Hint: If you are playing outside with your friends in a snow storm, would you rather be hit with a snowball or a rock?] (**3 points**)

Name:________________________________
Date:________________________________

## 9.9 Take Home Exercise (35 points total)

Write-up a summary of the important ideas covered in this lab. Questions you may want to consider are:

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

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

## 9.10 Possible Quiz Questions

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

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

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

Name:________________________________
Date:_________________________________

# 10 Kepler's Laws

## 10.1 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.

## 10.2 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. 10.1. Here $F_{gravity}$ is the gravitational attractive force between two objects whose masses are $M_1$ and $M_2$. The distance between the two objects is "R". The gravitational constant $G$ is just a small number that scales the size of the force. **The most important thing about gravity is that the force depends only on the masses of the two objects and the distance between them.** This law is called an Inverse Square Law because the distance between the objects is *squared*, and is in the denominator of the fraction. There are several laws like this in physics and astronomy.

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

- *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

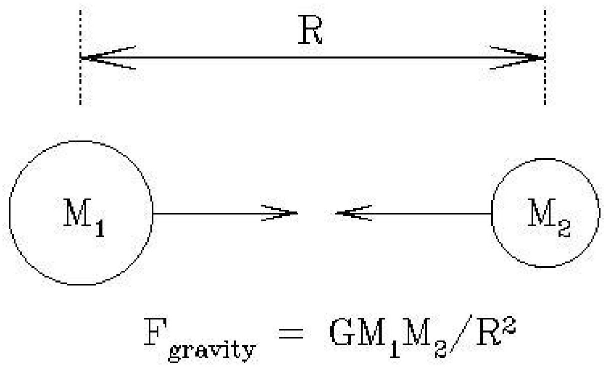



Figure 10.1: The force of gravity depends on the masses of the two objects ($M_1$, $M_2$), and the distance between them (R).

## 10.3 Kepler's Laws

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

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

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

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

Let's look at the first law, and talk about the nature of an ellipse. What is an ellipse? An ellipse is one of the special curves called a "conic section". If we slice a plane through a cone, four different types of curves can be made: circles, ellipses, parabolas, and hyperbolas. This process, and how these curves are created is shown in Fig. 10.2.

Before we describe an ellipse, let's examine a circle, as it is a simple form of an ellipse. As you are aware, the circumference of a circle is simply $2\pi R$. The radius, R, is the distance between the center of the circle and any point on the circle itself. In mathematical terms, the center of the circle is called the "focus". An ellipse, as shown in Fig. 10.3, 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. 10.4 is an ellipse with the two foci identified, "$F_1$" and "$F_2$".

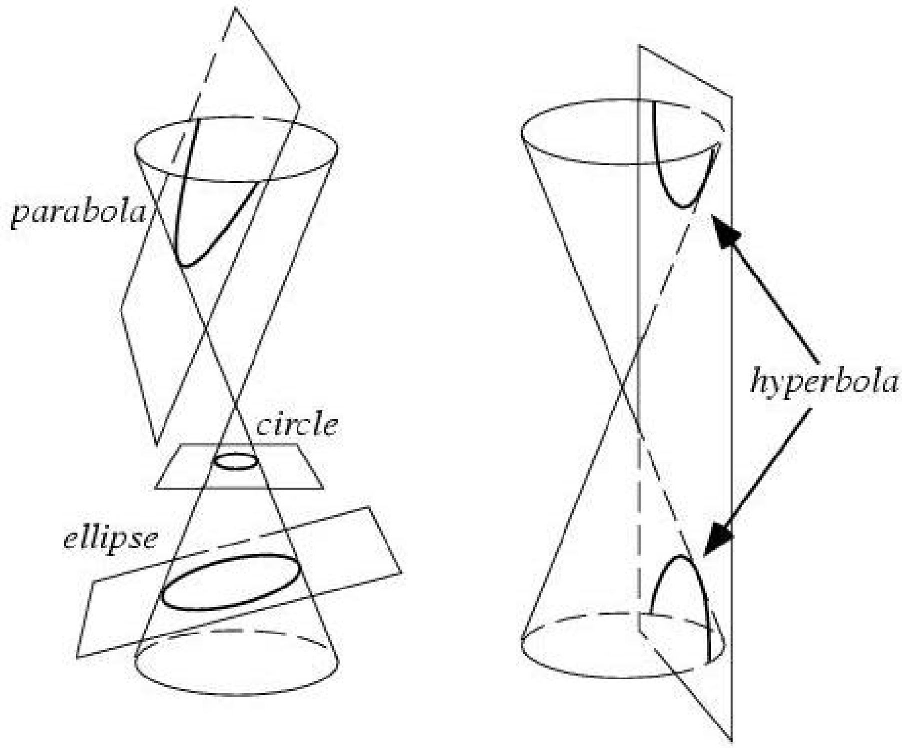



Figure 10.2: Four types of curves can be generated by slicing a cone with a plane: a circle, an ellipse, a parabola, and a hyperbola. Strangely, these four curves are also the allowed shapes of the orbits of planets, asteroids, comets and satellites!

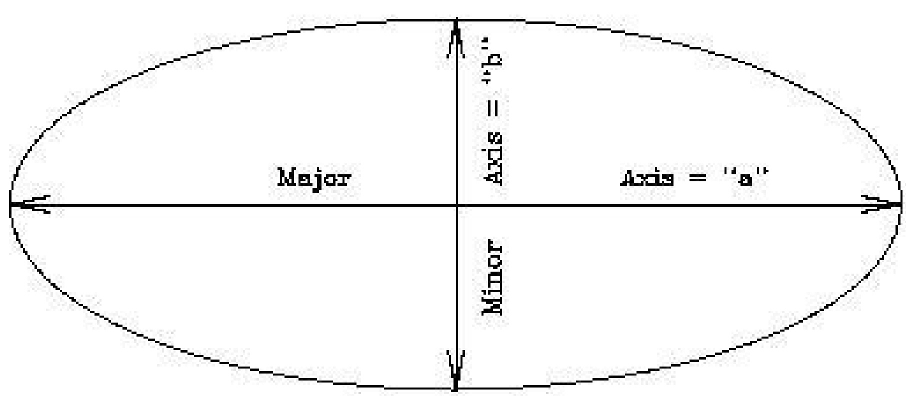



Figure 10.3: An ellipse with the major and minor axes identified.

**Exercise #1:** On the ellipse in Fig. 10.4 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**)

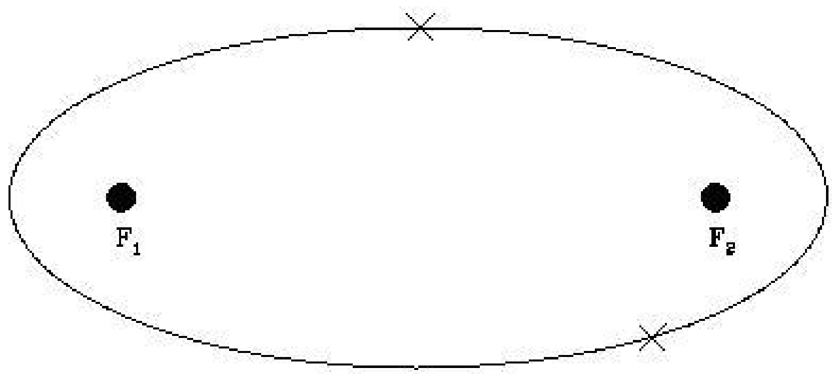



Figure 10.4: An ellipse with the two foci identified.

**Exercise #2:** In the ellipse shown in Fig. 10.5, 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**)

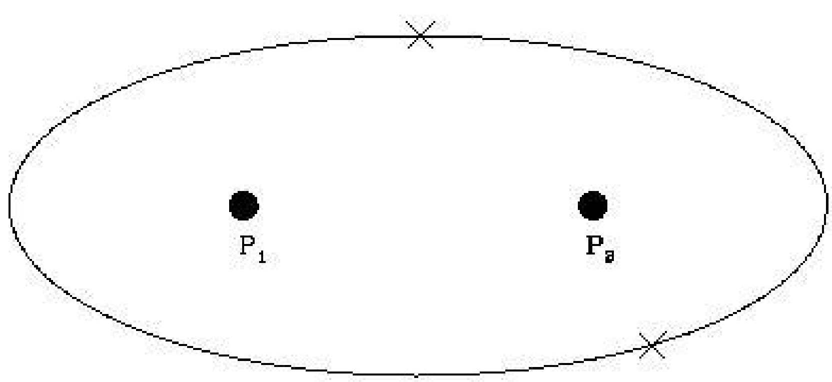



Figure 10.5: An ellipse with two non-foci points identified.

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.]

1. 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.

2. 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.

3. What is happening here? The orbit is now a circle. Where are the two foci located? In this case, what is a name that describes the distance between the focus point and the orbit? (**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 "Kepler's Law button" and then the "Second Law" button inside the Kepler's Law box.

Move the Initial Velocity slide bar to a value of 1.2. Hit Go.

1. 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 $1/R^2$ = ______________________?

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:

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

where "r" is the radial distance of the planet from the Sun, and "a" is the mean orbital radius (the semi-major axis).

3. 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**)

4. 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**)

5. 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 #5:** 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 "$\propto$". However, if we use units of 'years' for $P$ and 'AU' for $a$ we can replace the proportional sign with an equal sign:

$$P^2 = E^3 \tag{3}$$

Let's use equation (3) to make some predictions. If the average distance of Jupiter from the Sun is about 5 AU, what is its orbital period? Set-up the equation:

$$P_J^2 = a_J^3 = 5^3 = 5 \times 5 \times 5 = 125 \tag{4}$$

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:

$$\sqrt{P^2} = P = \sqrt{125} = 11.2 \;\; years \tag{5}$$

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

1. 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.

2. 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.

3. Fill in the missing orbital periods of the planets by running the Third Law simulator for each of them. (**3 points**)

Table 10.1: 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").

4. 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**)

## 10.4 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. 10.6 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.

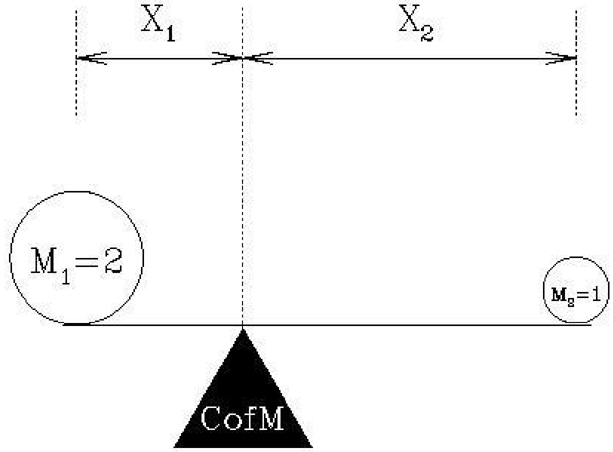
Most binary star systems have stars with similar masses ($\mathrm{M}_1 \approx \mathrm{M}_2$), but this is not always the case. In the first (default) binary star simulation, $\mathrm{M}_1 = 2\mathrm{M}_2$. The "mass ratio" ("$q$") in this case is 0.5.

Mass ratio is defined to be

$$q = \frac{M_2}{M_1} \tag{6}$$

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" window of the simulation.

**Exercise #6:** 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




$$M_1X_1 = M_2X_2$$

Figure 10.6: 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, $X_2 = 2X_1$.

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.

1. 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? (Remember Equation 6) 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.

2. Go back to Input and enter in the correct mass ratio for a binary star system with $M_1 = 4.0$, and $M_2 = 1.0$ (using Equation 6). 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. 10.6.] (**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.

3. 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!

4. 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.

5. 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? (**5 points**)

6. 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? (**5 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:______________________________

## 10.5 Take Home Exercise (35 points total)

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

- Describe the Law of Gravity and what happens to the gravitational force as *a)* as the masses increase, and *b)* the distance between the two objects increases

- Describe Kepler's three laws *in your own words*, and describe how you tested each one of them.

- Mention some of the things which you have learned from this lab

- Astronomers think that finding life on planets in binary systems is unlikely. Why do they think that? Use your simulation results to strengthen your argument.

## 10.6 Possible Quiz Questions

1. Describe the difference between an ellipse and a circle.

2. List Kepler's three laws.

3. How quickly does the strength ("pull") of gravity get weaker with distance?

4. Describe the major and minor axes of an ellipse.

## 10.7 Extra Credit (ask your TA for permission before attempting this, 5 points)

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?

Name:__________________________________
Date:___________________________________

# 11 Apendix A: Algebra Review

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

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

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

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

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

## 11.1 Solving for X

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

y = 7x + 14

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

21 = 7x + 14

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

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

7 = 7x (divide both sides by 7)

x = 1

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

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

Copy down the equation again:

$y^2 = 3x + 3$

Substitute x = 11:

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

Take the square root of both sides:

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

$y = 6$

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