ASTR 105G Lab Manual

Astronomy Department
New Mexico State University

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(http://astronomy.nmsu.edu/astro/Ast105labmanual.pdf)

Contents

Name:________________________________

Date:_________________________________

1 Tools for Success in ASTR 105G

1.1 Introduction

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

1.2 The Metric System

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

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

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

Table 1.1: Metric System Prefixes

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

1.3 Beyond the Metric System

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

1.4 Changing Units and Scale Conversion

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

1. Convert 34 meters into centimeters:

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

2. Convert 34 kilometers into meters:

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

4. How many centimeters are there in 400 inches?

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

1.4.1 Map Exercises

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

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

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

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

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

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

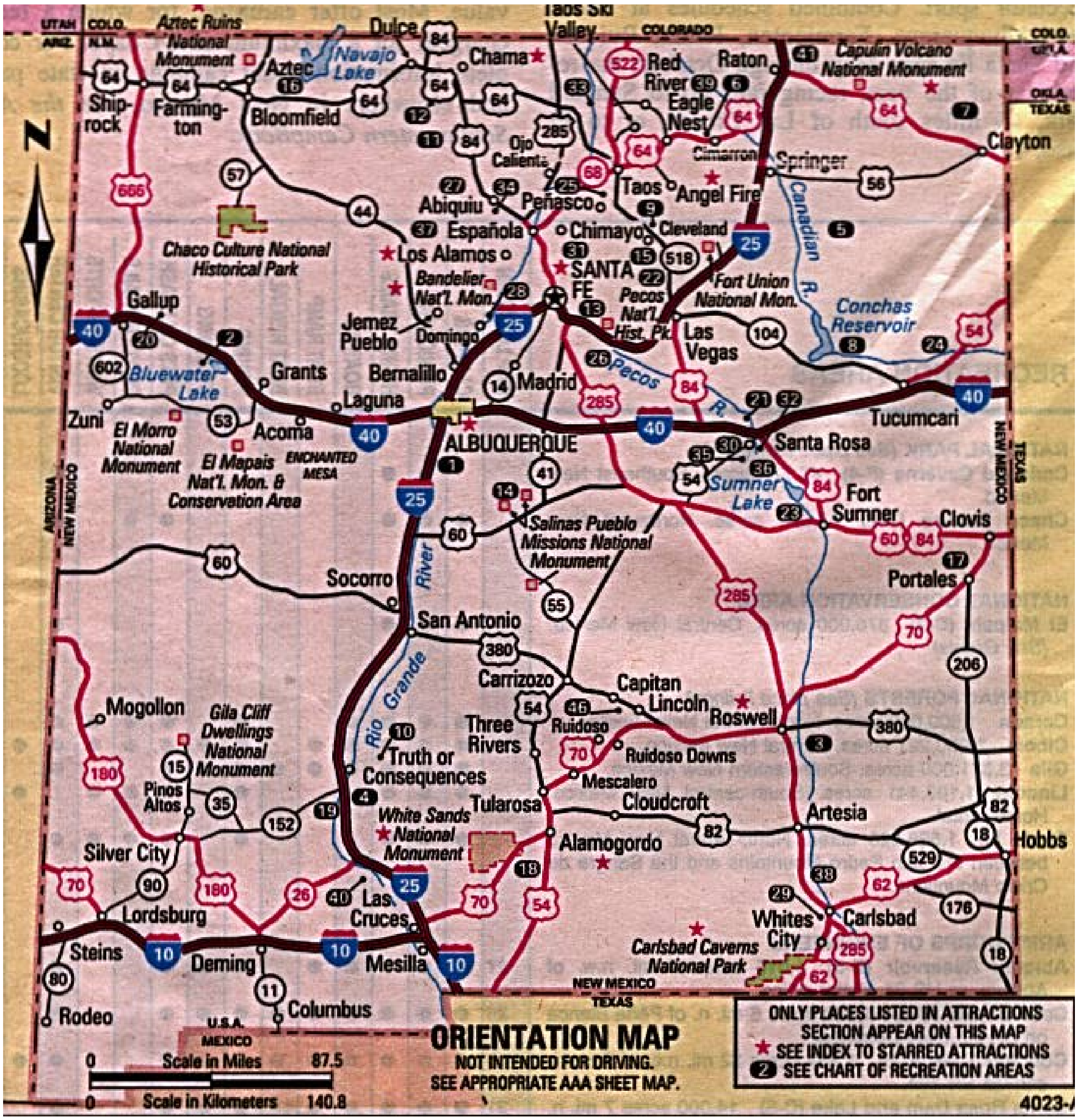


Figure 1.1: Map of New Mexico.

1.5 Squares, Square Roots, and Exponents

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

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

Your turn (2 points each):

10. $6^3 =$

11. $4^4 =$

12. $3.1^2 =$

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

- $\sqrt{100} = 10$

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

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

1.6 Scientific Notation

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

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

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

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

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

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

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

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

13. $121 = 121.0 =$

14. $735{,}000 =$

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

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

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

Your turn (2 points each):

16. $0.0121 =$

17. $0.0000735 =$

18. $0.0000000999 =$

19. $-0.121 =$

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

1.7 Calculator Issues

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

1.7.1 Scientific Notation on a Calculator

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

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

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

- 7.99921×10^{21}
- 2.2951324×10^{-6}

1.7.2 Order of Operations

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

i. Calculations must be done from left to right.

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

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

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

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

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

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

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

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

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

1.8 Graphing and/or Plotting

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

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

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

1.8.1 The Mechanics of Plotting

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

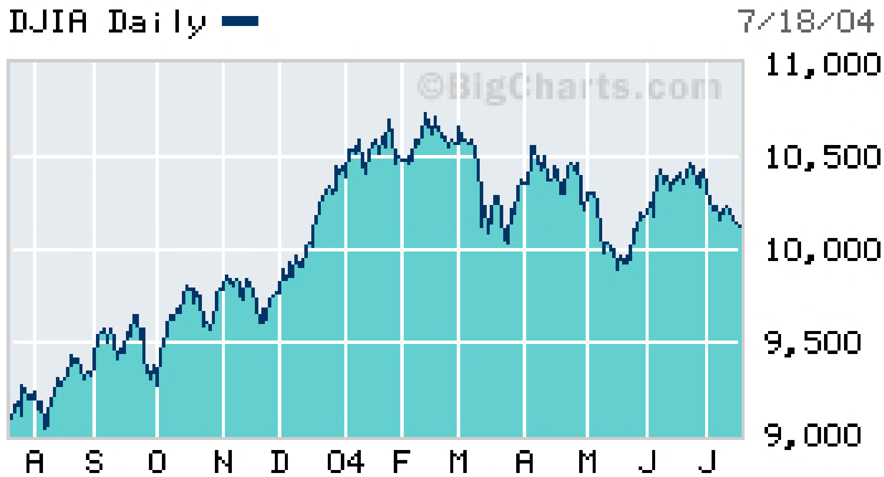


Figure 1.2: The change in the Dow Jones stock index over one year (from April 2003 to July 2004).

Table 1.2: Temperature vs. Altitude

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

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

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

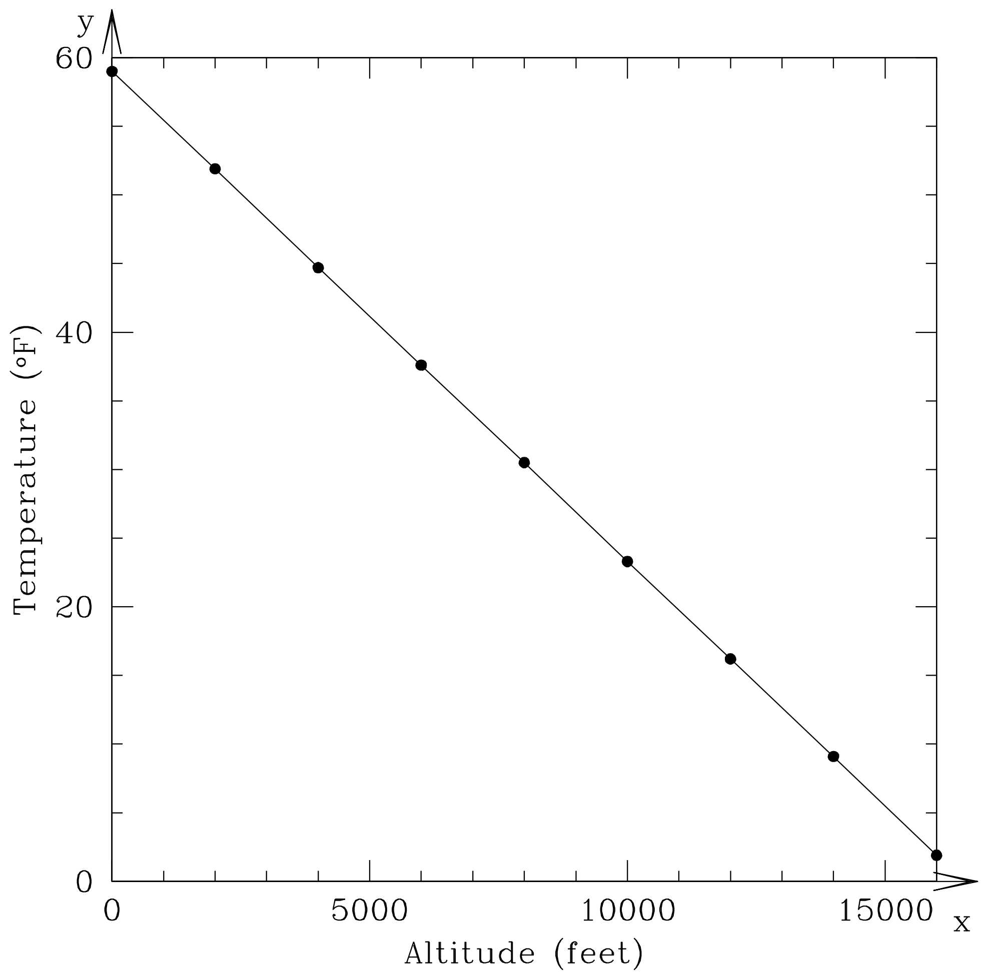


Figure 1.3: The change in temperature as you climb in altitude with the data from Table 1.2. At sea level (0 ft altitude) the surface temperature is 59°F. As you go higher in altitude, the temperature goes down.

1.8.2 Plotting and Interpreting a Graph

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

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

Date:____________________________________

2 The Origin of the Seasons

2.1 Introduction

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

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

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

2.2 The Seasons

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

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

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

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

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

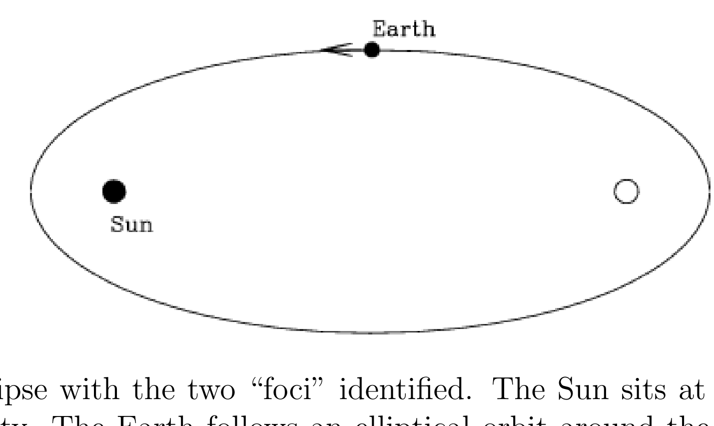


Figure 2.1: An ellipse with the two "foci" identified. The Sun sits at one focus, while the other focus is empty. The Earth follows an elliptical orbit around the Sun, but not nearly as exaggerated as that shown here!

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

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

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

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

Given that *we know* objects appear bigger when we are closer to them, let's take a look at the two pictures of the Sun you were given as part of the materials for this lab. One image was taken on January 23$^{\text{rd}}$, 1992, and one was taken on the 21$^{\text{st}}$ 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, since an object appears bigger when we get closer to it, when is the Earth closest to the Sun? (**2 points**)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.3 The Spinning, Revolving Earth

It is clear from the preceding subsection that your latitude determines both the annual variation in the amount of daylight, and the time of the year when you experience Spring, Summer, Autumn and Winter. To truly understand why this occurs requires us to construct a model. One of the key insights to the nature of the motion of the Earth is shown in the long exposure photographs of the nighttime sky (Figs. 2.2, 2.3).

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

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

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

direction of North.

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

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

Exercise #3: In this part of the lab, we will be using the mounted globes, a piece of string, a ruler, and the halogen desk lamp. **Warning: while the globe used here is made of fairly inexpensive parts, it is very time consuming to make. Please be careful with your globe, as the paint can be easily damaged.** Make sure that the piece of string you have is long enough to go slightly more than halfway around the globe at the equator–if your string is not that long, ask your TA for a longer piece of string. As you may have guessed, this globe is a model of the Earth. The spin axis of the Earth is actually tilted with respect to the plane of its orbit by 23.5°.

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

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

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

Experiment #1: Note that there is an illuminated half of the globe, and a dark half of the globe. The line that separates the two is called the "terminator". It is the location of sunrise or sunset. Using the piece of string, we want to measure the length of each arc that is in "daylight" and the length that is in "night". This is kind of tricky, and requires a bit of judgement as to exactly where the terminator is located. So make sure you have a helper to help keep the string *exactly* on the line of constant latitude, and get the advice of your lab partners of where the terminator is (it is probably best to do this more than once). Fill in the following table (**4 points**):

As you know, the Earth rotates once every 24 hours (= 1 Day). Each of the lines of constant latitude represents a full circle that contains 360°. But note that these circles get smaller in radius as you move away from the equator. The circumference of the Earth at the equator is 40,075 km (or 24,901 miles). At a latitude of 45°, the circle of constant latitude has a circumference of 28,333 km. At the arctic circles, the circle has a

Table 2.2: Position #1: Equinox Data Table

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

circumference of only 15,979 km. This is simply due to our use of two coordinates (longitude and latitude) to define a location on a sphere.

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

Table 2.3: Position #1: Length of Night and Day

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

18) The caption for Table 2.2 was "Equinox data". The word Equinox means "equal nights", as the length of the nighttime is the same as the daytime. While your numbers in Table 2.3 may not be exactly perfect, what do you conclude about the length of the nights and days for *all* latitudes on Earth in this experiment? Is this result consistent with the term Equinox? (**3 points**)

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

Table 2.4: Position #2: Solstice Data Table

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

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

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

19) Compare your results in Table 2.5 for +45° latitude with those for Minneapolis in Table 2.1. Since Minneapolis is at a latitude of +45°, what season does this orientation of the globe correspond to? (**2 points**)

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

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

Table 2.6: Position #3: Solstice Data Table

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

21) As in question #19, compare the results found here for the length of daytime and nighttime for the +45° degree latitude with that for Minneapolis. What season does this appear to be? (**2 points**)

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

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

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 21st) there are more daylight hours; at the start of the Autumn ($\sim$ Sept. 20th) and Spring ($\sim$ Mar. 21st), the days are equal to the nights. In the Winter (approximately Dec. 21st) the nights are long, and the days are short. We have also discovered that the seasons in the Northern and Southern hemispheres are exactly opposite. If it is Winter in Las Cruces, it is Summer in Sydney (and vice versa). This was clearly demonstrated in our experiments and is shown in Figure 2.4.

The length of the daylight hours is one reason why it is hotter in Summer than in Winter: the longer the Sun is above the horizon the more it can heat the air, the land and the seas.

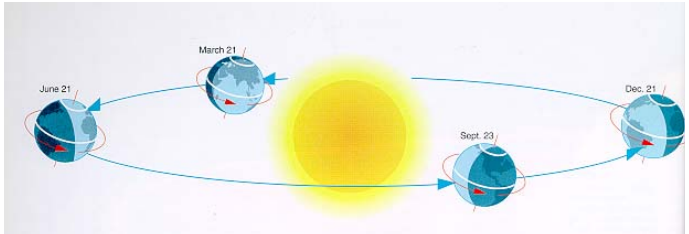


Figure 2.4: The Earth's spin axis always points to one spot in the sky, *and* it is tilted by 23.5° to its orbit. Thus, as the Earth orbits the Sun, the illumination changes with latitude: sometimes the North Pole is bathed in 24 hours of daylight, and sometimes in 24 hours of night. The exact opposite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

But this is not the whole story. At the North Pole, where there is constant daylight during the Summer, the temperature barely rises above freezing! Why? We will discover the reason for this now.

2.4 Elevation Angle and the Concentration of Sunlight

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

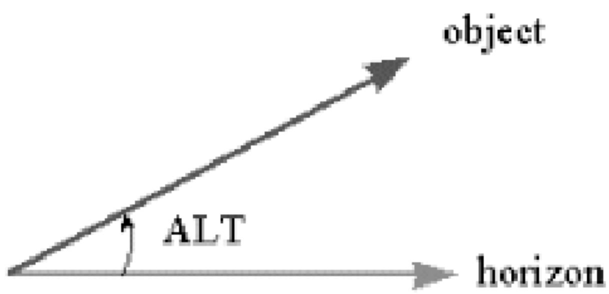


Figure 2.5: Altitude ("Alt") is simply the angle between the horizon, and an object in the sky. The smallest this angle can be is 0°, and the maximum altitude angle is 90°. Altitude is interchangeably known as elevation.

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

Exercise #4: Using the elevation angle apparatus, we now want to measure what happens when the Sun is at a higher or lower elevation angle. We mimic this by using a flashlight mounted on an arm that allows you to move it to just about any elevation angle. It is difficult to exactly model the Sun using a flashlight, as the light source is not perfectly uniform. But here we do as well as we can. Play around with the device. Turn on the flashlight and move the arm to lower and higher angles. How does the illumination pattern change? Does the illuminated pattern appear to change in brightness as you change angles? Explain. (**2 points**)

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

The diameter of the illuminated circle is ________________ cm.

Do you remember how to calculate the area of a circle? Does the formula πR^2 ring a bell?

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

Now, as you should have noticed at the beginning of this exercise, as you move the flashlight to lower and lower elevations, the circle changes to an ellipse. Now adjust the elevation angle to be 45°. Ok, time to introduce you to two new terms: the major axis and minor axis of an ellipse. Both are shown in Fig. 4.4. The minor axis is the smallest diameter, while the major axis is the longest diameter of an ellipse.

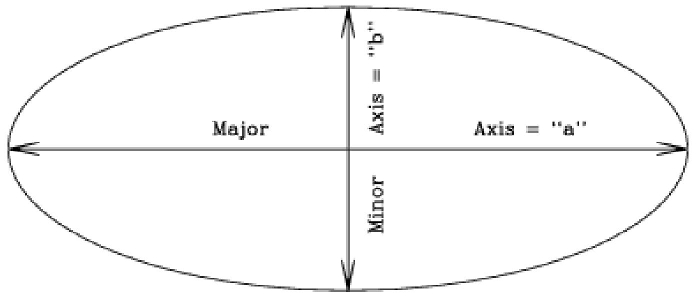


Figure 2.6: An ellipse with the major and minor axes defined.

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

The major axis has a length of $a =$ ____________ cm, while the minor axis has a

length of $b =$ ____________ cm.

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

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

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

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

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

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

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

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

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

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

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

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

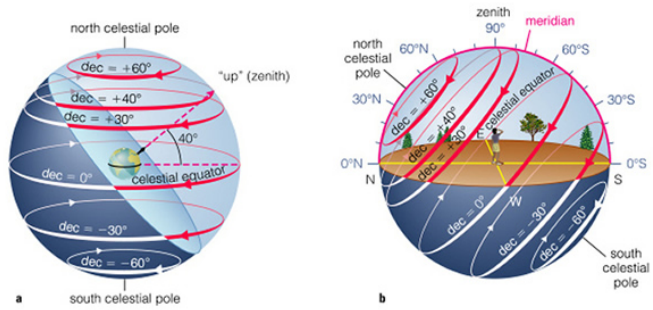


Figure 2.7: The Celestial Equator is the circle in the sky that is straight overhead ("the zenith") of the Earth's equator. In addition, there is a "North Celestial" pole that is the projection of the Earth's North Pole into space (that almost points to Polaris). But the Earth's spin axis is tilted by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

the equator, turn on the halogen lamp, and slowly rotate the entire apparatus around (while keeping the pin facing the Sun) you will notice that the shadow of the pin will increase and decrease in size. This is due to the apparent change in the elevation angle of the "Sun".

2.5 Summary (35 points)

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

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

2.6 Possible Quiz Questions

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

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

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

Name(s):____________________________
Date:______________________________

3 Phases of the Moon

3.1 Introduction

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

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

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

Your textbook probably has a figure showing the changing phases exhibited by the Moon each month. Generally, we start our 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!)

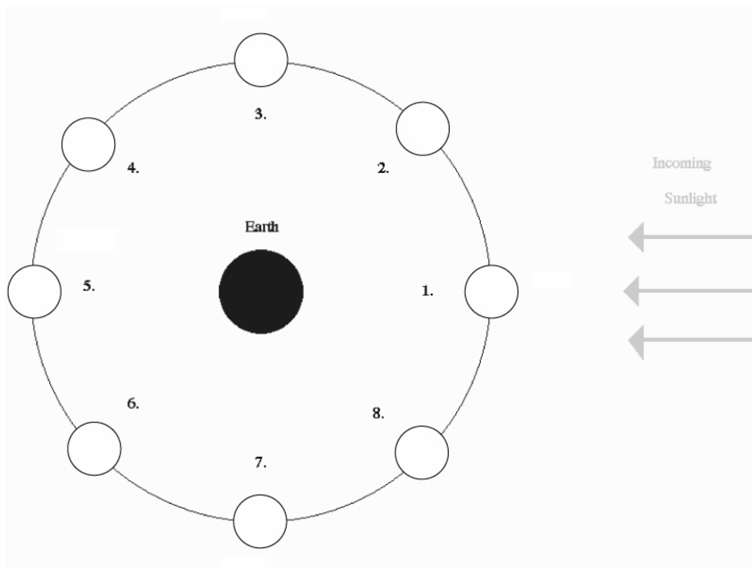
You will use the colored sphere and flashlight as props for this demonstration. Carefully read and thoroughly answer the questions associated with each of the five Exercises on the following pages. [Don't be concerned about eclipses as you answer the questions in these Exercises]. Using the dual-colored 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!

3.2 Exercise 1 (10 points)

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



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

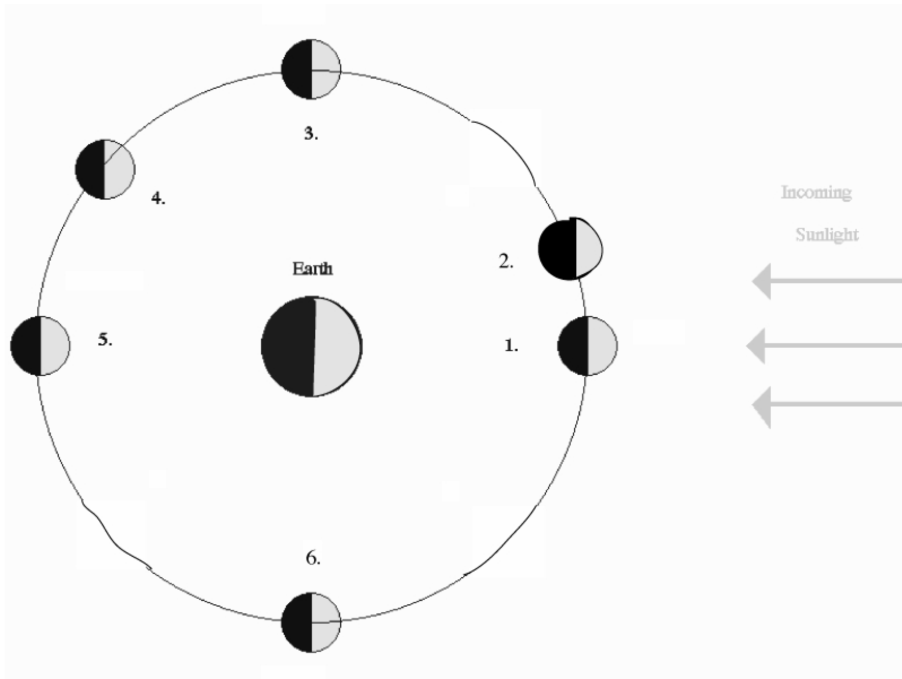
Ranking Order: Greatest A ____B ____C ____D ____E ____F ____G ____H ____Least

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

Carefully explain the reasoning for your result:

3.3 Exercise 2 (10 points)

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



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

Ranking Order: Greatest A ______B ______C ______D ______E ______F ______Least

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

Carefully explain the reasoning for your result:

3.4 Exercise 3 (10 points)

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

A B C D E

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

Ranking Order:

1) Waxing Gibbous

2) ____________________

3) ____________________

4) ____________________

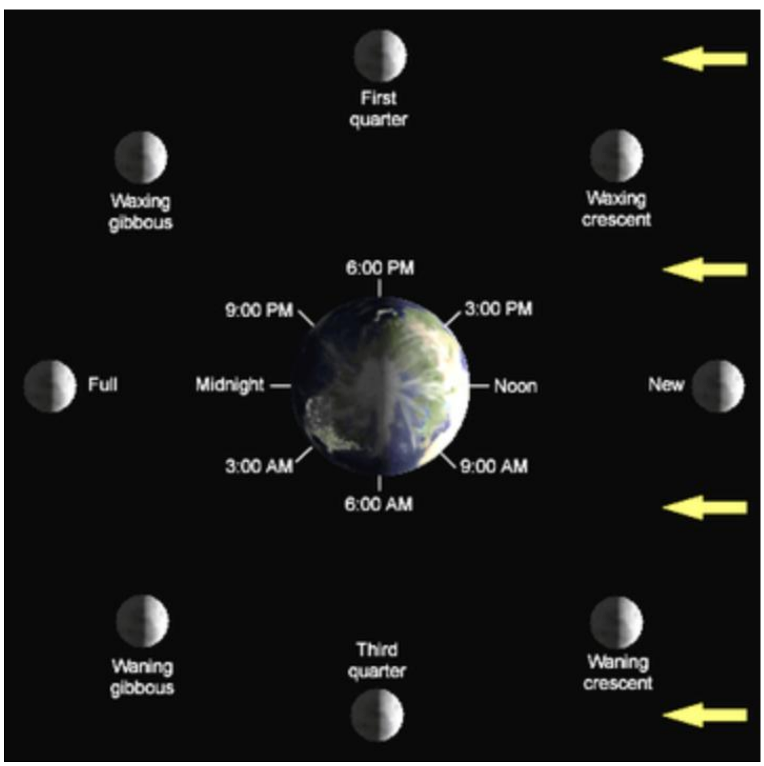
5) ____________________

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

3.5 Lunar Phases, and When They Are Observable

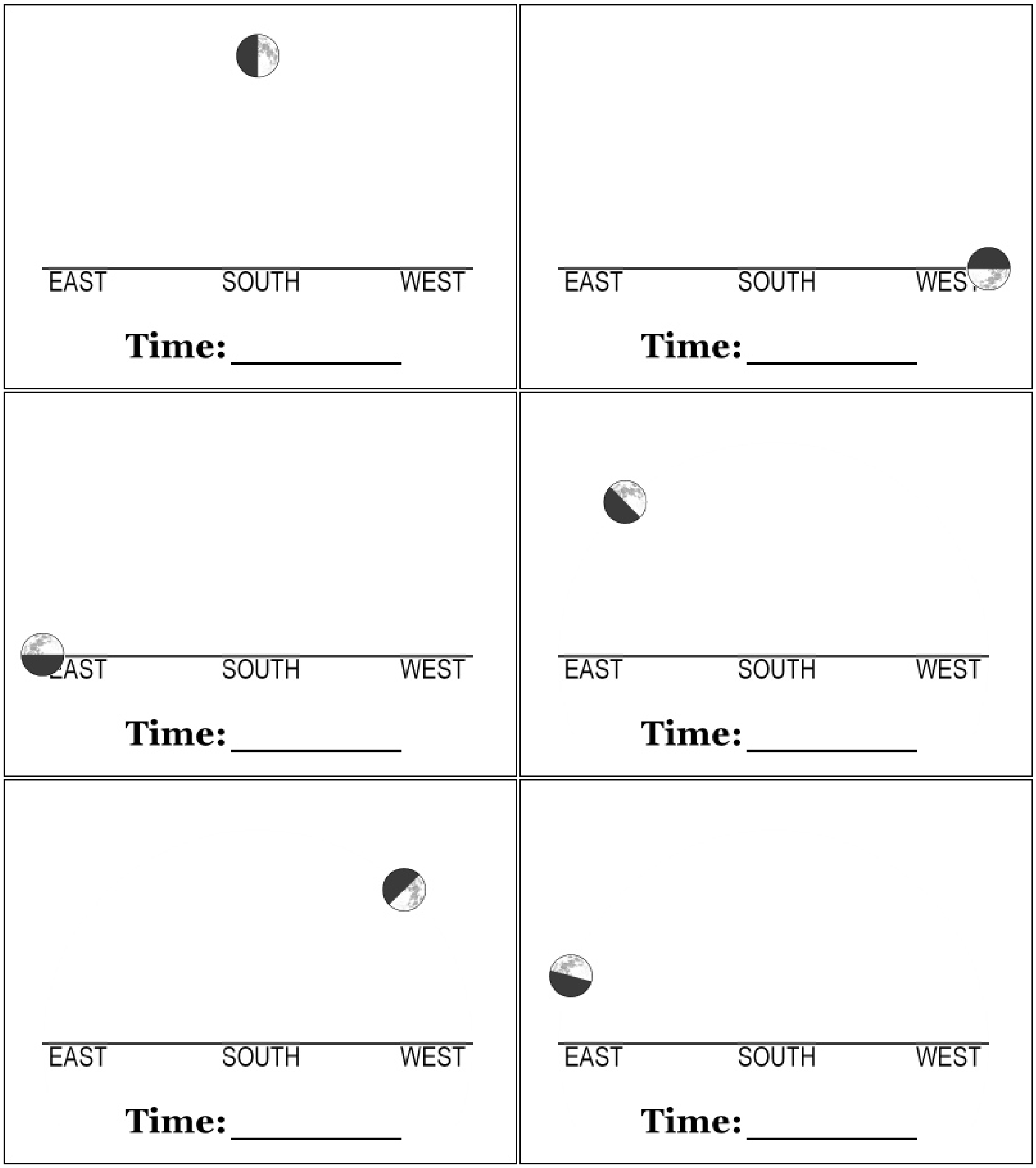
The next three exercises involve determining when certain lunar phases can be observed. Or, alternatively, determining the approximate time of day or night using the position and phase of the Moon in the sky.

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



3.6 Exercise 4 (6 points)

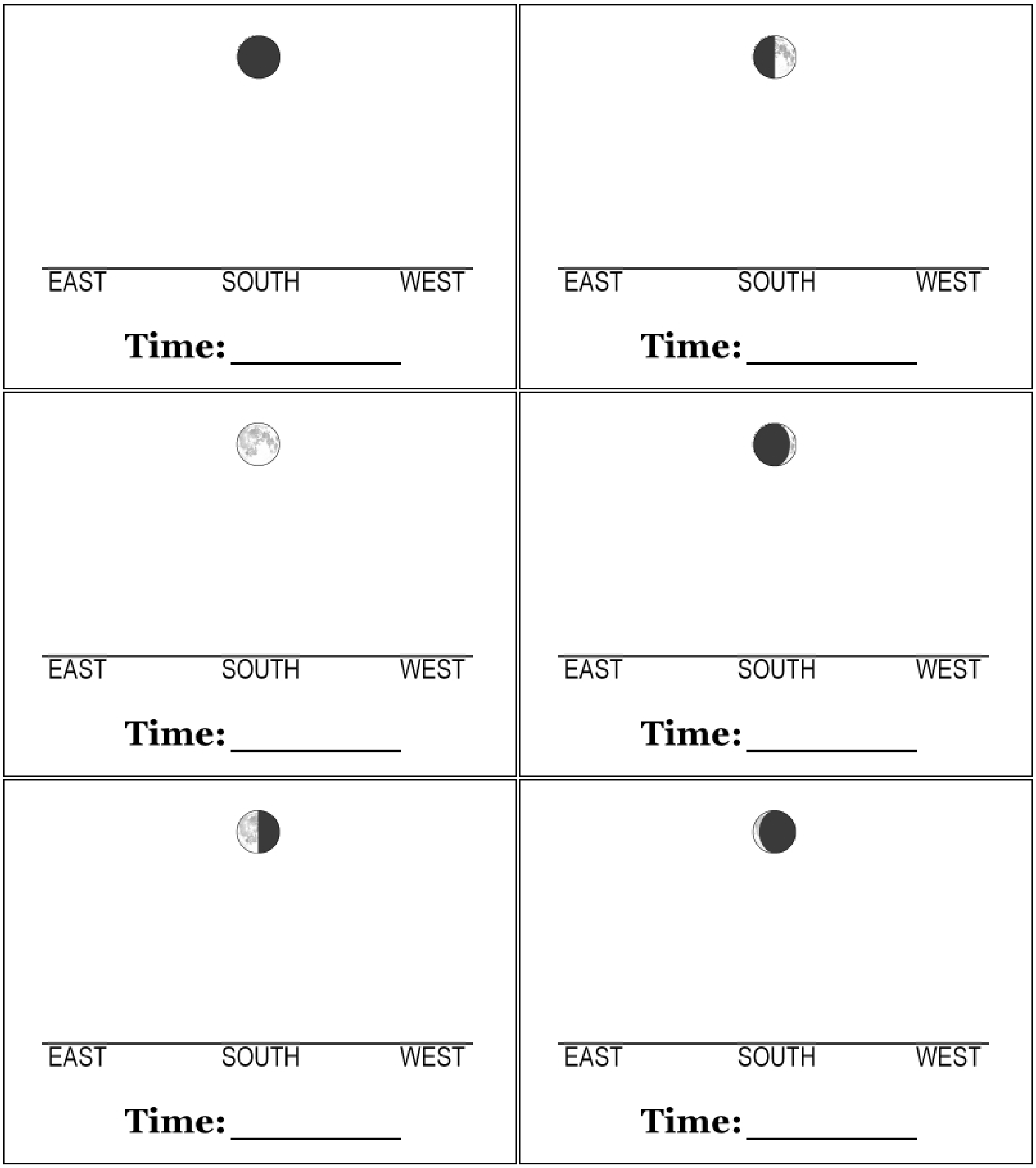
In the set of figures below, the Moon is shown in the first quarter phase at different times of the day (or night). Assume that sunset occurs at 6 p.m. and that sunrise occurs at 6 a.m.



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

3.7 Exercise 5 (6 points)

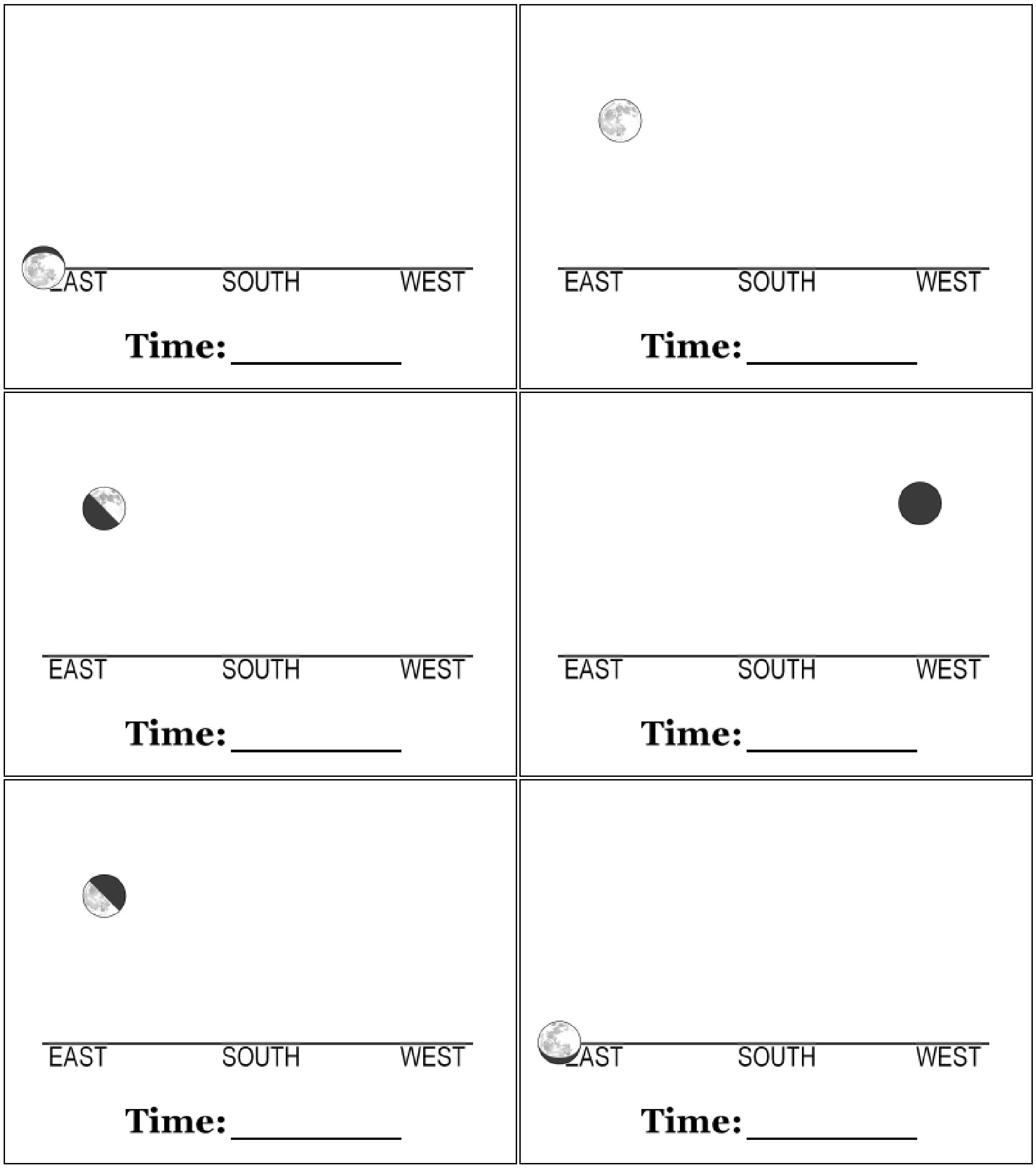
In the set of figures below, the Moon is shown overhead, at its highest point in the sky, but in different phases. Assume that sunset occurs at 6 p.m. and that sunrise occurs at 6 a.m.



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

3.8 Exercise 6 (6 points)

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



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

3.9 Demonstrating Your Understanding of Lunar Phases

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

Name:______________________________
Date:_______________________________

3.10 Take-Home Exercise (35 points total)

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

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

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

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

3.11 Possible Quiz Questions

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

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

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

Name:____________________

Date:____________________

4 Kepler's Laws and Gravitation

4.1 Introduction

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

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

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

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

4.2 Gravity

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

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

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

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

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

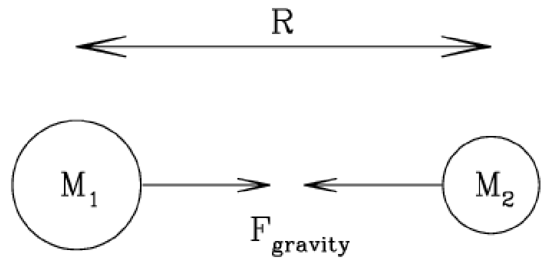


Figure 4.1: The force of gravity depends on the masses of the two objects (M_1, M_2), and the distance between them (R).

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

4.3 Kepler's Laws

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

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

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

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

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

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

Exercise #1: On the ellipse in Fig. 4.4 are two X's. Confirm that that sum of the distances between the two foci to any point on the ellipse is always the same by measuring

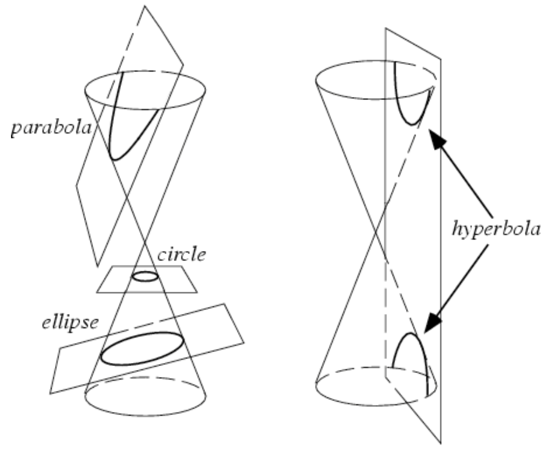


Figure 4.2: Four types of curves can be generated by slicing a cone with a plane: a circle, an ellipse, a parabola, and a hyperbola. Strangely, these four curves are also the allowed shapes of the orbits of planets, asteroids, comets and satellites!

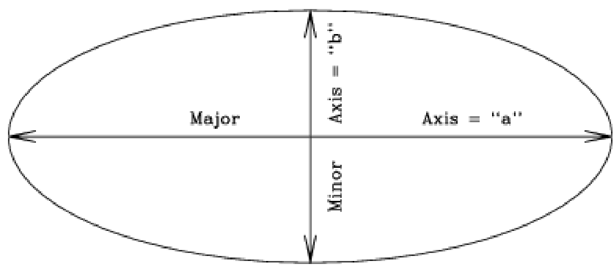


Figure 4.3: An ellipse with the major and minor axes identified.

the distances between the foci, and the two spots identified with X's. Show your work. (**2 points**)

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

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

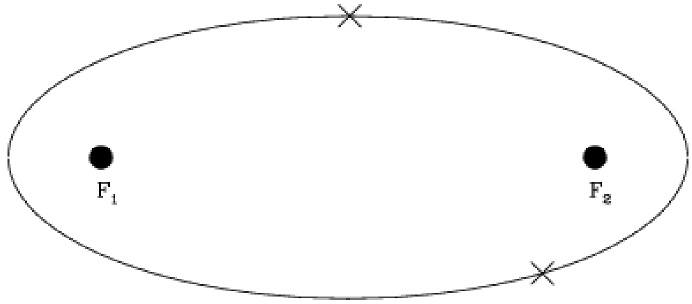


Figure 4.4: An ellipse with the two foci identified.

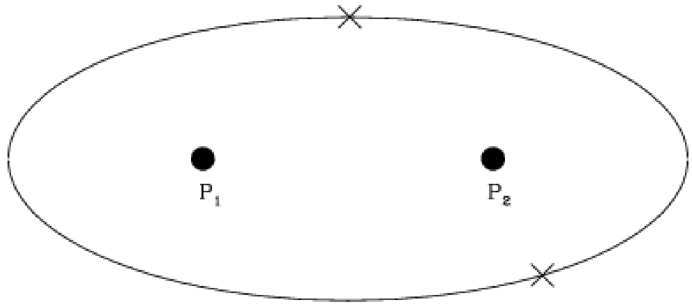


Figure 4.5: An ellipse with two non-foci points identified.

Satellites has been installed on the computer you are using. Look on the desktop for an icon, or use the start menu. Start-up the program, and you should see a title page window, with four boxes/buttons ("Getting Started", "Tutorial", "Simulations", and "Exit"). Click on the "Simulations" button. We will be returning to this level of the program to change simulations. Note that there are help screens and other sources of information about each of the simulations we will be running–do not hesitate to explore those options.

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

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

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

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

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

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

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

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

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

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

- If R = 1, what does $1/\mathrm{R}^2$ = ________________________?

- If R = 2, what does $1/\mathrm{R}^2$ = ________________________?

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

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

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

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

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

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

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

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

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

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

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

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

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

"C", and Kepler's Third Law equation becomes:

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

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

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

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

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

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

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

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

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

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

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

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

Table 4.1: The Orbital Periods of the Planets

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

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

4.4 Going Beyond the Solar System

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

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

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

In this simulation there are two stars in orbit around each other, a massive one (the blue one) and a less massive one (the red one). Note how the two stars move. Notice that the line connecting them at each point in the orbit passes through one spot–this is the location of something called the "center of mass". In Fig. 4.6 is a diagram explaining the center of mass. If you think of a teeter-totter, or a simple balance, the center of mass is the point where the balance between both sides occurs. If both objects have the same mass, this point is halfway between them. If one is more massive than the other, the center of mass/balance point is closer to the more massive object.

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

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

Use the slide bar so that Mass Ratio = 1.0. Click "Ok". This now sets up your new simulation. Click Run. Describe the simulation. What are the shapes of the two orbits? Where is

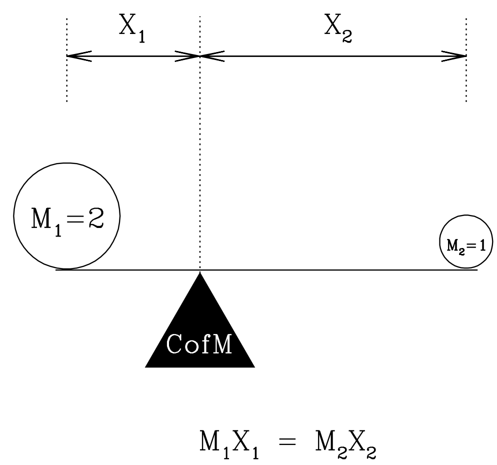


Figure 4.6: A diagram of the definition of the center of mass. Here, object one (M_1) is twice as massive as object two (M_2). Therefore, M_1 is closer to the center of mass than is M_2. In the case shown here, $X_2 = 2X_1$.

the center of mass located relative to the orbits? What does $q = 1.0$ mean? Describe what is going on here. **(4 points)**

Ok, now we want to run a simulation where only the mass ratio is going to be changed. Go back to Input and enter in the correct mass ratio for a binary star system with $M_1 = 4.0$, and $M_2 = 1.0$. Run the simulation. Describe what is happening in this simulation. How are the stars located with respect to the center of mass? Why? [Hint: see Fig. 4.6.] **(4 points)**

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

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

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

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

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

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

Sun, or into a planet, or cause it to be ejected completely out of the solar system. (You can see an example of the latter process by changing the Planet–Star Distance = 0.4 in the current simulation.)

4.5 Summary (35 points)

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

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

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

4.6 Possible Quiz Questions

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

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

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

Name:_________________________________

Date:_________________________________

5 The Orbit of Mercury

5.1 Introduction

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

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

Mercury and Venus are called "inferior" planets because their orbits are interior to that of the Earth. While the planets Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto are called "superior" planets, as their orbits lie outside that of the Earth. Because the orbits of Mercury and Venus are smaller than the Earth's, these planets can never be located very far from the Sun as seen from the Earth. As discovered by Galileo in 1610 (see Fig. 5.1), the planet Venus shows phases that look just like those of the Moon. Mercury also shows these same phases. As can be envisioned from Figure 5.1, when Mercury or Venus are on the far side of the Sun from Earth (a configuration called "superior" conjunction), these two planets are seen as "full". Note, however, that it is almost impossible to see a "full" Mercury or Venus because at this time the planet is very close to, or behind the Sun. When Mercury or Venus are closest to the Earth, a time when they pass between the Earth and the Sun (a configuration termed "inferior" conjunction), we would see a "new" phase. During their new phases, it is also very difficult to see Mercury or Venus because their illuminated hemispheres are pointed away from us, and they are again located *very* close to the Sun in the sky.

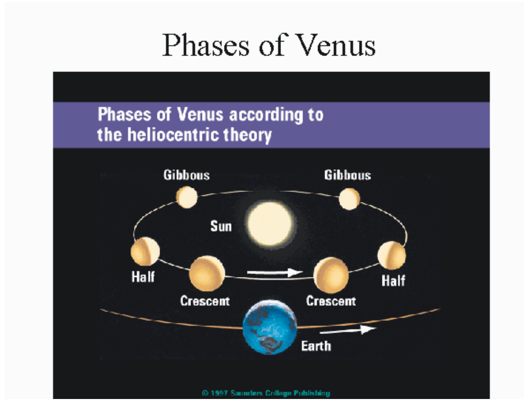


Figure 5.1: A diagram of the phases of Venus as it orbits around the Sun. The planet Mercury exhibits the same set of phases as it too is an "inferior" planet like Venus.

The best time to see Mercury is near the time of "greatest elongation". At the time of greatest elongation, the planet Mercury has its largest *angular* separation from the Sun as seen from the Earth. There are six or seven greatest elongations of Mercury each year. At the time of greatest elongation, Mercury can be located up to 28° from the Sun, and sets (or rises) about two hours after (or before) the Sun. In Figure 5.2, we show a diagram for the greatest elongation of Mercury that occurred on August 14, 2003. In this diagram, we plot the positions of Mercury and the Sun at the time of sunset (actually just a few minutes before sunset!). As this diagram shows, if we started our observations on July 24th, Mercury would be located close to the Sun at sunset. But as the weeks passed, the angle between Mercury and the Sun would increase until it reached its maximum value on August 14th. After this date, the separation between the Sun and Mercury quickly decreases as it heads towards inferior conjunction on September 11th.

You can see from Figure 5.2 that Mercury is following an orbit around the Sun: it was "behind" the Sun (superior conjunction) on July 5th, and quickly races around its orbit until the time of greatest elongation, and then passes between the Earth and the Sun on September 11th. If we used a telescope and made careful drawings of Mercury throughout this time, we would see the phases shown in Figure 5.3. On the first date in Figure 5.2 (July 24th), Mercury was still on the far side of the Sun from the Earth, and almost had a full phase (which it only truly has at the time of superior conjunction). The disk of Mercury on July 24th is very small because the planet is far away from the Earth. As time passes, however, the apparent size of the disk of Mercury grows in size, while the illuminated portion of the disk decreases. On August 14th, Mercury reaches greatest elongation, and the disk is half-illuminated. At this time it looks just like the first quarter Moon! As it continues to catch up with the Earth, the distance between the two planets shrinks, so the apparent size of Mercury continues to grow. As the angular separation between Mercury and the Sun shrinks, so does the amount of the illuminated hemisphere that we can see. Eventually Mercury becomes a crescent, and at inferior conjunction it becomes a "new" Mercury.

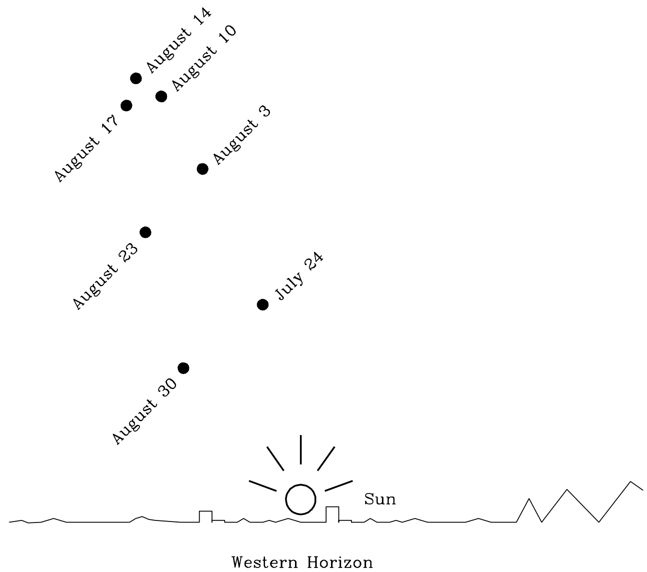


Figure 5.2: The eastern elongation of August, 2003. Mercury was at superior conjunction on July 5th, and quickly moved around its orbit increasing the angular separation between it and the Sun. By July 24th, Mercury could be seen just above the Sun shortly after sunset. As time passed, the angular separation between the Sun and Mercury increased, reaching its maximum value on August 14th, the time of greatest Eastern elongation. As Mercury continued in its orbit it comes closer to the Earth, but the angular separation between it and the Sun shrinks. Eventually, on September 11th, the time of inferior conjunction, Mercury passed directly between the Earth and the Sun.

5.1.1 Eastern and Western Elongations

The greatest elongation that occurred on August 14, 2003 was a "greatest Eastern elongation". Why? As you know, the Sun sets in the West each evening. When Mercury is visible *after* sunset it is located to the East of the Sun. It then sets in the West *after* the Sun has set. As you can imagine, however, the same type of geometry can occur in the morning sky. As Mercury passed through inferior conjunction on September 11th, it moved into the morning sky. Its angular separation from the Sun increased until it reached "greatest Western elongation" on September 27th, 2003. During this time, the phase of Mercury changed from "new" to "last quarter" (half). After September 27th the angular separation between the Sun and Mercury shrinks, as does the apparent size of the disk of Mercury, as it reverses the sequence shown in Figure 5.3. A diagram showing the geometry of eastern and western elongations is shown in Figure 5.4. [Another way of thinking about what each of these means, and an analogy that might come in useful when you begin plotting the orbit of Mercury, is to think about where Mercury is relative to the Sun at Noon. At Noon, the Sun is due south, and

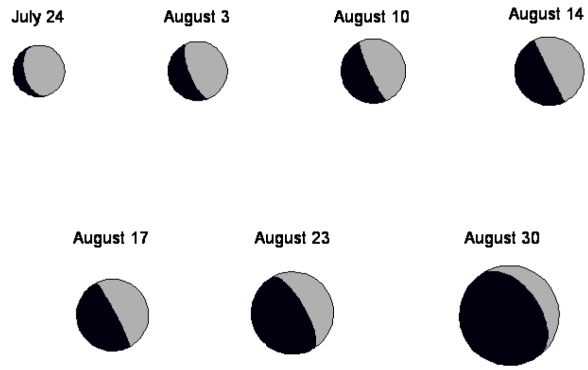


Figure 5.3: A diagram showing the actual appearance of Mercury during the August 2003 apparition. As Mercury comes around its orbit from superior conjunction (where it was "full"), it is far away from the Earth, so it appears small (as on July 24th). As it approaches greatest elongation (August 14th) it gets closer to the Earth, so its apparent size grows, but its phase declines to half (like a first quarter moon). Mercury continues to close its distance with the Earth so it continues to grow in size–but note that the illuminated portion of its disk shrinks, becoming a thin crescent on August 30th. As Mercury passes between the Earth and Sun it is in its "new" phase, and is invisible.

when facing the Sun, East is to the left, and West is to the right. Thus, during an Eastern elongation Mercury is to the left of the Sun, and during a Western elongation Mercury is to the right of the Sun (as seen in the Northern Hemisphere).]

5.1.2 Why Greatest Elongations are Special

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

Of course, plotting only one elongation is not sufficient to figure out the orbit of Mercury–you need to plot many elongations. In today's lab exercise, you will plot thirteen greatest

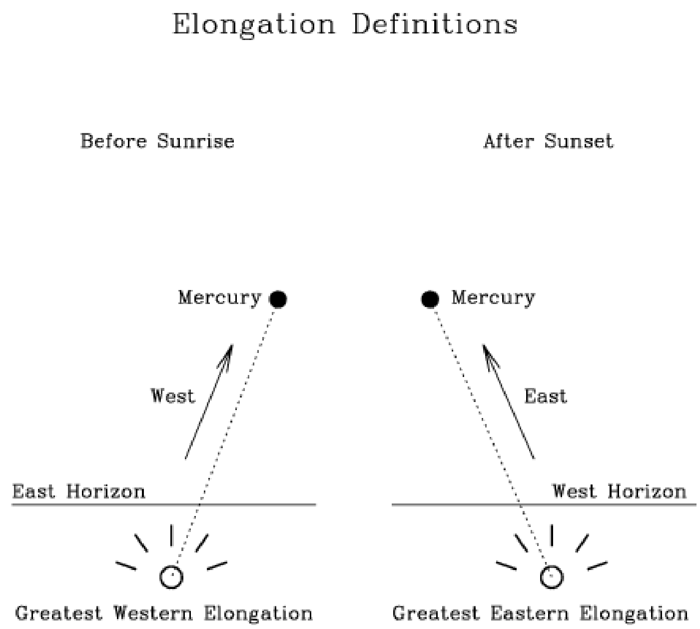


Figure 5.4: A diagram showing the geometry of greatest Western elongations (left side), and greatest Eastern elongations (right side). If you see Mercury–or any other star or planet–above the Western horizon after sunset, that object is located to the East of the Sun. The maximum angular separation between Mercury and the Sun at this time is called the greatest Eastern elongation. A greatest Western elongation occurs when Mercury is seen in the East *before* sunrise.

elongations of Mercury, and trace-out its orbit. There are a lot of angles in this lab, so you need to get comfortable with using a protractor. Your TA will help you figure this out. But the most critical aspect is to not confuse eastern and western elongations. Look at Figure 5.5 again. What kind of elongation is this? Well, as seen from the Earth, Mercury is to the left of the Sun. As described earlier (in the square brackets at the end of subsection 5.1.1), if Mercury is to the left of the Sun, it is an *eastern elongation*.

5.2 The Orbits of Earth and Mercury

As shown in the previous diagram, both the Earth and Mercury are orbiting the Sun. That means that every single day they are at a different position in their orbits. Before we can begin this lab, we must talk about how we can account for this motion! A year on Earth,

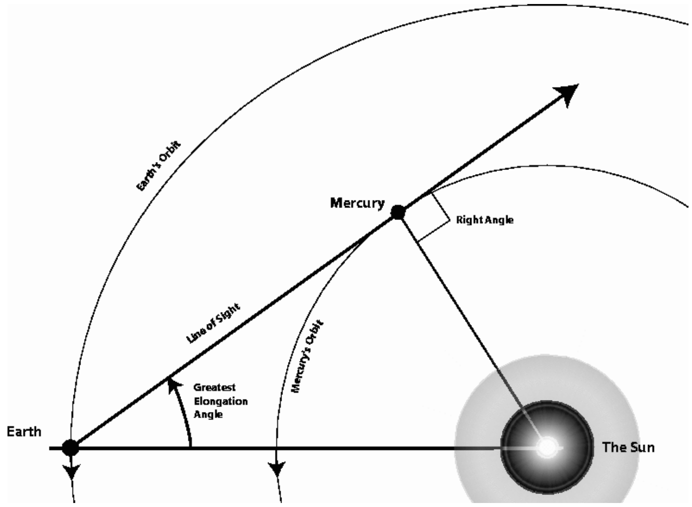


Figure 5.5: A diagram showing the orbital geometry of the Earth and Mercury during a greatest Eastern elongation. The orbits of the Earth and Mercury are the two large circles. The line of sight to Mercury at the time of greatest elongation is indicated. Note that at this time the angle between the Earth, Mercury, and the Sun is a *right* angle. The direction of motion of the two planets is shown by the arrows on the orbits.

the time it takes the Earth to complete one orbit around the Sun, is 365 days. If we assume that the Earth's orbit is a perfect circle, then the Earth moves on that circle by about 1 degree per day. Remember that a circle contains 360 degrees (360°). If it takes 365 days to go 360°, the Earth moves 360°/365 = 0.986 degrees per day (°/day). For this lab, we will assume that the Earth moves exactly one degree per day which, you can see, is very close to the truth. How far does the Earth move in 90 days? 90 degrees! How about 165 days?

5.2.1 The Data

In Table 5.1, we have listed the thirteen dates of the greatest elongations of Mercury, as well as the angle of each greatest elongation. **Note that the elongations are either East or West!** In the third column, we have listed something called the Julian date. Over long time intervals, our common calendar is very hard to use to figure out how much time has elapsed. For example, how many days are there between March 13^{th}, 2001 and December 17^{th} 2004? Remember that 2004 is a leap year! This is difficult to do in your head. To avoid such calculations, astronomers have used a calendar that simply counts the days that have passed since some distant day #1. The system used by astronomers sets Julian date 1 to January 1^{st}, 4713 BC (an arbitrary date chosen in the sixteenth century). Using this calendar, March 13^{th}, 2001 has a Julian date of 2451981. While December 17^{th} 2004 has a Julian date of 2453356. Taking the difference of these two numbers (2453356 − 2451981) we find that there are 1,375 days between March 13^{th}, 2001 and December 17^{th} 2004.

Exercise #1: Fill-in the Data Table
The fourth and fifth columns of the table are blank, and must be filled-in by you. The fourth

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

Table 5.1: Elongation Data For Mercury

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

Exercise #2: Plotting your data.
Before we describe the plotting process, go back and review Figure 5.5. Unlike that diagram, you do not know what the orbit of Mercury looks like–this is what you are going to figure out during this lab! But we do know two things: the first is that the Earth's orbit is nearly a perfect circle, and two, that the Sun sits at the exact center of this circle. On the next page is a figure containing a large circle with a dot drawn at the center to represent the Sun. At one position on the large circle we have put a little "X" as a reference point. The large circle here is meant to represent the Earth's orbit, and the "X" is simply a good starting point.

To plot the first elongation of Mercury from our data table, using a pencil, draw a line connecting the X, and the Sun using a straight edge (ruler or protractor). The first elongation in the table (September 1, 2002) is 27.2 degrees East. Using your protractor, put the "X" that marks the Earth's location at the center hole/dot on your protractor. Looking back to Figure 5.5, that elongation was also an *eastern* elongation. So, using that diagram as a guide, measure an angle of 27.2 degrees on your protractor and put a small mark on the worksheet. Now, draw a line from the Earth's location through this mark just like the “line of sight” arrow in Figure 5.5. Now, rotate your protractor so that the 90 degree mark is on this line and towards the position of the Earth, while the reference hole/dot is on the same line. Slide the protractor along the line until the 0° (or 180°) reference line intersects the center of the Sun. Mark this spot with a dark circle. This is the position of Mercury!

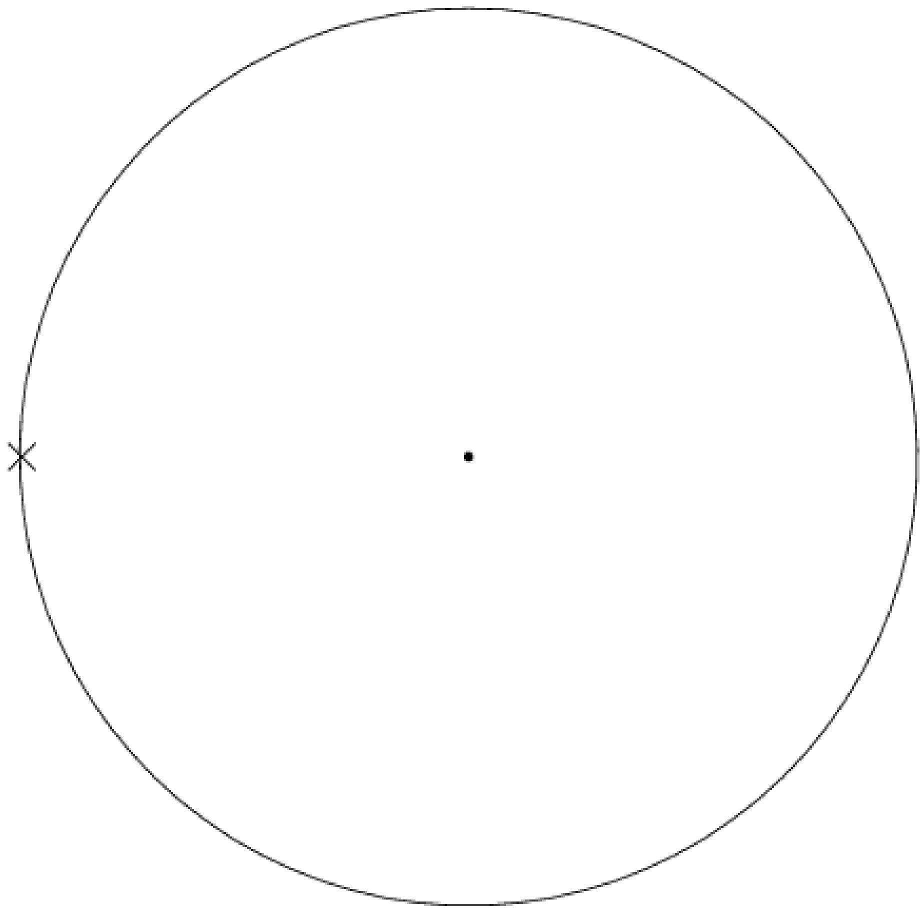
This is the procedure that you will use for all of the elongations, so if this is confusing to you, have your TA come over and clarify the technique for you so that you don't get lost and waste time doing this incorrectly.

Ok, now things become slightly more difficult—the Earth moves! Looking back to Figure 5.5, note the arrows on the orbits of Earth and Mercury. This is the direction that both planets are moving in their orbits. For the second elongation, the Earth has moved 42 degrees. We have to locate where the Earth is in its orbit before we can plot the next elongation. So, now put the center hole/dot of your protractor on the Sun. Line up the 0/180 degree mark with the first line that connected the Earth and Sun. Measure an angle of 42 degrees (in the correct direction) and put a small mark. Draw a line through this mark that intersects the position of the Sun, the mark, and the orbit of the Earth. Put an X where this line intersects the Earth's orbit. This is the spot from where you will plot the next elongation of Mercury.

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

[Hints: It is helpful to label each one of the X's you place on the Earth's orbit with the elongation number from Table 5.1. This will allow you to go back and fix any problems you might find. Note that you will have a large number of lines drawn in this plot by the time you get finished. Use a sharp pencil so that you can erase some/all/pieces of these lines to help clean-up the plot and reduce congestion. You might also find it helpful to simply put a “left” or a “right” each time you encounter East and West in Table 5.1 to insure you plot your data correctly.]

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



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$P_{\rm orb}$(Mercury) = ________________ days.

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

5.3 Summary (35 points)

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

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

5.4 Possible Quiz Questions

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

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

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

Name:______________________________
Date:______________________________

6 Scale Model of the Solar System

6.1 Introduction

The Solar System is large, at least when compared to distances we are familiar with on a day-to-day basis. Consider that for those of you who live here in Las Cruces, you travel 2 kilometers (or 1.2 miles) on average to campus each day. If you go to Albuquerque on weekends, you travel about 375 kilometers (232.5 miles), and if you travel to Disney Land for Spring Break, you travel ∼ 1,300 kilometers (∼ 800 miles), where the '∼' 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 (∼ 7,900 miles), or 10 times the Las Cruces-to-Los Angeles distance. Obviously, such a trip is impossible–to get to the southern Indian Ocean, you would need to travel on the surface of the Earth. How far is that? Since the Earth is a sphere, you would need to travel 20,000 km to go halfway around the Earth (remember the equation Circumference = 2πR?). This is a large distance, but we'll go farther still.

Next, we'll travel to the Moon. The Moon, Earth's natural satellite, orbits the Earth at a distance of ∼ 400,000 kilometers (∼ 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 ∼ 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*, ∼ 150 million kilometers (∼ 93 million miles), is referred to as one **Astronomical Unit** (AU). When we look at the planets in our Solar System, we can see that the planet Mercury, which orbits nearest to the Sun, has an average distance of 0.4 AU and Pluto, the planet almost always the furthest from the Sun, has an average distance of 40 AU. Thus, the Earth's distance from the Sun is only 2.5 percent of the distance between the Sun and planet Pluto!! Pluto is very far away!

The purpose of today's lab is to allow you to develop a better appreciation for the distances between the largest objects in our solar system, and the physical sizes of these objects relative to each other. To achieve this goal, we will use the length of the football field in Aggie

Memorial Stadium as our platform for developing a scale model of the Solar System. A *scale model* is simply a tool whereby we can use manageable distances to represent larger distances or sizes (like the road map of New Mexico used in Lab #1). We will properly distribute our planets on the football field in the same *relative* way they are distributed in the real Solar System. *The length of the football field will represent the distance between the Sun and the planet Pluto.* We will also determine what the sizes of our planets should be to appropriately fit on the same scale. Before you start, what do you think this model will look like?

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

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

6.2 The Distances of the Planets From the Sun

Fill in the first and second columns of Table 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 6.1: Planets' average distances from Sun.

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

Next, we need to convert the distance in AU into the unit of a football field: the yard. This is called a "scale conversion". Determine the SCALED orbital semi-major axes of the planets, based upon the assumption that the Sun-to-Pluto average distance in Astronomical Units (which is already entered into the table, above) is represented by 100 yards, or goal-line to goal-line, on the football field. To determine similar scalings for each of the planets, you must figure out how many yards there are per AU, and use that relationship to fill in the values in the third column of Table 6.1.

6.3 Sizes of Planets

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

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

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

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

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

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

Using this equation, fill in the values in Table 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

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

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

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

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

large, we can actually see that it is a round object with our naked eyes (unlike the planets, 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!

6.4 Questions About the Football Field Model

When all of the "planets" are in place, note the relative spacing between the planets, and the size of the planets relative to these distances. 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× that of its current value! When this happens, some of the innermost planets in our solar system will be "swallowed-up" by the Sun. Which ones? (**5 points**).

6.5 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 6.4: Planets' average distances from Sun.

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

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

Object	Actual Diameter (km)	Scaled Diameter (feet)	Object
Sun	$\sim$ 1,400,000	561.7	
Mercury	4,878		
Venus	12,104		
Earth	12,756	5.1	height of 12 year old
Mars	6,794		
Jupiter	142,800		
Saturn	120,540		
Uranus	51,200		
Neptune	49,500		
Pluto	2,200	0.87	soccer ball


COLORADO
Aztec
FARMINGTON
Shiprock
Bloomfield
NAVAJO
Chama
Raton
Taos
Questa
Eagle Nest
Cimarron
Española
Los Alamos
White Rock
SANTA FE
LAS VEGAS
GALLUP
Milan
Grants
ALBUQUERQUE
Bernalillo
Moriarty
Santa Rosa
Belen
Los Lunas
Mountainair
Magdalena
Socorro
Carrizozo
Ruidoso
ROSWELL
Tularosa
ALAMOGORDO
Truth or Consequences
Silver City
Hatch
LAS CRUCES
Deming
Lordsburg
Mesilla
Artesia
TEXAS
GOUSHA
N

6.6 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"?

6.7 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:________________________________
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, $inches^3$, $miles^3$).

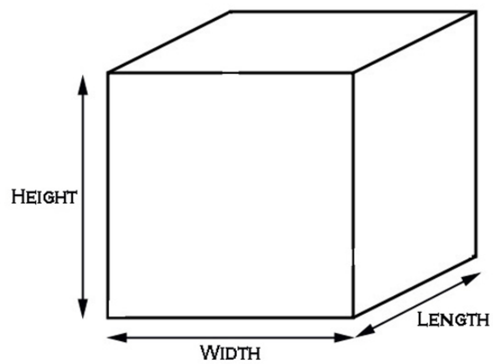


Figure 7.1: A rectangular solid has sides of length, width, and height.

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, a "Eureka" can (or overflow vessel), a container of water, and an empty plastic cup. 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*. 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, and the Eureka can. Fill the tin can with water until it comes out of the spout (you might use one of your graduated cylinders to collect the overflow). Take your finger and pass it under the bottom of the spout to remove the drop of water that (usually) clings to the spout. Now, hold the appropriate sized, empty, dry, graduated cylinder under the spout and drop in the first object. Read the graduated cylinder to find how much water was displaced, *the volume*, and record this value 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. Using a big cylinder with a small object will lead to errors, as the big cylinders are harder to

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

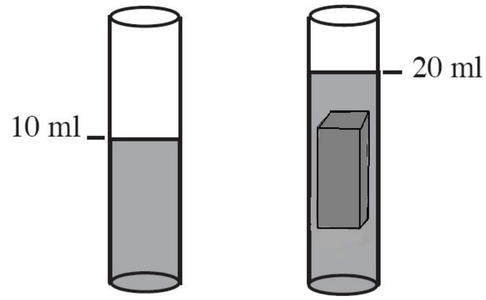


Figure 7.2: The rectangular object displaces 10 ml of water. Therefore, it has a volume of 10 ml = 10 cm^3.

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

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

Object Column #1	**Mass (g)** #2	Volume of Water (ml) #3	**Volume** cm^3 #4	**Density** g/cm^3 #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.

measure the volume of the five metal "cubes" (do not assume they are perfect cubes!) using 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?

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

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

$$\text{r} = \text{Volume(Gabbro)/Volume(Pumice)} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \ \%$$

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:

$$1 - \text{r} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \ \%$$

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, well first determine Earth's circumference (which will lead us to the Earth's radius and then to the Earth's volume) and then determine the Earth's mass.

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:

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

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

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

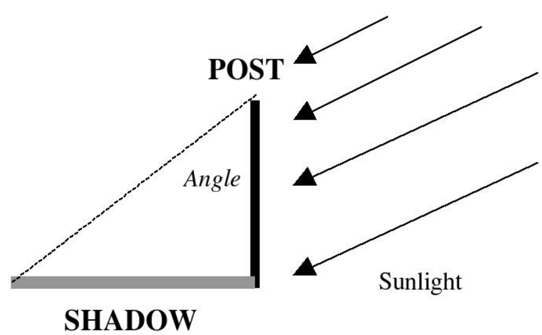


Figure 8.1: The geometry of a vertical post sitting in sunlight.

Calculate the shadow angle for each of your three shadow-length measurements, and also for the Boulder, Colorado shadow-length measurement. Write these angle values in the appropriate locations in Table 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. 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:

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

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

AVERAGE EARTH RADIUS VALUE = $\mathbf{R_E}$ = ____________________ kilometers (3 points)

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 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 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.

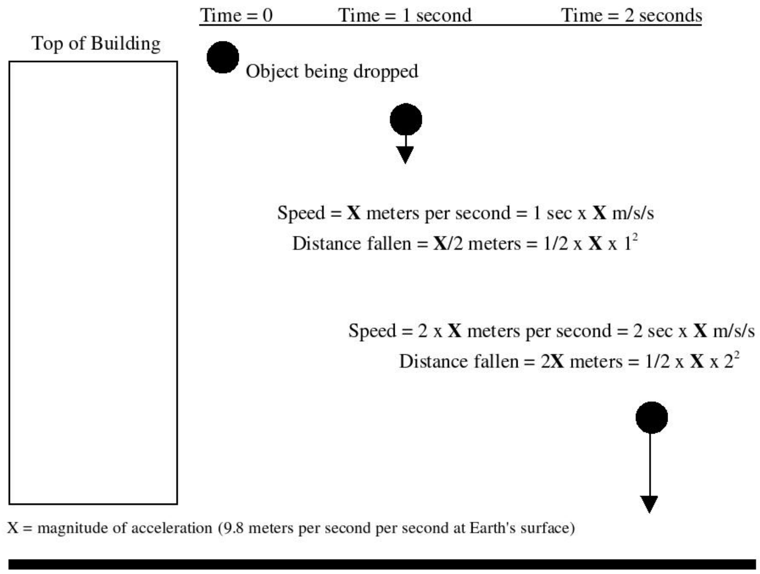


Figure 8.2: The distance a dropped object will fall during a time interval t is proportional to t^2. A dropped object speeds up as it falls, so it travels faster and faster and falls a greater distance as t increases.

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

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

since:

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

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 =			

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

$\mathbf{M_E}$ **= Average Acceleration** $\times$ $(\mathbf{R_E})^2$ **/ 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!*:

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

  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:	______________________	**m**^{3} (4 points)
Estimate of Earth's Density:	____________________	**kg/m**^{3} (4 points)
Converted Density of the Earth:	___________________	**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 π)? 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 Reflectance Spectroscopy

9.1 Introduction

With this lab, we will look at the wavelength dependence of the visible reflectance of various objects, and learn what this can tell us about the composition of those objects. This is one technique by which we determine the composition of various solar system objects (*e.g.* Martian rocks, asteroids, clouds on Jupiter). We will specifically apply this method of investigation, using a hand-held reflectance spectrometer, to the reflectance characteristics of several different colored sheets of construction paper. We will then use these known spectra for different colors to identify some "mystery" objects for which we know only their reflectance as a function of wavelength.

We will use an ALTA reflectance spectrometer for this lab. This is an instrument that can quantitatively measure the reflectance in nine wavelength channels covering visible and near infrared wavelengths. The ALTA reflectance spectrometer provides measurements in units of millivolts. As the intensity of the measured (reflected) light changes, the displayed number (voltage) will change in the same proportion. That is, if the intensity of measured reflected light decreases by a factor of two, the displayed value will also decrease by a factor of two. What we will ultimately be interested in for each wavelength and for each object is the percentage of incident light that is reflected. That is, if all the light of a particular wavelength is reflected, that object has a 100% reflectance at that wavelength. If none of the incident light is reflected (it is all absorbed), the object has a zero-percent reflectance at that wavelength.

When we apply reflectance spectroscopy to solar system objects, the Sun is the source of the light that is reflected. Thus, if we know the spectral characteristics (intensity as a function of wavelength) of the Sun, we can measure the intensity of reflectance at our chosen wavelengths accurately. With the ALTA reflectance spectrometer, we do not use sunlight as our 'source'. Rather, the spectrometer itself has nine bulbs (arranged in a circular pattern) that emit light of specified wavelengths (indicated on the buttons on the front of the instrument) and one detector which measures reflected radiation. The emitted light reflects off the object of interest and is measured by the detector located at the center of the circular pattern of bulbs. By proceeding through the nine wavelengths, we obtain the intensity of reflected light at each wavelength, and from this we can determine the reflectance spectrum of our objects of interest.

9.2 Exercises

Start by pressing one of the wavelength buttons on the front of the spectrometer and while depressing this button, turn the spectrometer over. You should see one of the bulbs arranged in a circular pattern illuminated (unless you are pressing one of the two near-infrared wavelength buttons). Release the button you are holding and press a different button; you should now see a different bulb illuminated. Remember, the 'bulb' at the center is actually the detector, which measures the reflected light.

1. Our first order of business is to determine what the instrument signal is when no light is available. This is called the *dark voltage* value and must be subtracted from all subsequent measurements with the spectrometer. Turn the spectrometer on and set it down on the table; the value currently in the display area is the dark voltage. Write this number down, as it will be subtracted from all subsequent measured values. Also write the unit number or letter of the spectrometer. (**2 points**)

   DARK VOLTAGE READING = ______________________________
   SPECTROMETER # or Letter = ______________________________
   (located in the upper right corner on the front of the spectrometer)

2. Now, since our spectrometer is not calibrated (we do not know what millivolt values to expect for 100 percent reflection, and there is no reason why this value must be the same for each wavelength), we will use a piece of white poster board to determine the 'standard' against which our reflectance spectra of several colored papers will be compared. In order to do this, we will measure the value (in millivolts) of reflected light from the white poster board for each of the nine wavelength channels of the spectrometer. Do this by:

   - Placing the spectrometer onto the white poster board
   - Sequentially pressing the nine wavelength buttons on the spectrometer
   - While pressing each button, note the millivolt value that appears in the display and write this value down in Measured Value column of Table 9.1 for the appropriate wavelength

   Remember, we are measuring the intensity of the light that has been: a) emitted by the spectrometer bulb, then b) reflected off the poster board, and then finally, c) measured by the spectrometer.

   Since it is a white surface that we are measuring the reflectance from, we will expect that the reflectance (percent of light reflected) will not vary too much among the nine wavelengths (since 'white' is the combination of all wavelengths). We will assume that each wavelength is 100 percent reflected from the white surface. After determining the measured 'calibration' values for each wavelength, subtract the 'Dark Voltage' value from these calibration values to obtain the 'standard' value for each wavelength, and write these values in the right-hand column of Table 9.1. (**9 points**)

Wavelength (nanometers)	**Measured Value** (millivolts)	**Standard** (Measured - Dark Voltage)
470		
555		
585		
605		
635		
660		
695		
880		
940		

Table 9.1: White poster board calibration determination. (Recall that 1 nanometer = 10^{-9} m = 1 billionth of a meter.)

3. Rather than comparing the reflectance spectra of rocks on Mars, as the Mars Pathfinder camera did, or clouds on Jupiter (as the Voyager and Galileo spacecraft have done), you will obtain and compare the reflectance spectra of several different colors of construction paper. When you have measured the spectra of the three pieces of colored paper, you will plot their spectra.

   For each piece of colored paper,

   - Measure the reflectance of that piece of paper at each wavelength in the same manner as you determined the spectrometer's 'Measured Value' above, writing the corresponding millivolt value for each wavelength in the Meas. column in Table 9.2.
   - For each wavelength for each piece of paper, calculate the Measured minus Dark Voltage value. To do this, subtract your instrument's Dark Voltage value from the Meas. column value at each wavelength for each colored piece of paper.
   - Determine the Reflectance value of each colored sheet of paper at each wavelength using the formula below, in which 'STANDARD Value' is the value in the right-most column of Table 9.1 at the appropriate wavelength. The REFLECTANCE values you arrive at should have values between 0 and 1. Write your calculated reflectance values in the "Reflect." columns of Table 9.2 for the appropriate colored piece of paper. (**20 points**)

   $$\textbf{Reflectance} = \frac{\textbf{MeasuredValue} - \textbf{DarkValue}}{\textbf{STANDARDValue}}$$

4. On the sheets of graph paper at the end of this lab, plot the Reflectance values [column 3 Reflect. values in Table 9.2] you have calculated for each of the 3 colored pieces of paper. For each piece of colored paper and the calculated Reflectance values, draw a dot at the appropriate Reflectance value (y-axis) and appropriate wavelength point (x-axis). After you have drawn all 9 dots for a single sheet of colored paper, connect the

λ	Red Paper			Green Paper			Blue Paper		
(nm)	Meas.	Meas.-Dark	Reflect.	Meas.	Meas.-Dark	Reflect.	Meas.	Meas.-Dark	Reflect.
470									
555									
585									
605									
635									
660									
695									
880									
940									

Table 9.2: ALTA Reflectance Spectrometer Values (millivolts)

dots. This curve you have drawn is a **Reflectance Spectrum.** Repeat this procedure for your Reflectance results for the other two sheets of colored paper. Clearly label your three resulting curves. (**15 points**)

5. Compare your three curves (reflectance spectra of the colored sheets of paper) with the spectra of the two mystery objects (A and B). The two mystery curves are the spectra for two separate objects. These objects are included among those listed below. Using your knowledge of the color of the objects in the list below, a) determine which object each of the mystery spectra corresponds to, and b) describe below how you have made this determination. You may find it useful to refer to Figure 6.6 on page 157 of your text to relate wavelength to color. (**7 points each**)

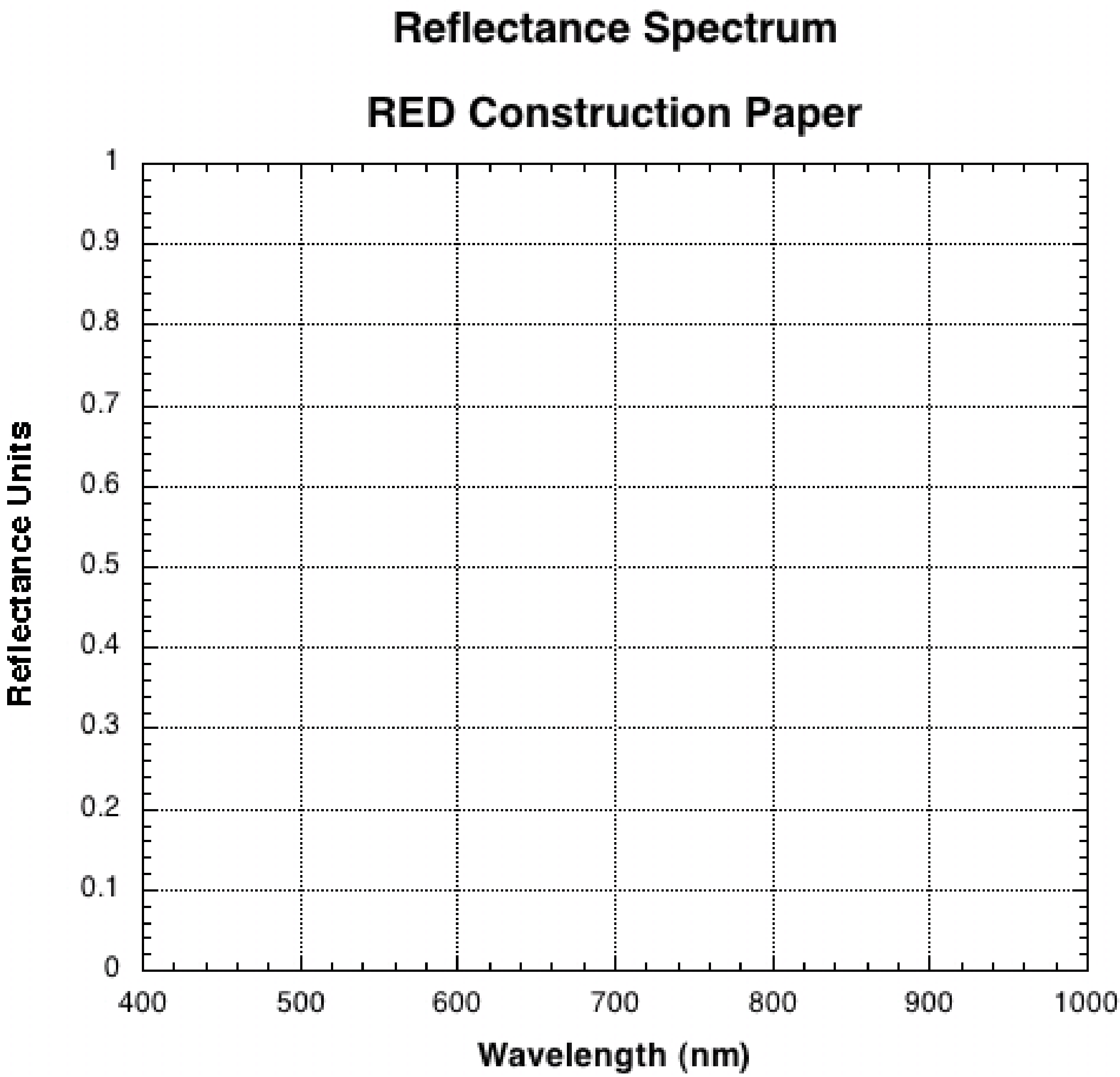
Tomato	blade of grass	White Paper
Black Paper	Eggplant	Navel Orange
Pink Flamingo	Neptune (page 215 of text)	Lemon

Object #   :

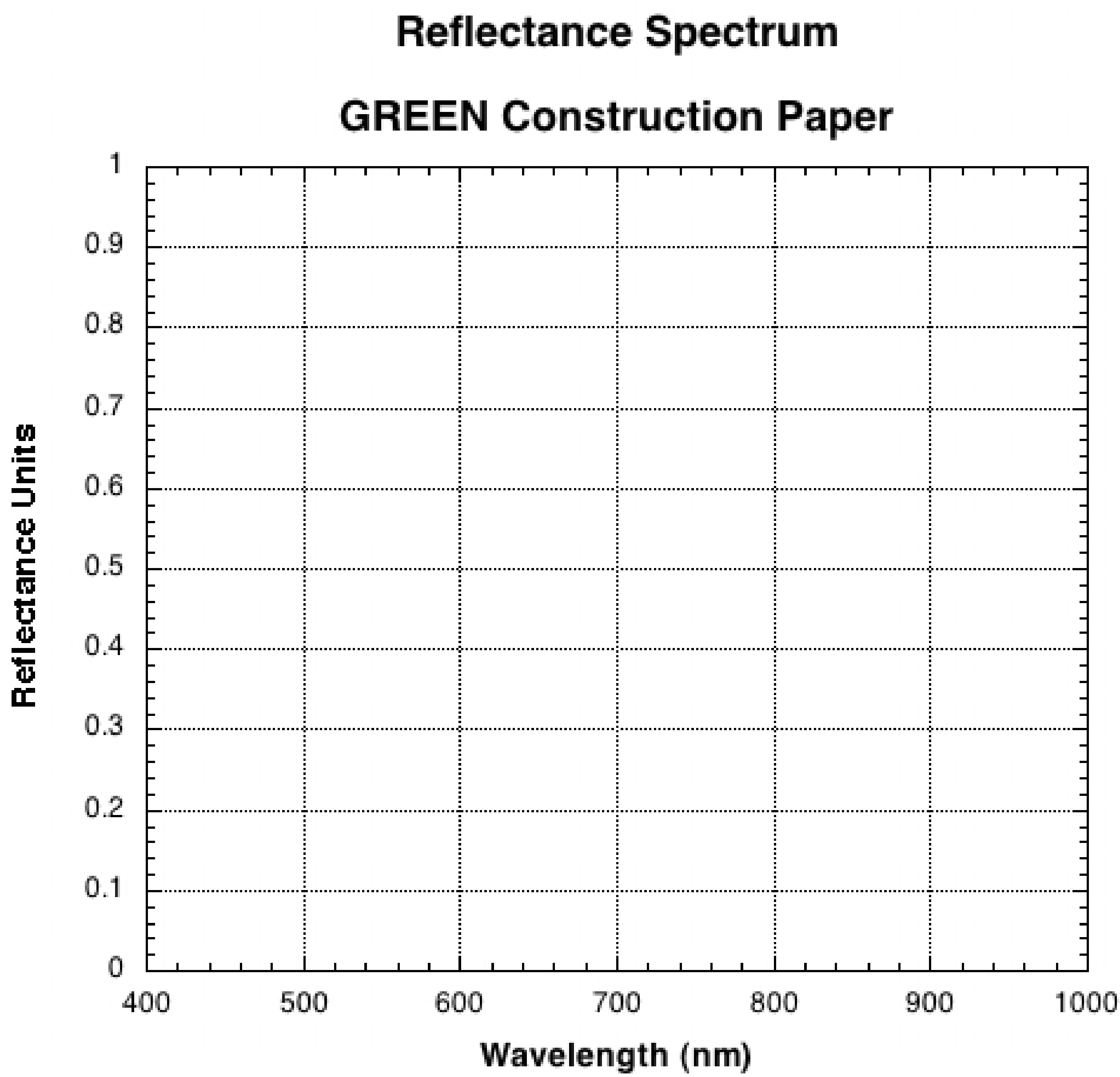
Object #   :

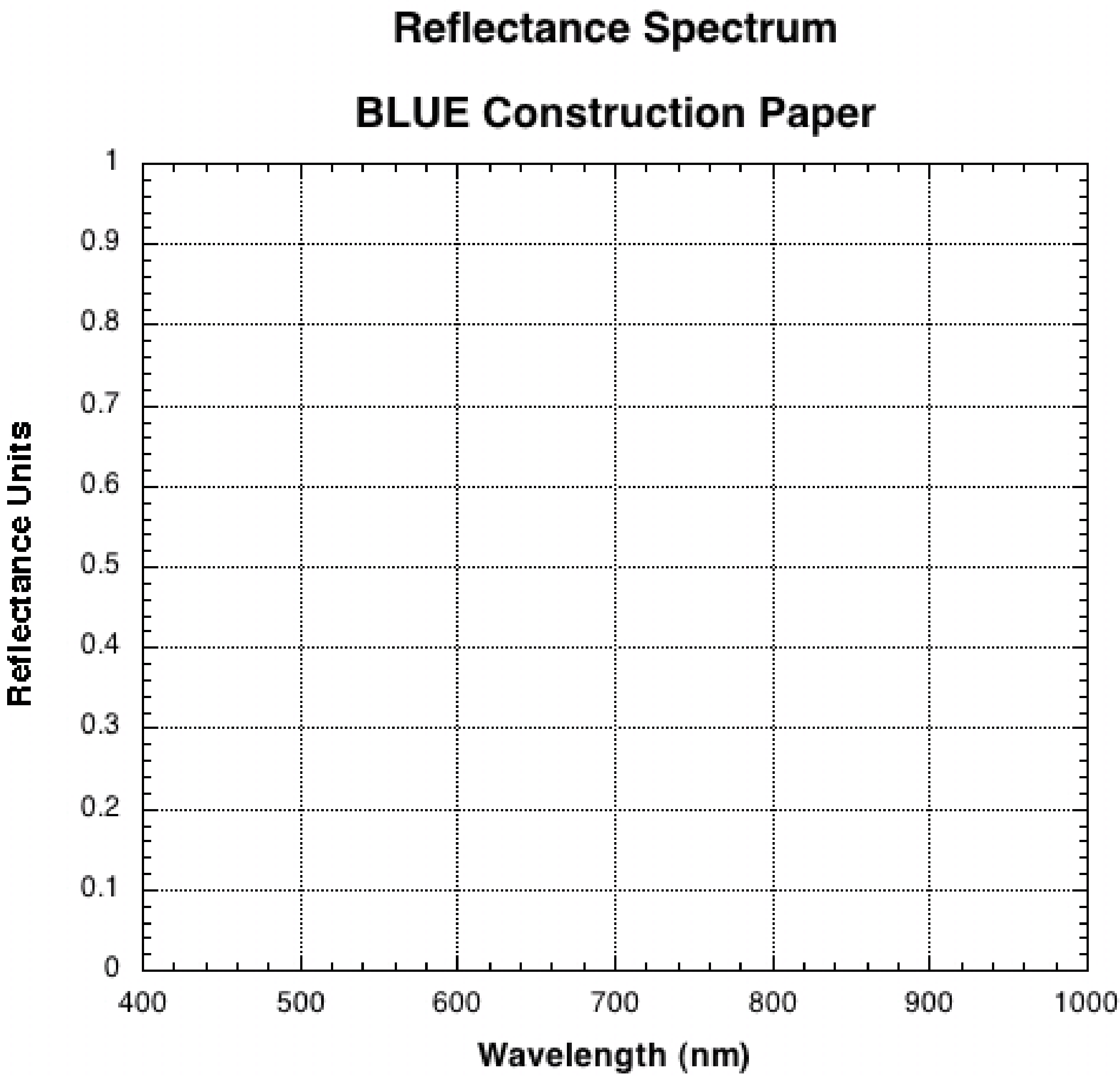
Mystery Planet:

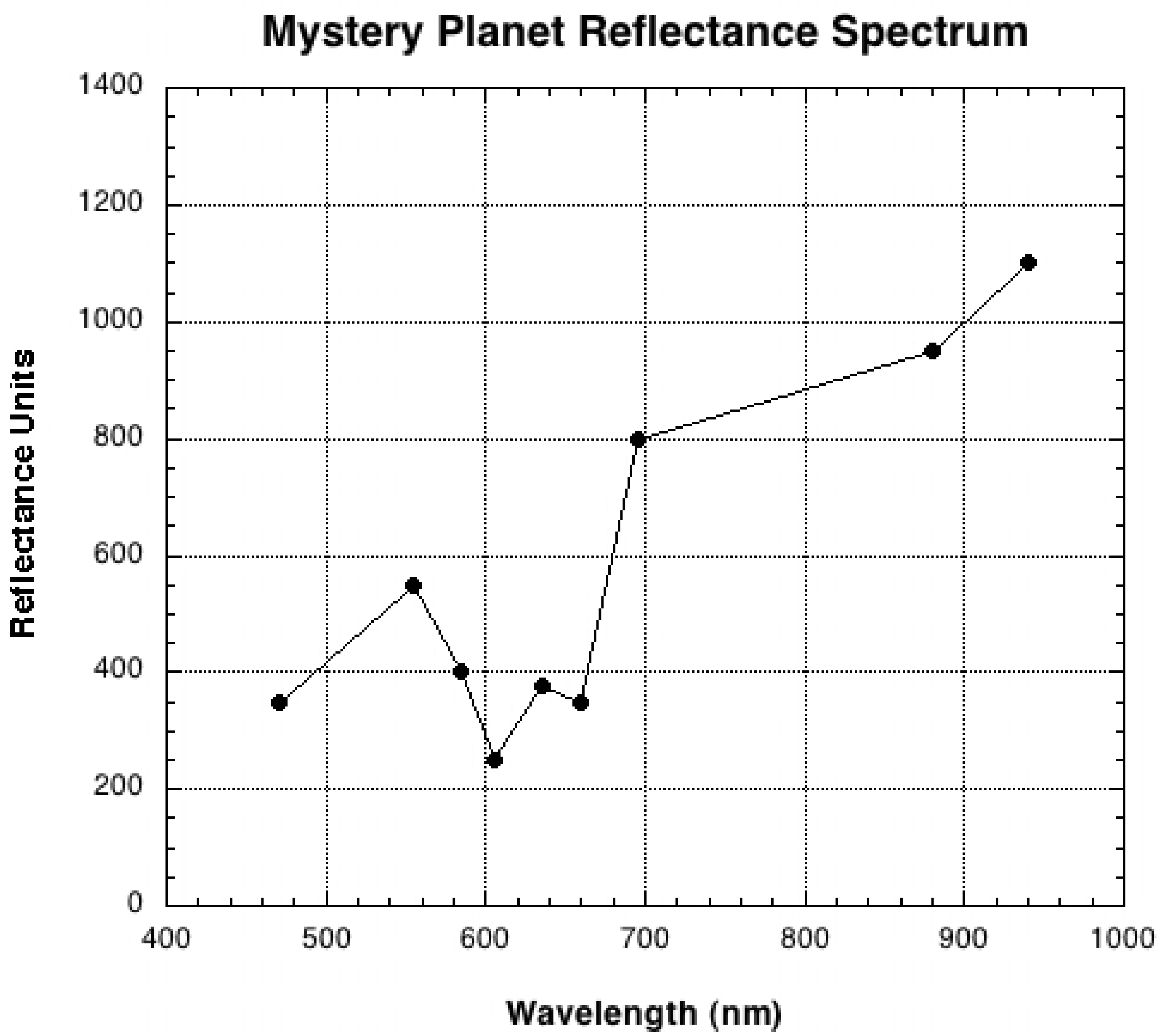
The last graph in this lab shows a reflectance spectrum for a newly discovered planet that was just visited by a NASA spacecraft. Does this planet have vegetation on its surface? Justify your answer. (**5 points**)



Reflectance Spectrum
RED Construction Paper
Reflectance Units
Wavelength (nm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
400
500
600
700
800
900
1000


Reflectance Spectrum
GREEN Construction Paper
Reflectance Units
Wavelength (nm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
400
500
600
700
800
900
1000


Reflectance Spectrum
BLUE Construction Paper
Reflectance Units
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
400
500
600
700
800
900
1000
Wavelength (nm)


Mystery Planet Reflectance Spectrum
Reflectance Units
Wavelength (nm)
1400
1200
1000
800
600
400
200
0
400
500
600
700
800
900
1000

Name:________________________________
Date:_________________________________

9.3 Take Home Exercise (35 points total)

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

1. Why does the planet Jupiter appear brighter in the night sky than Mars, even though Mars is much closer to Earth than Jupiter? [Hint: the third column in Table 8.1 on page 200 of your textbook might be helpful.] (**10 points**)

2. Imagine that the colored lightbulbs in the Alta reflectance spectrometers emitted twice as much light as they actually do. In this brighter bulb situation, would you determine "Reflect." values that are the same as those you have written in Table 9.2, or would you determine different (larger, smaller) Reflect. values with these brighter bulbs? Why? (**10 points**)

3. Clearly describe a concept you have learned in this lab, or last week in class, during our discussions about radiation. Describe something that you have not already addressed by answering other questions in this lab. (**15 points**)

9.4 Possible Quiz Questions

1. What is meant by the term "wavelength of light"?
2. What are the physical units of wavelength?
3. What is the definition of the word "spectroscopy"?
4. If a blade of grass is "green", why does it look green?

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

Look up the spectrum of chlorophyll. Note that a spectrum can either be a "reflection" spectrum or an "absorption" spectrum. One is simply the inverse of the other. So, depending on the author's preference, they will plot one or the other type of spectrum for chlorophyll. Chlorophyll is why most plants look green. Describe how chlorophyll interacts with light. What does chlorophyll do for plants? Why do you think it works this way? Rocks, ices, and gases all have complicated spectra, absorbing some wavelengths of light, and reflecting (or transmitting) others. The uniqueness of the spectra of these items allows astronomers to determine the composition of an object by using spectroscopy.

Name:____________________________
Date:____________________________

10 Locating Earthquakes

10.1 Introduction

Because of convective motions in the mantle of the Earth, which are driven by heat transfer from the hotter interior regions up through the cooler crust, stresses build up in the outer rigid crust. Sometimes these stresses are relieved by abrupt slippages, or *earthquakes*, that generate shock waves that propagate outward from the quake site. Earthquakes can result in loss of lives and considerable damage to buildings as well as transportation and communication systems.

The actual slippage in Earth's crust usually occurs miles below the surface. The exact site is called the *focus* of the earthquake. The point on the Earth's surface directly above the focus is called the *epicenter*.

The shock waves generated by the quake are called *seismic* waves (from the Greek word "seismos," which means to shake). There are three types of waves. The first type is called **L waves**, which travel only on the Earth's surface and are similar to water waves on the ocean. Next are **P waves**, which are compressional waves, and can travel through gases, liquids or solids. The motion associated with **S waves**, which are shear waves, is perpendicular to the direction of motion. The S waves dissipate quickly in liquids and gases.

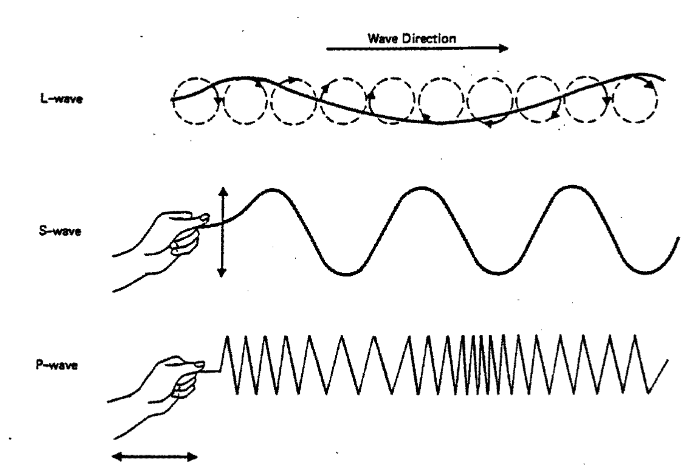


Figure 6–17. ***Three Types of Waves.*** **Earthquakes produce three types of waves. L-waves travel on the earth's surface. S-waves and P-waves travel through the earth.**

Figure 10.1: Different types of waves.

The P waves travel almost twice as fast as S waves, thus the P wave shock will arrive at a remote station before the S wave shock will. A *seismometer* is an instrument that consists of a massive base and a detector that picks up seismic waves. If the speed of the waves through the local crust is known and you have a seismometer so you can record the shocks, then at any single station you can determine how far you are from the focus of the quake.

Use the following graph to determine the average speed of the P and S waves for a typical Earth crust. Assume that we are going to be dealing with *shallow earthquakes* in the state of New Mexico, *i.e.,* those that have depths of 20 km or less. Put the wave speed values you read off of Figure 10.2 into Table 10.1. (**4 points**)

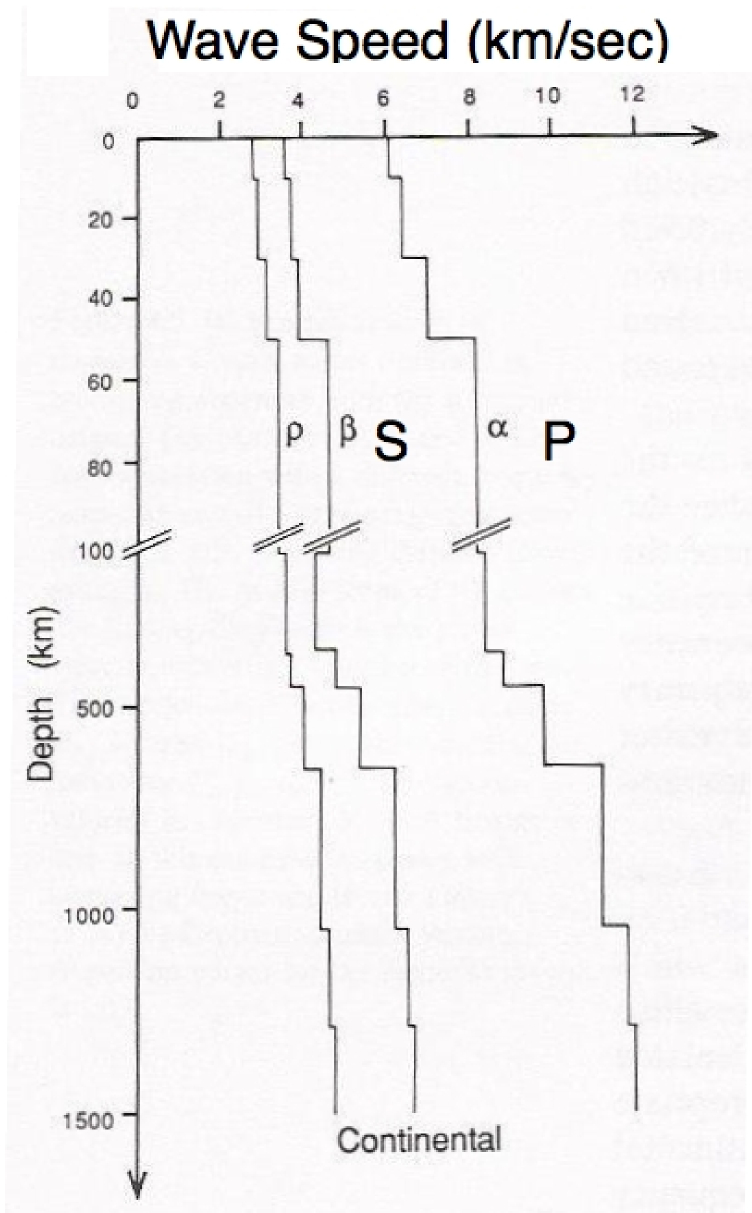


Figure 10.2: Wave speeds as a function of depth.

Type of Wave	Speed of Wave (km/sec)
P Wave	
S Wave	

Table 10.1: Comparison of P and S wave travel times.

10.2 Locating an Earthquake

10.2.1 Finding the Distances

Consider the problem of locating a small local quake. We will use real earthquake data from seismic stations in Alamogordo, Albuquerque, El Paso, Las Cruces, Santa Fe, and Socorro. The data for five different earthquakes that took place in New Mexico can be found at the end of this lab. Choose an earthquake for your group to analyze (tell your TA, as they might want different groups to do different earthquakes!). Write down which earthquake you are analyzing (numbers 1-5) in the space below:

Earthquake #: ________

Copy the P and S wave onset times from your data sheet for your earthquake into Table 10.2.

Table 10.2: P and S wave arrival times at six seismic stations.

Station	Onset of P wave	Onset of S wave	δt (sec)	dist. to focus (km)
Alamogordo				
Albuquerque				
El Paso				
Las Cruces				
Santa Fe				
Socorro, NM				

δt ("delta-t") is the difference between the arrival time of a P wave and the arrival time of an S wave at any given seismic station. Calculate δt for each of the six stations and place these values in Table 10.2. (**12 points**)

Now we must calculate the distance that the wave traveled from the earthquake's focus to each recording station. If X is the distance between the focus and the seismograph and $v_P = speed\ of\ P\ wave$ and $v_S = speed\ of\ S\ wave$, then:

$$\frac{X}{v_P} = t_P = time\ of\ travel\ for\ P\ wave \tag{9}$$

and

$$\frac{X}{v_S} = t_S = time\ of\ travel\ for\ S\ wave. \tag{10}$$

Since $\delta t = t_S - t_P$, substituting from Equations (1) and (2) above gives us

$$\delta t = \frac{X}{v_S} - \frac{X}{v_P}. \tag{11}$$

Equation (3) can be rewritten as

$$\delta t = \frac{(v_P \times X) - (v_S \times X)}{v_S \times v_P} \tag{12}$$

If we factor out X, multiply both sides by $v_P \times v_S$, and divide by $v_S - v_P$, we find that the distance between the earthquake focus and any given seismic station is

$$X = \delta t \times \frac{v_P \times v_S}{v_P - v_S} \tag{13}$$

Compute the distances to the six stations using Equation (5) and insert these values into Table 10.2 (**12 points**).

10.2.2 Determining the Location

Now you will use the map to determine the site of the quake. First, figure out the number of centimeters that correspond to 1 km by measuring the scale bar on your map (lower left corner of map) with a ruler.

140.8 km = ________ cm

1 km = the above number /140.8, = ________ cm = S, the scale factor

Copy the distances from Table 10.2 into the second column of Table 10.3. Then convert the true distances in Table 10.3 from km to *scaled distances* in cm:

scaled distance = true distance × S

Insert these numbers into Table 10.3 (**6 points**).

Set the compass for each scaled distance and place the point of the compass at the station and draw an arc on the map located at the end of the lab (**10 points**). When you are done, you will use your results in conjunction with the information on the last page of the lab regarding the geology of New Mexico to answer the following questions.

Table 10.3: Distance from each seismic station to earthquake focus.

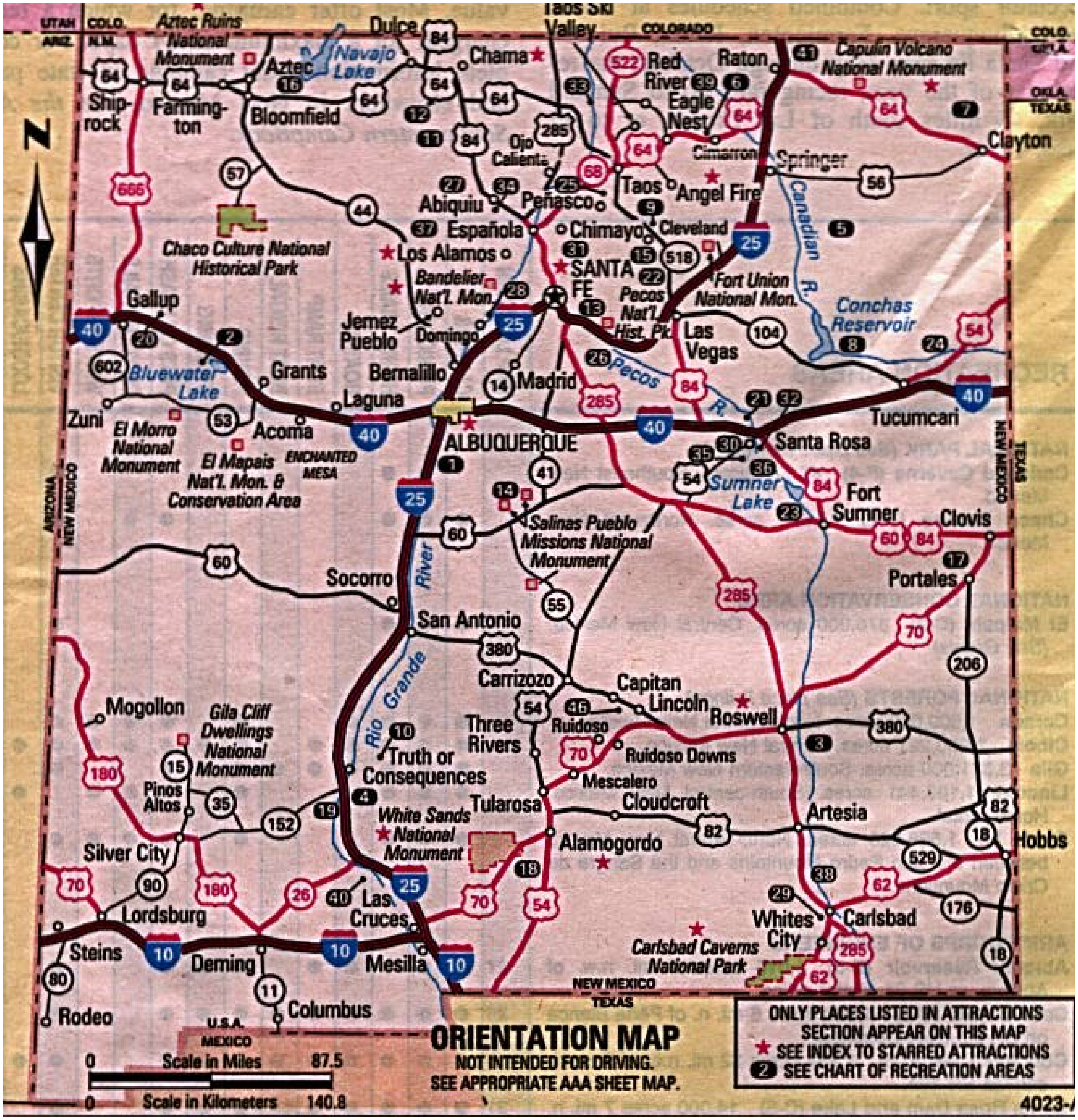
Station	Dist. to focus (km)	Scaled Dist. to focus (cm)
Alamogordo		
Albuquerque		
El Paso		
Las Cruces		
Santa Fe		
Socorro, NM		

10.3 In-Lab Questions

1. What was the site of this local quake? What might be the cause of small quakes in this region? (**10 points**)

2. What is your best estimate of the time the quake occurred? (**5 points**)

3. Based on the size of the intersecting region of your diagram, what can you say about the depth of the quake? (**6 points**)


ORIENTATION MAP
NOT INTENDED FOR DRIVING.
SEE APPROPRIATE AAA SHEET MAP.
ONLY PLACES LISTED IN ATTRACTIONS SECTION APPEAR ON THIS MAP
★ SEE INDEX TO STARRED ATTRACTIONS
2 SEE CHART OF RECREATION AREAS
Scale in Miles
0
87.5
Scale in Kilometers
0
140.8
UTAH
COLO.
ARIZ.
N.M.
COLORADO
OKLA.
TEXAS
ARIZONA
NEW MEXICO
U.S.A.
MEXICO
N
Aztec Ruins National Monument
Aztec
Navajo Lake
Dulce
Chama
Taos Ski Valley
Red River
Eagle Nest
Raton
Capulin Volcano National Monument
Clayton
Shiprock
Farmington
Bloomfield
Ojo Caliente
Cimarron
Springer
Taos
Angel Fire
Abiquiu
Peñasco
Española
Chimayo
Cleveland
Chaco Culture National Historical Park
Los Alamos
Bandelier Nat'l. Mon.
SANTA FE
Pecos Nat'l. Hist. Pk.
Fort Union National Mon.
Canadian R.
Conchas Reservoir
Gallup
Jemez Pueblo
Domingo
Las Vegas
Bluewater Lake
Grants
Bernalillo
Madrid
Pecos R.
Laguna
Zuni
El Morro National Monument
Acoma
El Mapais Nat'l. Mon. & Conservation Area
ENCHANTED MESA
ALBUQUERQUE
Tucumcari
Santa Rosa
Sumner Lake
Fort Sumner
Clovis
Salinas Pueblo Missions National Monument
Portales
Socorro
Rio Grande River
San Antonio
Carrizozo
Capitan
Lincoln
Roswell
Mogollon
Gila Cliff Dwellings National Monument
Three Rivers
Ruidoso
Ruidoso Downs
Truth or Consequences
Mescalero
Pinos Altos
Tularosa
Cloudcroft
Artesia
White Sands National Monument
Alamogordo
Hobbs
Silver City
Las Cruces
Lordsburg
Whites City
Carlsbad
Carlsbad Caverns National Park
Steins
Deming
Mesilla
NEW MEXICO
TEXAS
Rodeo
Columbus
4023-

Name:___________________________________
Date:___________________________________

10.4 Take Home Exercise (35 points total)

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

1. When large earthquakes occur, stations within a few thousand km of the focus detect both P and S waves. On the opposite side of the Earth only P waves are detected. Review the nature of the P and S waves and argue that there is a molten region at about 3500 km from the center of the Earth (compared to the Earth's 6378 km radius). [A figure will be helpful here.] How might you detect a smaller solid central core if there were one? (**20 points**)

2. a) Clearly describe how you would design a spacecraft mission to Mars to determine whether or not Mars has molten metal in its core, including what properties of Mars you would want to measure. b) Would you want one or more than one lander? c) If you could only have an orbiter mission to Mars (no landers), what measurements would you want it to make to help you determine whether or not Mars has a molten metal core. [Hint: the measurement will *not* be the reflected sunlight or blackbody radiation.] (**15 points**)

10.5 Possible Quiz Questions

1. What is an earthquake?
2. How are earthquakes generated?
3. What is an "L-wave"?
4. What is an "S-wave"?
5. What is a "P-wave"?
6. Do all the different kinds of waves travel at the same speeds?

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

Below is a brief summary about the geology of New Mexico. Using this guide, and *additional research*, describe why we have earthquakes in New Mexico. Why are the earthquakes in New Mexico usually so much smaller (less intense) than those that are common to California?

This Geological summary is from the 1990 New Mexico Magazine Vacation Guide.

Geology

New Mexico's geology is as diverse and colorful as its culture, history and people. From the low-lying flatlands of the south to the soaring peaks of the northern mountains, the state's terrain climbs 10,000 feet in altitude creating a landscape of dramatic contrasts.

The creation of New Mexico's present landscape began some 70 million years ago during the Cenozoic era. About this time the Rocky Mountains were born during the Lara-mide Revolution, a general uplifting of the Earth's crust.

The ancient seas that covered most of New Mexico in earlier times slowly disappeared, and along with them went the dinosaurs and abundant marine life of the Triassic, Jurassic and Cretaceous periods.

Volcanic activity has played an integral role in shaping New Mexico's terrain. Evidence of centuries of volcanism is apparent across the state. Rising well over 1,700 feet above the surrounding land, Shiprock is a volcanic neck–the core of all that remains of a long-eroded volcano.

Valle Grande, located in the center of the Jémez Mountains, is one of the world's largest calderas. The violent eruption that created it released over 75 cubic miles of molten rock, which slowly cooled as it flowed over the land. Today the crater contains 176 square miles of meadow land where wildflowers bloom and cattle graze peacefully.

To the south, Little Black Peak in Valley of Fires State Park erupted barely 1,000 years ago, emitting what is now 44 miles of ropey pa hoe hoe lava flows, more than 150 feet thick in some places. As it spread and cooled, the lava formed domes, tubes, caves and fissures. This area is among the most recent and best preserved examples of such lava flows in the continental U.S.

Seismic activity continues to alter the land. Tension in the Earth's crust along a pair of parallel fault lines running down the center of New Mexico has resulted in the formation of the great Rio Grande Rift Valley. This huge trough, which contains the Rio Grande, is 30 miles across at Albuquerque and widens considerably to the south.

Many of the state's mountains, including the Sandìa, Manzano and Sacramento ranges, were formed from fault blocks that were tilted and raised as the Earth's crust was uplifted.

In New Mexico's arid environment, water is a scarce and precious resource that is, nevertheless, a powerful force in the sculpting of geological features.

Circulating underground water dissolves salt, gypsum and limestone deposits to form subterranean realms such as Carlsbad Caverns, one of the largest cave systems in the world.

When the roofs of such caverns collapse, sink holes are formed and lakes develop. Bottomless Lakes State Park near Roswell plays on a harmless exaggeration of the depth of these unique features, the deepest of which is about 90 feet.

Winds blowing in from gypsiferous Lake Lu-cero have built up what is now White Sands National Monument. Here, sparkling snow-white sand crests in dunes up to 50 feet high. The 275 square-mile monument contains more than 8 billion tons of gypsum and is the largest dune field of its kind in the world.

Earthquake # 1

Since 1973 (when recording of earthquakes in the US became more precise and organized), the three most powerful earthquakes to hit New Mexico were all of magnitude 5.0. This earthquake, the first of these three, occurred during the night of January 4, 1976. In locations near the earthquake's epicenter, the event was felt by everybody. Only buildings in poor repair suffered significant damage. Most other damage was on the level of things falling off of shelves.

Table 10.4: Data for Earthquake 1.

Reporting Station	P-wave Onset Time (MST)	S-wave Onset Time (MST)
Alamogordo	23:24:37.1	23:25:22.4
Albuquerque	23:24:01.4	23:24:21.1
El Paso	23:24:52.3	23:25:48.5
Las Cruces	23:24:41.4	23:25:29.8
Santa Fe	23:24:08.2	23:24:32.8
Socorro	23:24:12.2	23:24:39.6

Earthquake # 2

This earthquake, the second of the three most powerful felt in New Mexico, occurred during early in the morning on January 2, 1992. This earthquake was felt by most people in the area, but did not cause significant damage, aside from knocking over a few small objects like vases.

Table 10.5: Data for Earthquake 2.

Reporting Station	P-wave Onset Time (MST)	S-wave Onset Time (MST)
Alamogordo	04:46:20.6	04:46:52.9
Albuquerque	04:46:49.0	04:47:41.6
El Paso	04:46:28.9	04:47:07.1
Las Cruces	04:46:32.2	04:47:12.8
Santa Fe	04:46:50.0	04:47:43.4
Socorro	04:46:41.3	04:47:28.3

Earthquake # 3

Of the three that have been at magnitude 5.0, this earthquake is the most recent: during the afternoon of August 10, 2005. Reports indicate that this earthquake was powerful enough to be felt, and caused clearly visible effects (like sloshing liquid, wobbling furniture, parked cars rocking), but no significant damage.

Table 10.6: Data for Earthquake 3.

Reporting Station	P-wave Onset Time (MDT)	S-wave Onset Time (MDT)
Alamogordo	16:09:38.0	16:10:31.9
Albuquerque	16:09:05.8	16:09:36.7
El Paso	16:10:00.0	16:11:09.7
Las Cruces	16:09:51.6	16:10:55.4
Santa Fe	16:08:50.7	16:09:10.9
Socorro	16:09:23.5	16:10:07.1

Earthquake # 4

This earthquake, one of the most powerful New Mexico earthquakes in recent history, was of magnitude 4.8. It occurred on the morning of January 29, 1990. In locations near the earthquake's epicenter, the event was felt by everybody. Only buildings in poor repair had significant damage. Most other damage was on the level of broken dishware, or things falling off of shelves.

Table 10.7: Data for Earthquake 4.

Reporting Station	P-wave Onset Time (MST)	S-wave Onset Time (MST)
Alamogordo	06:16:42.3	06:17:05.0
Albuquerque	06:16:22.7	06:16:31.3
El Paso	06:17:00.1	06:17:35.5
Las Cruces	06:16:49.7	06:17:17.7
Santa Fe	06:16:37.1	06:16:56.0
Socorro	06:16:18.4	06:16:24.0

Earthquake # 5

This earthquake, among the most powerful New Mexico earthquakes in recent history, was of magnitude 4.7. It occurred during the night of November 28, 1989. This earthquake was felt by most people in the area, but did not cause significant damage, aside from knocking over stuff on shelves.

Table 10.8: Data for Earthquake 5.

Reporting Station	**P-wave Onset Time (MST)**	**S-wave Onset Time (MST)**
Alamogordo	23:55:10.2	23:55:32.9
Albuquerque	23:54:50.6	23:54:59.2
El Paso	23:55:27.9	23:56:03.3
Las Cruces	23:55:17.5	23:55:45.5
Santa Fe	23:55:05.0	23:55:24.0
Socorro	23:54:46.3	23:54:51.8

Name:________________________________

Date:________________________________

11 The Surface of the Moon

11.1 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 11.1 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.

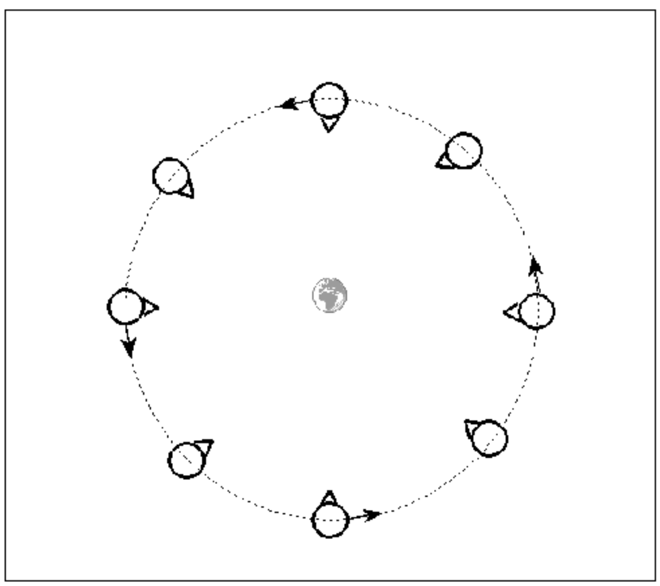


Figure 11.1: The Moon's "synchronous" orbit (not drawn to scale). Note how the Moon spins exactly once during its 27.3 day orbit around the Earth, but keeps the same face pointing towards the Earth.

On the Moon, there are extensive lava flows, rugged highlands, and many impact craters of all different sizes. The overlapping of these features implies relative ages. Because of the lack of ongoing mountain building processes, or weathering by wind and water, the accumulation of volcanic processes and impact cratering is readily visible. Thus by looking at the images of the Moon, one can trace the history of the lunar surface. Most of the images in this lab were taken by NASA spacecraft or by the Apollo Astronauts.

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

11.2 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 11.2, 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 11.2 also shows that the rock beneath the crater becomes fractured (full of cracks).

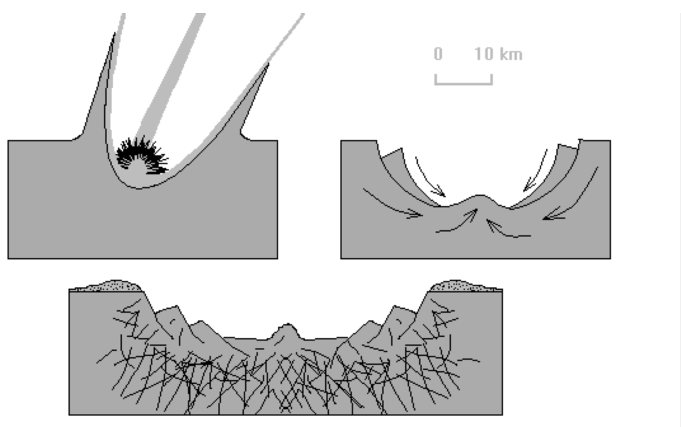


Figure 11.2: Formation of an Impact Crater.

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

11.3 Relative Ages on the Moon

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

11.4 Lab Stations

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

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

11.5 The Surface of the Moon

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The structure of the Earth is shown in the diagram, below. There are three main structures: the crust (where we live), the mantle, and the core. The crust is cool and brittle, the mantle is hotter, and "plastic" (it flows), and the core is very hot and very dense. The density of a material is simply its mass (in grams or kilograms) divided by its volume (in centimeters or meters). Water has a density of 1 gm/cm^3. The density of the Earth's crust is about 3 gm/cm^3, while the mantle has a density of 4.5 gm/cm^3. The core is very dense: 14

Table 11.1: 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%

gm/cm^3 (this is partly due to its composition, and partly due to the great pressure exerted by the mass located above the core). The core of the Earth is almost pure iron, while the mantle is a mixture of magnesium, silicon, iron and oxygen. The average density of the Earth is 5.5 gm/cm^3.

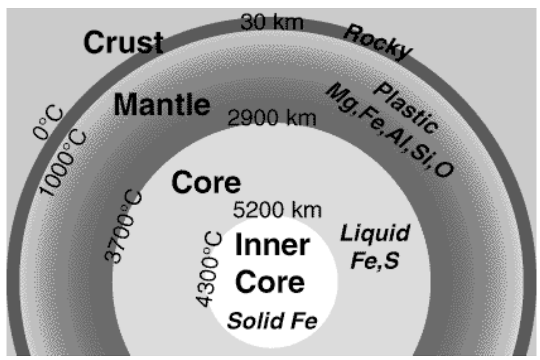


Figure 11.3: The internal structure of the Earth, showing the dimensions of the crust, mantle and core, as well as their composition and temperatures.

Before the astronauts brought back rocks from the Moon, we did not have a good theory about its formation. All we knew was that the Moon had an average density of 3.34 gm/cm^3. If the Moon formed from the same material as the Earth, their compositions would be nearly identical, as would their average densities. In Table 11.1, we present a comparison of the composition of the Moon to that of the Earth. The data for the Moon comes from analysis of the rocks brought back by the Apollo astronauts.

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

Table 11.2: Chemical Composition of the Earth and Moon

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

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

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

The final theory for the formation of the Moon is called the "Giant Impact" theory. In this model, a large body (about the size of the planet Mars) collided with the Earth, and the resulting explosion sent a large amount of material into space. This material eventually collapsed (coalesced) to form the Moon. Most of the ejected material would have come from the crust and the mantle of the Earth, since it is the material closest to the Earth's surface. In Table 11.6 is a comparison of the composition of the Earth's crust and mantle compared to that of the Moon.

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

11.7 Summary

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

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

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

11.8 Possible Quiz Questions

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

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

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

Name:____________________________

Date:____________________________

12 Introduction to the Geology of the Terrestrial Planets

12.1 Introduction

There are two main families of planets in our solar system: the Terrestrial planets (Earth, Mercury, Venus, and Mars), and the Jovian Planets (Jupiter, Saturn, Uranus, and Neptune). The terrestrial planets are rocky planets that have properties similar to that of the Earth. In contrast, the Jovian planets are giant balls of gas. Table 12.1 summarizes the main properties of the planets in our solar system (Pluto is an oddball planet that does not fall into either categories, sharing many properties with the "Kuiper belt" objects discussed in the lab # 16).

Table 12.1: 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 12.1 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 12.2.

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 12.2: 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.

12.2 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 12.1, 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 12.2. 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.

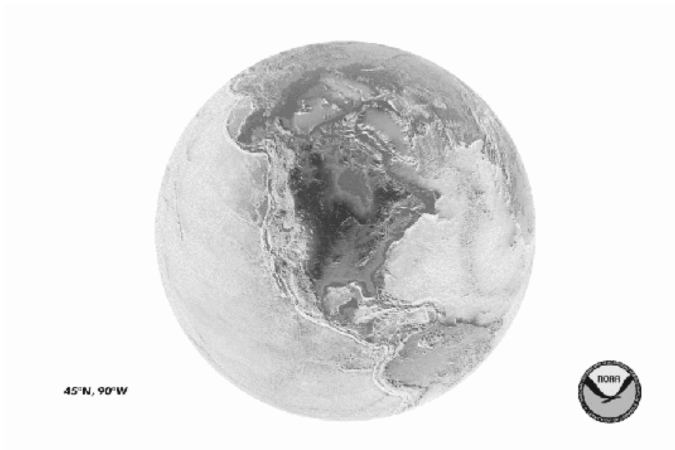


Figure 12.1: A topographic map showing one hemisphere of Earth centered on North America. In this 3D representation the continents are correctly rendered.

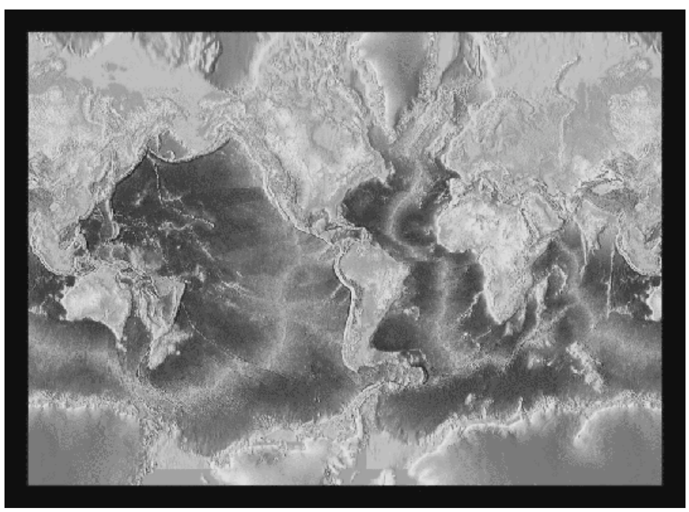


Figure 12.2: A topographic map showing the entire surface of the Earth. In this 2D representation, the continents are incorrectly rendered. Note that Antarctica (the land mass that spans the bottom border of this map) is 50% smaller than North America, but here appears massive. You might also be able to compare the size of Greenland on this map, to that of the previous map.

12.3 Global Comparisons

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

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

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

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

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

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

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

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

5. Using the above information, make an educated guess on why Mercury does not have as many large maria as the Moon, even though both objects have been around for the same

amount of time. [Hint: Maria are caused by the impacts of *large* bodies.] **(3 points)**

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

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

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

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

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

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

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

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

12.4 Detailed Comparison of the Surfaces of the Terrestrial Planets

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

In the Moon lab (lab # 11), we discussed how impact craters form. For large impacts, the center of the crater may "rebound" and produce a central mountain (or several small peaks). Sometimes an impact is large enough to crack the surface of the planet, and lava flows into the crater filling it up, and making the floor of the crater smooth. On the Earth, water can also collect in a crater, while on Mars it might collect large quantities of dust.

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

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

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

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

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

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

15. Describe the differences between young and old craters on the Earth. What happens to these craters over time? **(4 points)**

12.5 Erosion Processes and Evidence for Water

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

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

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

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

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

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

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

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

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

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

20. What is going on in this photo (#27)? How were these features formed? Why do the

small craters not show the same sort of "teardrop" shapes? **(2 points)**

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

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

12.6 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 12.3, 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. 12.4), in places where the heat rises, we get an upwelling 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.

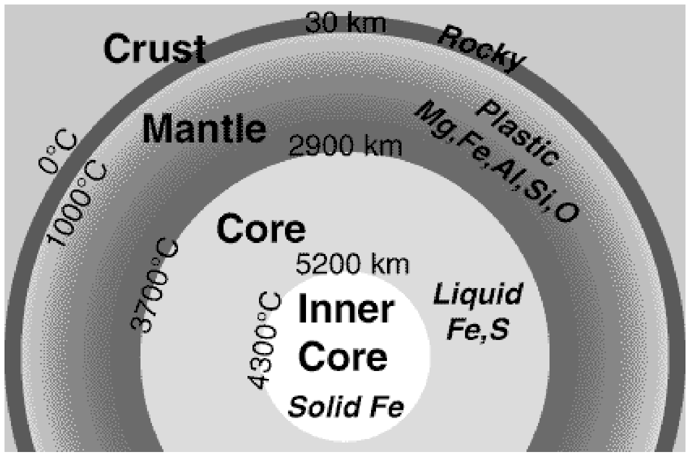


Figure 12.3: A cut-away diagram of the structure of the Earth showing the hot core, the mantle, and the crust. The core of the Earth is very hot, and is composed of both liquid and solid iron. The mantle is a zone where the rocks are partially melted ("plastic-like"). The crust is the cold, outer skin 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.

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

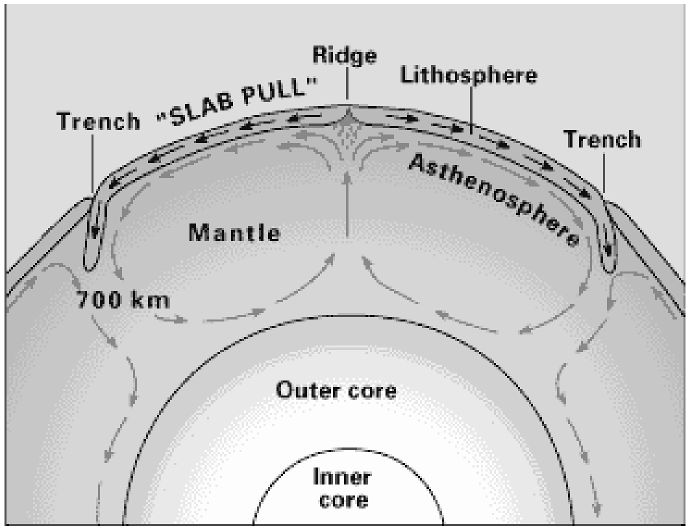


Figure 12.4: The escape of the heat from the Earth's core sets-up a boiling motion in the mantle. Where material rises to the surface it pushes apart the plates and volcanoes, and mountain chains are common. Where the material is cooling, it flows downwards (subsides) back into the mantle pulling down on the plates ("slab-pull'). This is how the large crustal plates move around on the Earth's surface.

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

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

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

26. In the next set (Photos #42 to #44) are some false-color images of Venusian volcanoes. Among these are both overhead shots, and 3D images. Because Venus was mapped using radar, we can reconstruct the data to create images as if we were located on, or near, the surface of Venus. *Note, however, that the vertical elevation detail has been exaggerated by a factor of ten!* It might be hard to tell, but Venus is also dominated by one main type of Volcano, what is it? **(3 points)**

12.7 Summary (35 points)

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

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

12.8 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?

12.9 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:________________________________

13 Heating and Cooling of Planets (and Daytime Observations)

13.1 Heating and Cooling Introduction

With this lab exercise we will investigate the ability of the radiant energy from the Sun to heat an object (planet, sidewalk, water-filled can). How rapidly, or how much, an object warms is dependent upon several factors, which are discussed below. The knowledge you should gain from this lab includes how the rate of warming depends upon the reflectivity of an object, and how effectively an object (surface of a planet, for example) can cool via emission of radiant energy.

The local temperature at a given location on a planet, including the air temperature near the ground, is dependent upon a number of important factors. Global factors include the tilt of the planet's rotational axis relative to its path around the Sun and the eccentricity of the planet's orbit. Naturally, local factors can also affect the local temperature.

Several global and local factors that affect a planet's globally-averaged temperature and also the local temperature are as follows:

- The length of daylight hours, dependent upon the rotation rate of a planet, determines the ratio of solar heating during the day and infrared cooling (emitted to space) during both the day and night.
- The slant angle of the incoming sunlight affects the local sunlight intensity and explains why sloped parts of your face such as your nose sunburn more easily than the more vertical regions. This effect is a function of latitude and season on those planets that have a non-zero axial tilt.
- The degree of ellipticity of a planet's orbit can affect the seasonal changes or can induce sunlight intensity variations that are similar to axially-induced seasonal variations. This has a major impact for Mercury and Pluto and somewhat less for Mars. For the Earth it only causes about $\pm 3\%$ variations in incoming solar intensity throughout a year.
- The degree to which the atmosphere serves as an insulating blanket (including greenhouse effects) can affect the daily averaged temperature and the range of temperature between the coldest and warmest times of a day.
- For the terrestrial planets, the albedo (percent reflectivity) of the local clouds and surface can also greatly affect short term temperature variations as well as the planet's globally averaged temperature. See Figure 13.1.

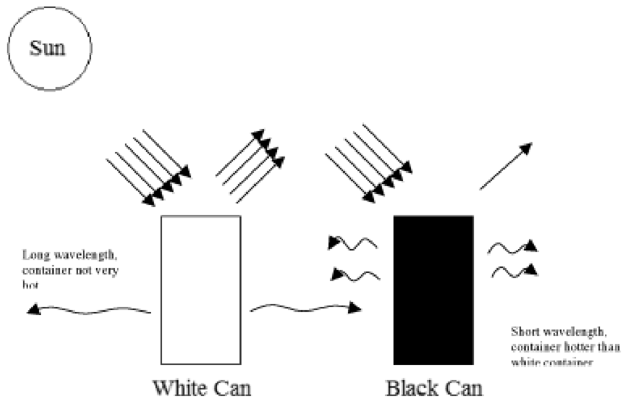


Figure 13.1: The white can has a high albedo and reflects most of the light (80% in this case). The black can has a low albedo and absorbs most of the light (only 20% reflected here), and this can will be more likely to heat.

13.2 Heating and Cooling Rates

Divide into groups of 3–4 people. Each of these groups will be provided one soft drink can that has been painted white and two additional cans that have been painted black. Each group will also be provided with three thermometers, one for each can. Additionally, each group will be provided with two pieces of 'insulating' cardboard.

Working in the shade of the observatory domes, place your three cans on one of the pieces of cardboard provided (this will insulate the cans from the cold, or hot, ground). Add 200 milliliters of cold water (colder than the local air temperature) to each of your 3 cans. When the cans are filled, place a thermometer in each of the cans. The thermometers will have been in the cold water prior to this, so they will already be at the approximate water temperature. Allow the thermometers to equilibrate with the water in the cans for 3 minutes or so.

Now take the cans and place them in the sunlight on the piece of insulating cardboard. Record the temperatures of these three sunlit cans in Table 13.1. (Be sure to keep track of which black can is which). Also, record in Table 13.2 the temperatures of the shaded white and black cans. *These two cans, which all four groups will use, will be located on the north side of the open telescope dome. Each group will record data for the two shaded cans, plus their three cans, for a total of five cans.*

At five minute intervals (use a watch with a second hand or its equivalent), record in the tables the temperatures indicated on each of the five thermometers (again, taking care to not mix up the two black sunlit cans). Continue this process through 25 minutes. This will give you one temperature at time 'zero' and 5 subsequent temperature readings.

After 25 minutes have passed and you have tabulated the minute 25 temperature, place the ‘can-cozy’ (insulator) on one of the black cans and move your three sunlit cans into the shade. Continue to measure the temperatures of all five cans at 5-minute intervals through 45 minutes.

Table 13.1: The effect of albedo on local heating and cooling rates. Times 0-25 are during the sunlit heating phase, and times 30-45 are during the shaded cooling phase. (**10 points**)

Time	Temp. of White Can	Temp. of Black Can 1	Temp. of Black Can 2
0			
5			
10			
15			
20			
25			
30			
35			
40			
45			

Table 13.2: Heating and cooling rates in the shade. These cans remain in the shade throughout the course of the entire experiment. (**10 points**)

Time	Temp. of White Can	Temp. of Black Can
0		
5		
10		
15		
20		
25		
30		
35		
40		
45		

13.3 Heating and Cooling Questions

1. Plot the values of each of the five temperatures versus time *using five different line styles or symbols* on the graph paper provided. Be sure to label each of the curves. (**10 points**)

Figure 13.2: Plot of temperature (°C) vs. time (minutes) for all five cans.

2. For each can, calculate the average heating rate, using the equation given below, during the initial 25 minutes of the experiment (the time interval during which the three cans were in the sunlight). The calculated values will be in units of degrees Centigrade per minute. Insert your calculated heating rates into Table 13.3. (**5 points**)

$$Heating\ Rate = \frac{(Temperature\ after\ 25\ min.\ -\ Initial\ Temperature)}{25\ minutes} \tag{14}$$

Table 13.3: Heating rate values for different cans.

Can	**Heating Rate (°C/min)**
White can (in sunlight)	
Black can 1 (in sunlight)	
Black can 2 (in sunlight)	
White can (in shade)	
Black can (in shade)	

3. Which color can (black or white) has the largest heating rate when in the sunlight? Did you expect this result? Why or why not? Can you think of any other processes, in addition to radiative heating, that might have played a role in heating the water in these sunlit cans? (**3 points**)

4. What do you think was the process responsible for any warming or cooling experienced by the two shaded cans? Is there a color dependence to this temperature change in the shade? Did you expect this? Why or why not? (**5 points**)

5. Subtract the heating rate you calculated for the shaded white can from the heating rate you calculated for the sunlit white can, and write this value below:

   White can: **sunlit heating rate − shaded heating rate** = ____________________

   Subtract the heating rate you calculated for the shaded black can from the heating rate you calculated for each of the two sunlit black cans:

   Black can Number 1: **sunlit heating rate − shaded heating rate** = ___________

Black can Number 2: **sunlit heating rate − shaded heating rate** = ____________

How do these 'corrected' radiative heating rates, which account for other processes than radiative heating, compare between the one white and two black sunlit cans? Is this in better or worse agreement with your expectations? (**3 points**)

6. Let's examine the cooling rates, as indicated by the temperatures measured after minute 25 of the experiment. Calculate the averaged cooling rates for **each** of the five cans, using the minute 45 and 25 temperatures and the twenty minute interval:

$$Averaged\ Cooling\ Rate = \frac{(Temp.\ after\ 25\ min.\ -\ Temp.\ after\ 45\ min.)}{20\ minutes} \quad (15)$$

White can (sunlit) : averaged cooling rate = ____________________________

Black can (insulated): averaged cooling rate = ____________________________

Black can (bare) : averaged cooling rate = ____________________________

White can (shaded) : averaged cooling rate = ____________________________

Black can (shaded) : averaged cooling rate = ____________________________

Of the three cans that originally spent 25 minutes in the sunlight, which had the smallest cooling rate (cooled most slowly)? Why do you think this is the situation? Did you expect this? Why or why not? (**3 points**)

7. Of the three sunlit cans, which had the **greatest** cooling rate (cooled most rapidly)? What processes do you believe are responsible for the cooling of this can? Do these processes also play a role in the cooling of the other cans? (**3 points**)

13.4 Daytime Observing Introduction

Venus is the Earth's closest planetary neighbor. It has been viewed by civilizations of people on Earth for centuries, for it shines brightly in the morning or evening sky, earning the name "morning star" or "evening star." [At one time, it was thought to be two different objects, one that appeared in the evening sky and another that appeared in the morning sky.] Venus shines so brightly in our sky in part because of its proximity to Earth, and in part due to its highly reflective cloud layers, which completely surround the planet and hide the surface from our view.

Venus has also played a key role in our understanding of the universe around us. For centuries, it was believed that the Sun, the Moon, all of the known planets, and the stars in the sky revolved around the Earth. This belief was known as the *geocentric model* of the universe, which placed the Earth at the center of it all. However, it was telescopic observations of Venus that changed our view of the universe. Galileo Galilei (1564-1642) was the first person to use a telescope to observe Venus. Over time, he noted that Venus, like the Moon, exhibited phases, changing from a small, disk-like object to a large crescent shaped object.

Galileo was aware of a new model that described the universe, the Sun-centered, or *heliocentric model* developed by Nicolaus Copernicus (1473-1543). This model was extremely controversial because it removed the Earth from its privileged position at the center of the universe. Nevertheless, Galileo found that the heliocentric model could completely explain the observed phases of Venus.

In this lab, you will observe Venus through a telescope, as Galileo did, and deduce information about Venus' relative distance from Earth throughout its orbit and its motion around the Sun. You may also observe Mercury, weather permitting, since it can also be visible during the daytime.

13.5 Telescopic Observations

Observe Venus and/or Mercury through the telescope at the Tombaugh Campus Observatory and draw and label what you see on the observation log at the end of this lab. Comment in the space below on what you saw. What shape were they? Were they what you expected? Were they disappointing? Did they appear to be a certain color? **The more descriptive you can be, the better. (3 points)**

13.6 Phases of Venus

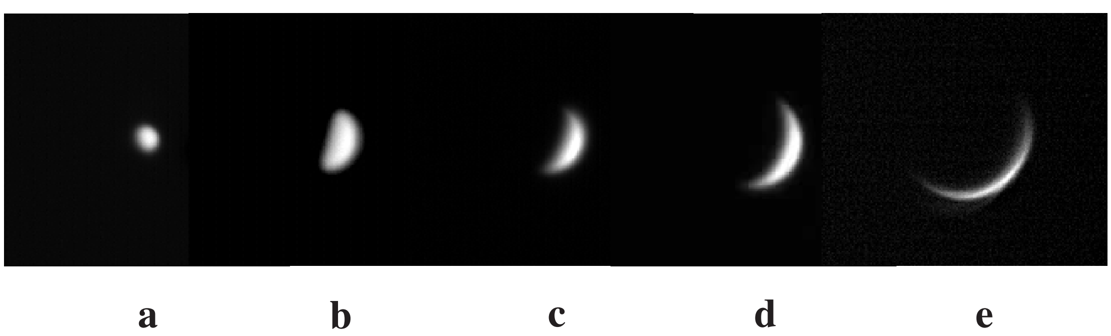


Figure 13.3: Phases of Venus as recorded through a 16" telescope (slightly larger than the ones at the Tombaugh Campus Observatory) at Calvin College. These images came from their web page: `http://www.calvin.edu/academic/phys/observatory/venus.html`.

Figure 13.3 shows five telescopic observations of Venus. Using your knowledge of the phases of the Moon, fill in Table 13.4 with the *name* of the phase shown in each panel of Fig. 13.3. [More than one panel can show the same phase.] (**5 points**)

Table 13.4: Phases of Venus corresponding to Figure 13.3.

Panel	**Phase**
a	
b	
c	
d	
e	

13.7 Heliocentric Model

Figure 13.4 shows a schematic of the orbits of the Earth and Venus in the heliocentric model. Using Fig. 13.4, label the various Venus circles, labeling each one with the letter corresponding to the phases seen in panels of Fig. 13.3 (**a**, **b**, **c**, **d**, and **e**). In other words, match the pictures of Venus in Figure 13.3 with the orbital locations in Figure 13.4. Shade in one half of Venus in each location to illustrate which side is receiving sunlight. (**5 points**)

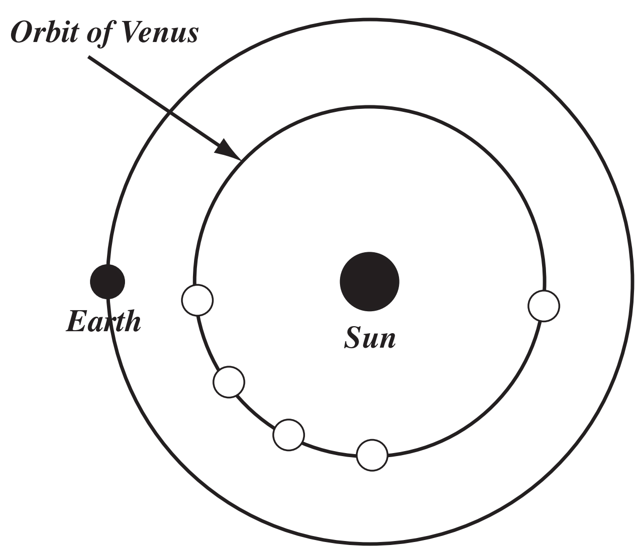


Figure 13.4: Orbit of Venus around the Sun.

Name:__________________________________
Date:___________________________________

13.8 Take Home Exercise (35 points total)

In the space provided, answer the following questions:

13.8.1 Heating and Cooling

1. What relationship is there between the 'can cozy' and some planetary characteristic of Venus, or Earth, or Mars? (**10 points**)

2. If you had conducted this experiment in July, how might your results differ from those we have obtained during this time of year? What if you had conducted this experiment in mid-December? (**5 points**)

13.8.2 Daytime Observations

3. It takes Venus approximately 7 months to complete one orbit around the Sun. However, we observe Venus through a full set of phases in slightly less than that time. What other motion needs to be accounted for when predicting when we will see a particular phase of Venus from Earth? (**5 points**)

4. Comment on the role that the telescope played in changing our view of the universe in the 1600's. Do you think this role still continues today? Please give an example to support your viewpoint. (**10 points**)

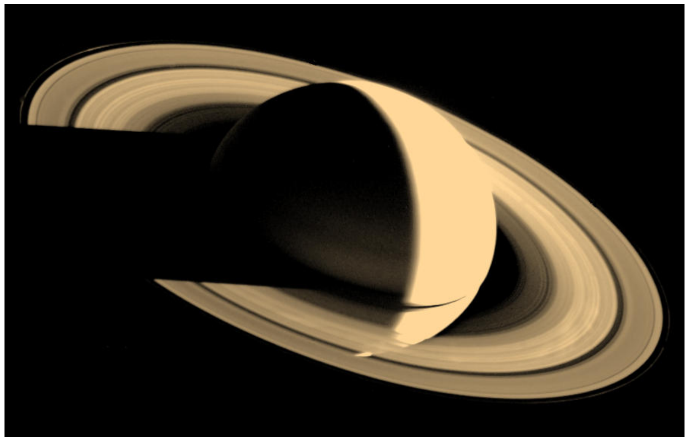
5. Summarize the difference between the geocentric and heliocentric models of the universe and discuss how Galileo's observations of Venus influenced this debate. (**5 points**)

13.9 Possible Quiz Questions

1. Name one factor that could change a planet's globally averaged temperature.
2. How does an atmosphere change a planet's temperature?
3. What is meant by the term "albedo"?
4. How does a hot object cool?
5. What does the term "inferior planet" mean?

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

Consider the image of a crescent Saturn below, taken by the Voyager 1 spacecraft on November 16, 1980.



Remember that Saturn is about 9.5 AU from the Sun. With a good enough telescope, would you ever be able to see a similar view of Saturn (that is, in the crescent phase) from Earth? (**1 points**)

If so, sketch a diagram similar to Figure 13.4 in the lab, showing a possible arrangement of the Sun, Earth, and Saturn that would allow you to see a crescent Saturn. (**2 points**)

If not, explain why we are sometimes able to see a crescent Venus but never a crescent Saturn. Drawing a diagram may help. (**2 points**)

Name:
Date:
Object:
Telescope:

Draw the object as it looks to you through the telescope

Name:______________________________
Date:_______________________________

14 The History of Water on Mars

Scientists believe that for life to exist on a planet (or moon), there must be liquid water available. Thus, one of the priorities for NASA has been the search for water on other objects in our solar system. Currently, these studies are focused on three objects: Mars, Europa (a moon of Jupiter), and Enceladus (a moon of Saturn). It is believed that both Europa and Enceladus have liquid water below their surfaces. Unfortunately, it will be very difficult to find out if their subsurface oceans harbor lifeforms, as they are below very thick sheets of ice. Mars is different. Mars was discovered to have polar ice caps more than 350 years ago. While much of the surface ice of these polar caps is "dry ice", frozen carbon dioxide, we believe there is a large quantity of frozen water in the polar regions of Mars.

Mars has many similarities to Earth. The rotation period of Mars is 24 hours and 37 minutes. Martian days are just a little longer than Earth days. Mars also has seasons that are similar to those of the Earth. Currently, the spin axis of Mars is tilted by 25° to its orbital plane (Earth's axis is tilted by 23.5°). Thus, there are times during the Martian year when the Sun never rises in the northernmost and southernmost parts of the planet (winter above the "arctic circles"). And times of the year in these same places where the Sun never sets (northern or southern summer). Mars is also very different from the Earth: its radius is about 50% that of Earth, the average surface temperature is very cold, −63 °C (= −81 °F), and the atmospheric pressure at the surface is only 1% that of the Earth. The low temperatures and pressures mean that it is hard for liquid water to currently exist on the surface of Mars. Was this always true? We will find that out today.

In this lab you will be examining a notebook of images of Mars made by recent space probes and looking for signs of water. You will also be making measurements of some valleys and channels on Mars to enable you to distinguish the different surface features left by small, slow flowing streams and large, rapid outflows. You will calculate the volumes of water required to carve these features, and consider how this volume compares with other bodies of water.

14.1 Water Flow Features on Mars

The first evidence that there was once water on Mars was revealed by the NASA spacecraft Mariner 9. Mariner 9 reached Mars in 1971, and after waiting-out a global dust storm that obscured the surface of Mars, started sending back images in December of that year. Since that time a flotilla of spacecraft have been investigating Mars, supplying insight into the history of water there.

Figure 14.1: A dendritic drainage pattern in Yemen (left), and an anastomosing drainage in Alaska (right).

14.1.1 Warrego Valles

The first place we are going to visit is called "Warrego Valles", where the "Valles" part of its name indicates valleys (or canyons). The singular of Valles is Vallis. The location of Warrego is indicated by the red dot on the map of Mars that is the first image ("Image #1") in the three ring binder.

The following set of questions refer to the images of Warrego Valles. Image #2 is a wide view of the region, while Image #3 is a close-up.

1. By looking at the morphology, or shape, of the valley, geologists can tell how the valley was formed. Does this valley system have a dendritic pattern (like the veins in a leaf) or an anastomosing pattern (like an intertwined rope)? See Figure 14.1. (**1 point**)

2. Overlay a transparency film onto the **close-up** image. Trace the valley pattern onto the transparency. How does a valley like this form? Do you think it formed slowly over time, or quickly from a localized water source? Why? (**3 points**)

3. Now, on the wide-field view, trace the boundary between the uplands and plains on your close-up overlay (the transparency sheet) and label the Uplands and the Plains. Is Warrego located in the uplands or on the plains? (**2 points**)

4. Which terrain is older? Recall that we can use crater counting to help determine the age of a surface, so let's do some crater counting. *Overlay the transparency sheet on the wide-view image.* Pick out two square regions on the wide view image (#2), each 5 cm × 5 cm. One region should cover the smooth plains ("Icaria Planum") and the other should cover the upland region. Draw these two squares on the transparency sheet. Count all the impact craters greater than 1 millimeter in diameter within each of the two squares you have outlined. Write these numbers below, with identifications. Which region is older? What does this exercise tell you about when approximately (or relatively) Warrego formed? (**5 points**)

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

   First, we need to add up the total length of all the branches of the valley. Note that in the close-up image there are two well-defined valley systems. A more compact one near the right edge, and the bigger one to the left of that. Let's concentrate on the bigger one that is closer to the middle of the image. Measure the length, in millimeters, of each branch and the main trunk. Be careful not to count the same length twice. Sometimes it is hard to tell where each branch ends. You need to use your own judgment and be consistent in the way you measure each branch. Now add up all your measurements and convert the sum to kilometers. In this image 1 mm = 0.5 km. What is the total length ℓ of the valley system in kilometers? Show your work. (**3 points**)

6. Second, we need to find the average width of the valley. Carefully measure the width of the valley (in millimeters) in several places. What is the average width? Convert this to kilometers. Show your work. (**2 points**)

7. Finally, we need to know the depth. It is hard to measure depths from photographs, so we will make an estimate. From other evidence that we will not discuss here, the depth of typical Martian valleys is about 200 meters. Convert this to kilometers. (**1 point**)

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

Image #4 is a recent image of one small "tributary" of the large valley network you have just measured (it is the leftmost branch that drains into the big valley system you explored). In this image the scientists have made identifications of a number of features that are much too small to see in image #3. Note that these researchers traced the valley network for this tributary and note where dust has filled-in some of the valley, or where "faults", cracks in the crust of the planet (orange line segments), have occurred. In addition, in the drawing on the right the dashed circles locate very old craters that have been eroded away. Using all of this information, you can begin to make good estimates of the age, and the sequences of events. Near the bottom they note a "crater with lobate ejecta that postdates valleys." This crater, which is about 2 km in diameter, was created by a meteorite impact that occurred after the valley formed. *By doing this all along all of the tributaries of the Warrego Valles* the age of this feature can be estimated. Ansan & Mangold (2005) conclude that the Warrego valley network began forming 3.5 billion years ago, from a period of rain and snow that may have lasted for 500 million years.

Clean-off transparency for the next section!

14.1.2 Ares and Tiu Valles

We now move to a morphologically different site, the Ares and Tiu Valles. These valleys are found near the equator of Mars, in the "Margaritifer Terra". This region can be found in the upper right quadrant of image #5 and is outlined in red. Note that the famous "Valles Marineris", the "grand canyon" of Mars (which dwarfs our Grand Canyon), is connected to the Margaritifer Terra by a broad, complicated canyon. In the close up, image #6, the two valles are identified (ignore the numbered white boxes, as they are part of a scientific study of this region). In this false-color image, elevation is indicated where the highest features are in white and brown, and the lowest features are pale green.

The next set of questions refer to Ares and Tiu Valles. On the wide scale image, the spot where the Mars Pathfinder *spacecraft landed is indicated. Can you guess why that particular spot was chosen?*

9. First, which way did the water flow that carved the Ares and Tiu Valles? Did water flow south-to-north, or north-to-south? How did you decide this? [Note that the latitude is indicated on the right hand side of image #6.] (**2 points**)

10. In our first close-up image (#7), there are two "teardrop islands". These two features can be found close to the "l" in the Pathfinder landing site label in image #6. There are other features with the same shape elsewhere in the channel. In image #8, we provide a wide field view of the "flood plains" of Tiu and Ares centered on the two teardrop islands of image #7. *Lay the transparency on this image and make a sketch of the pattern of these channels.* **Now add arrows to show the path and direction**

the flowing water took. Look at the pattern of these channels. Are they dendritic or anastomosing? (**3 points**)

11. Now we want to get an idea of the volume of water required to form Ares Valles. Measure the length of the channel from the top end of the biggest "island" above the Pathfinder landing site (note there are two islands here, a smaller one with a deep crater, and a bigger one with a shallow crater. We want you to measure the channel that goes by this smaller island on the right side and to the left of the big island, and the channel that goes around the bigger island on the right to where they both join-up again at the top of this big island) to the bottom right corner of the image. In this image, 1 mm = 10 km. What is the total length of these channels? Show your work (**3 points**)

12. Measure the channel width in several places and find the average width. On average, how wide is the channel in km? Show your work (**2 points**)

13. The average depth is about 200 m. How much is that in km? (**1 point**)

14. Now multiply your answers (in units of km) to **find the volume of the channel in km^3.** Use the same ratio of water volume to channel volume that we used in Question 3 to find the volume of water required to form the channel. Lake Michigan holds 5,000 km^3 of water, how does it compare to what you just calculated? Show your work. (**4**

points)

15. Obviously, the Ares and Tiu Valles formed in a different fashion than Warrego. We now want to examine the feature named "Hydaspis Chaos" in image #6. This feature "drains into" the Tiu Vallis. In image #9, we present a wide view image of this feature. In image #10, we show a close up of a small part of Hydaspis. Why do you think such features were given the name "Chaos" regions? (**2 points**)

16. Scientists believe that Chaos regions are formed by the sudden release of large amounts of groundwater (or, perhaps, the sudden melting of ice underneath the surface), causing massive, and rapid flooding. Does such an idea make sense to you? Why? What evidence for this hypothesis is present in these images to support this idea? (**4 points**)

17. In image #11 is a picture taken at the time of the disembarkation of the little Pathfinder rover (named "Sojourner") as it drove down the ramp from its lander. Is the surrounding terrain consistent with its location in the flood plain of Ares Vallis? Why/why not?

(**3 points**)

18. Recent research into the age of the Ares and Tiu Valles suggest that, while they began to form around 3.6 billion years ago (like Warrego), water still flowed in these channels as recently as 2.5 billion years ago. Thus, the flood plains of Ares and Tiu are much younger than Warrego. Do you agree with this assessment? How did you arrive at this conclusion? (**4 points**)

19. You have now studied Warrego and Ares Valles up close. **Compare and contrast the two different varieties of fluvial (water-carved) landforms in as many ways as you can think of (at least three!).** Do you think they formed the same way? How does the volume of water required to form Ares Valles compare to the volume of water required to form Warrego Valles? (**5 points**)

14.2 The Global Perspective

In image #12 is a topographic map of Mars that is color-coded to show the altitude of the surface features where blue is low, and white is very high. Note that the northern half of Mars is lower than the southern half, and the North pole is several km lower than the South pole. The Ares and Tiu Valles eventually drain into the region labeled "Chryse Planitia" (longitude 330°, latitude 25°).

20. If there was an abundance of water on Mars, what would the planet look like? How might we prove if this was feasible? For example, scientists estimate the age of the northern plains as being formed between 3.6 and 2.5 billion years ago. How does this number compare with the ages of the Ares and Tiu Valles? Could they be one source of water for this ocean? (**5 points**)

One way to test the hypothesis that the northern region of Mars was once covered by an ocean is to look for similarities to Earth. Over the history of Earth, oceans have covered large parts of the current land masses/continents (as one once covered much of New Mexico). Thus, there could be ancient shoreline features from past Earth oceans that we can compare to the proposed "shoreline" areas of Mars. In image #13 is a comparison of the Ebro river basin (in Spain) to various regions found on Mars that border the northern plains. The Ebro river basin shown in the upper left panel was once below sea level, and a river drained into an ancient ocean. The sediment laid down by the river eventually became sedimentary rock, and once the area was uplifted, the softer material eroded away, leaving ridges of rock that trace the ancient river bed. The other three panels show similar features on Mars.

If the northern part of Mars was covered by an ocean, where did the water go? It might have evaporated away into space, or it could still be present frozen below the surface. In 2006, NASA sent a spacecraft named Phoenix that landed above the "arctic circle" of Mars (at a latitude of 68° North). This lander had a shovel to dig below the surface as well as a laboratory to analyze the material that the shovel dug up. Image #14 shows a trench that Phoenix dug, showing sub-surface ice and how chunks of ice (in the trench shadow) evaporated (technically "sublimated", ice changing directly into gas) over time. The slow sublimation meant this was water ice, not carbon dioxide ice. This was confirmed when water was detected in the samples delivered to the onboard laboratory.

21. Given all of this evidence presented in the lab today, Mars certainly once had abundant surface water. We still do not know how much there was, how long it was present on the surface, or where it all went. But explain why discovery of large amounts of subsurface water ice might be important for astronauts that could one day visit Mars (**5 points**)

Name:______________________________

Date:_______________________________

14.3 Take Home Exercise (35 points total)

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

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

2. Scientists believe that life (the first, primitive, single cell creatures) on Earth began about 1 billion years after its formation, or 3.5 billion years ago. Scientists also believe that liquid water is essential for life to exist. Looking at the ages and lifetimes of the Warrego, Ares and Tiu Valles, what do you think about the possibility that life started on the planet Mars at the same time as Earth? What must have Mars been like at that time? What would have happened to this life? (**15 points**)

14.4 Possible Quiz Questions

1. Is water an important erosion process on Mars?
2. What does “dendritic” mean?
3. What does “anastomosing” mean?

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

In this lab you have found that dendritic and anastomosing "river" patterns are found on Mars, suggesting there was free flowing water at some time in Mars' history. Use web-based resources to investigate our current ideas about the history of water on Mars. Then find images of both dendritic and anastomosing features on the Earth (include them in your report). Describe where on our planet those particular patterns were found, and what type of climate exists in that part of the world. What does this suggest about the formation of similar features on Mars?

Name:______________________________
Date:_______________________________

15 The Volcanoes of Io

15.1 Introduction

During this lab, we will explore Jupiter's moon Io, the most volcanically active body in the Solar System. The reason for Io's extreme level of volcanic activity is due to the intense tidal 'stretching' it experiences because of its proximity to Jupiter, and due to its interaction with the moons Europa and Ganymede. The regions of the surface where molten lava from the interior comes up from below are very hot, but in general the rest of the surface is quite cold (about -172^oC = -279^oF) since Io is 5.2 AU from the Sun. Regions of different surface temperatures emit different amounts of thermal (blackbody) radiation, since the amount of thermal energy emitted is proportional to the temperature raised to the 4th power: T^4. We will use *infrared* observations, obtained with the Galileo spacecraft in the late 1990's, to determine the temperatures of some of the volcanic regions on Io, and estimate the total amount of energy being emitted by the volcanoes on Io.

Supplies:

1. Exercise squeeze balls and thermometers
2. Visual and thermal images of regions on Io
3. A map of Io with various features identified by name
4. A transparency sheet for temperature fitting of blackbodies

15.2 Introduction to Io

Io (pronounced eye-Oh) is one of the four large moons of Jupiter discovered by Galileo. Images of these four moons (Io, Europa, Ganymede, and Callisto) are shown in Figure 15.2. Io, Ganymede and Callisto are all larger than the Earth's moon, while Europa is slightly smaller. It is clear from Figure 15.2 that Io appears to be quite different from the other Galilean satellites (especially when viewed in color!): it has few obvious impact craters, and has a mottled surface that is unlike any other object in the solar system. Even before the two Voyager probes first flew past Io back in the late 1970's, it was already known that it was an unusual object. The Voyager images of Io certainly suggested that it was covered with volcanoes and lava flows, but it was not until an image showing an erupting volcano, also shown in Figure 15.2, that the case was clinched. From the imaging data, astronomers estimate that there may be as many as 200 volcanoes on Io!

Why does Io have so many volcanoes? It has to do with a process called "tidal heating". As you have learned in the lectures this semester, the gravitational pull on one body by a second massive body raises tides—an example are those caused by the Moon upon the Earth's

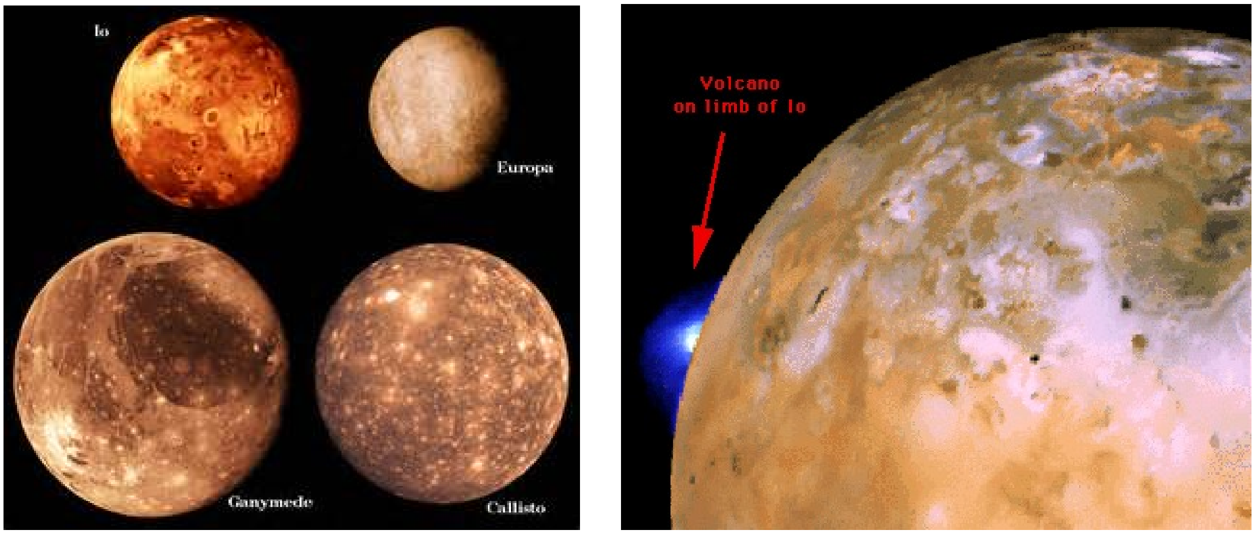


Figure 15.2: Left: The four Galilean moons of Jupiter. Right: An erupting volcano on Io seen in a Voyager image.

oceans. As we have also found this semester, the orbits of objects in the solar system are not perfect circles, but ellipses. That means the distance of an object orbiting a larger body (planet around the Sun, or moon around a planet) is constantly changing. In the case of Io, we have an object that has about the same mass as the Earth's moon, but it orbits Jupiter, an object that has 300 times the mass of the Earth! We have learned that the force of gravity is directly proportional to the mass of an object, Newton's second law: F = ma. For gravity, Newton's second law is $F = (Gm_1m_2)/r^2$ ("G" is the "gravitational constant"). Thus, even a slightly eccentric orbit, as demonstrated in Figure 15.3, means that large changes in tidal force are felt as Io goes around Jupiter (the $1/r^2$ term in the equation). In fact, the surface of Io rises and falls by about 100 meters over an orbit! This should be compared to the approximate 0.3 meter rise and fall of the Earth's surface due to the Moon's pull.

The reason that Io's orbit is so eccentric is due to the gravity of Europa and Ganymede. First, let's look at the orbital periods (i.e., the time it takes the moon to orbit Jupiter a single time) of these three moons: P_{Io} = 1.769 days, P_{Europa} = 3.551 days, and $P_{Ganymede}$ = 7.155 days. It we take the ratios of these orbital periods we get the following answers: $P_{Europa}/P_{Io} = 2.0$, $P_{Ganymede}/P_{Io} = 4.0$. What does this mean? Well, it tells you that every 3.551 days Europa and Io will be in the same exact location (relative to each other), and that every 7.155 days Ganymede, Europa *and* Io will be in the same relative places! A diagram of this is shown in Figure 15.3. The term astronomers use for such an arrangement is "orbital resonance". Because of these orbital resonances, the gravitational tug on Io is amplified, as it and Europa (and it and Ganymede) make close approaches on a regular, and repeating basis. Thus, Europa and Ganymede continually pull on Io, making its orbit more eccentric. [Note that we believe that Europa also has considerable tidal heating, and this heating may mean that below its frozen surface, there is a large ocean of liquid water that could support primitive life. This might even be happening on Ganymede.] The tidal heating causes the

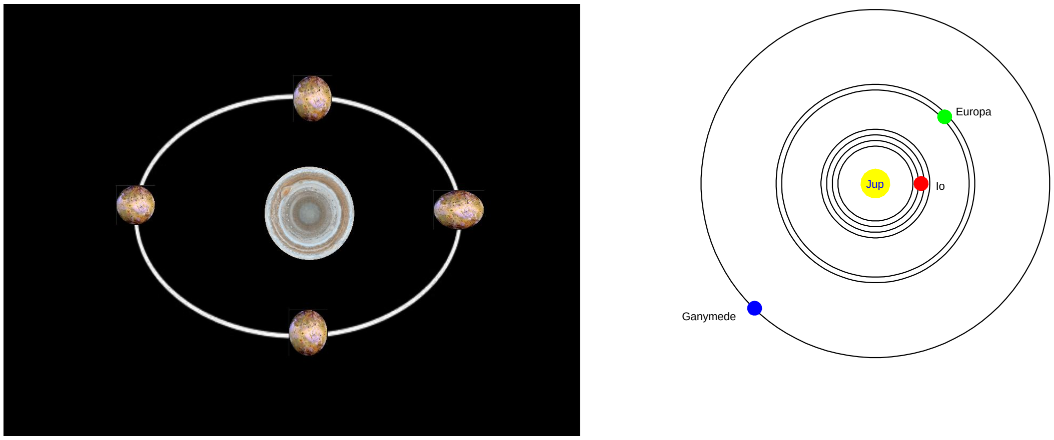


Figure 15.3: Left: Because Io's orbit around Jupiter is an ellipse, the distance is constantly changing, and so is the gravitational force exerted on Io by Jupiter (note that this figure is not to scale, and the ellipticity of the orbit and the shape of Io have been grossly exaggerated to demonstrate the effect). This changing force causes Io to stretch and relax over each orbit. Right: The tidal forces exerted by Europa and Ganymede distort the orbit of Io because the orbits of all three moons are in "resonance": for every four trips Io makes around Jupiter, Europa makes two, and Ganymede makes one. This resonance enhances the gravitational forces of Europa and Ganymede, as these three moons keep returning to the same (relative) places on a regular basis. This repeated and periodic tugging on Io causes its orbit to be much more eccentric than it would be if Europa and Ganymede did not exist.

interior of Io to become molten, and this liquid rises to the surface, where it erupts in volcanoes. We will return to Io later in this lab, but before we do so, we must cover several complicated topics that will allow us to better understand what is happening on Io.

15.3 The Electromagnetic Spectrum

Before we begin today's lab, we have to review what is meant by the term "spectrum", and "wavelength". As we have discussed in class, light is an energy wave that travels through space. For now, we can use the analogy that waves of light are like waves of water: they have crests, and troughs. The "wavelength" is the distance between two crests, as shown in Fig. 15.4. The energy contained in light is directly related to the wavelength: low energy light has long wavelengths, while high energy light has short wavelengths. Thus, scientists have constructed several categories of light based on wavelength, and which you have certainly heard about: Gamma-ray, X-ray, Ultraviolet, Visible, Infrared, Microwave and Radio. Gamma- and X-rays have very short wavelengths and have lots of energy, so they penetrate through materials, and often damage them as they pass through. Ultraviolet light causes sunburns and skin cancer. Visible light is what our eyes detect. We feel intense infrared light as "heat", microwaves cook our food, while radio waves allow you to listen to music and watch television. The common textbook plot of the electromagnetic spectrum is shown in Fig 15.5. When we break-up light and plot how much energy is coming out at each wavelength, we construct a "spectrum". A spectrum of an object supplies a lot of information, and is the main tool astronomers use to understand the objects they study.

We can also think of the electromagnetic spectrum as a way to represent temperature. For example, objects that emit X-rays are at temperatures of millions of degrees, while objects that emit visible light have temperatures of thousands of degrees (like the Sun), while infrared sources have temperatures of 100's of degrees. To understand this concept, we must talk about "blackbody" radiation.

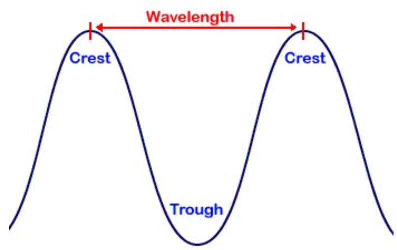


Figure 15.4: The wavelength is the distance between two crests.

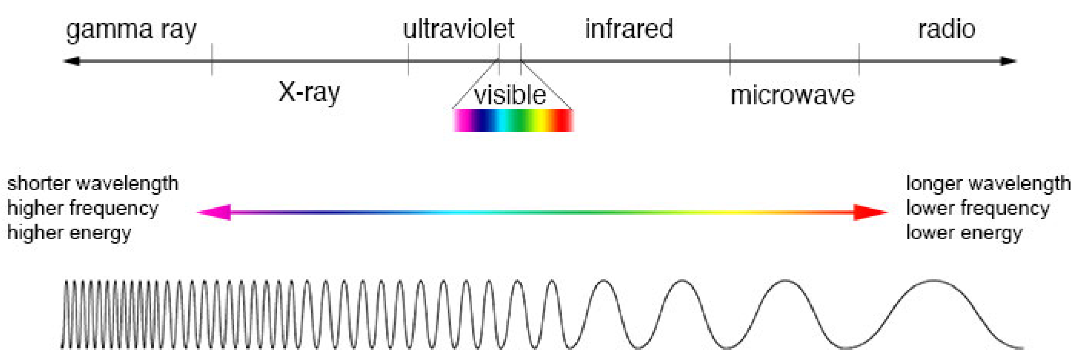


Figure 15.5: The electromagnetic spectrum.

15.4 Blackbody Radiation Review

Let us review the properties of **blackbody radiation**. A blackbody is an object that exactly satisfies the Stefan-Boltzmann law (named for the two scientists who first figured it out), and has a spectrum that is always the same shape, no matter what temperature the source has, as shown in Fig. 15.6. While real objects do not exactly behave like this, many objects come very close and in general we assume that most solar system objects (including

Io) are blackbodies.

The Stefan-Boltzmann law states that *the total amount of energy at all wavelengths emitted by a blackbody at temperature T is proportional ("$\propto$") to the fourth power of its temperature*, which can be written in equation form as:

$$E \propto T^4. \tag{16}$$

Here E is the amount of energy emitted by *each square meter* of the object each second. You might be wondering to yourself why we write E $\propto$ T^4, instead of E = T^4. In fact, the real blackbody equation is E = $s$$T^4$, where "$s$" is the "Stefan-Boltzmann constant." The Stefan-Boltzmann constant is a special number that makes the equation work, and insures that the output energy is in Watts (or another appropriate energy unit), instead of °F^4. You measure the energy of a light bulb in Watts, not the fourth power of degrees Fahrenheit. The actual value of s is 5.6703 × 10^{-8}. This is a horrible number to deal with, so we will use a technique that does not require us to remember it!

As noted in Fig. 15.6, the Wein displacement law relates the temperature of a blackbody, and the wavelength (λ) of its maximum emission: $\lambda_{\max} \times$ T = 3670, where 3670 is the value of "Wien's constant" when wavelength is measured in micrometers, and radiant energy in Watts/m^2 (as we will use in this lab).

Definition of Temperature

Before we go any further in understanding blackbodies, we must define the temperature scale that is used in the Stefan-Boltzmann formula, and in Wien's law. In the United States, our weather forecasts use the Fahrenheit scale. This scale was developed around the idea that in our everyday experience, a big number like "100° F" would be "hot", and "0° F" would be "very cold." On this scale water boils at 212° F, and freezes at 32° F. The Fahrenheit scale is not very easy to work with, in that it has 180° F between the boiling and freezing point of water (two processes that are easy to observe, allowing accurate calibration). With the development of the metric system, based on powers of 10, a temperature scale was developed where the freezing point of water was defined to be 0°, and the boiling point was set to 100°. This is the "Celsius" scale (denoted by "° C"), predominantly used outside the United States.

Both the Fahrenheit and Celsius scales, however, cannot be used with the blackbody energy equation. Why? Because both scales have "zeroes" and negative temperatures. Even in Las Cruces, the temperature often goes to 0° C or below on the Celsius scale during winter (and once in a while, as in 2010, it goes below zero on the Fahrenheit scale!). Look at our equation again, E $\propto$ T^4. If the temperature changes from 3° C to 0° C, the amount of energy emitted by a blackbody *would go from positive to zero.* If this object got colder and colder, however, its emitted energy would increase! For example, if its temperature had now dropped to −3° C, the emitted energy would be the *same* as it was at +3° C: E = −3 × −3 × −3 × −3 = 81 = 3 × 3 × 3 × 3. Do you see why this is? The fourth power (or any even power in the exponent) means that a negative number will turn out positive: $(10)^4$ =

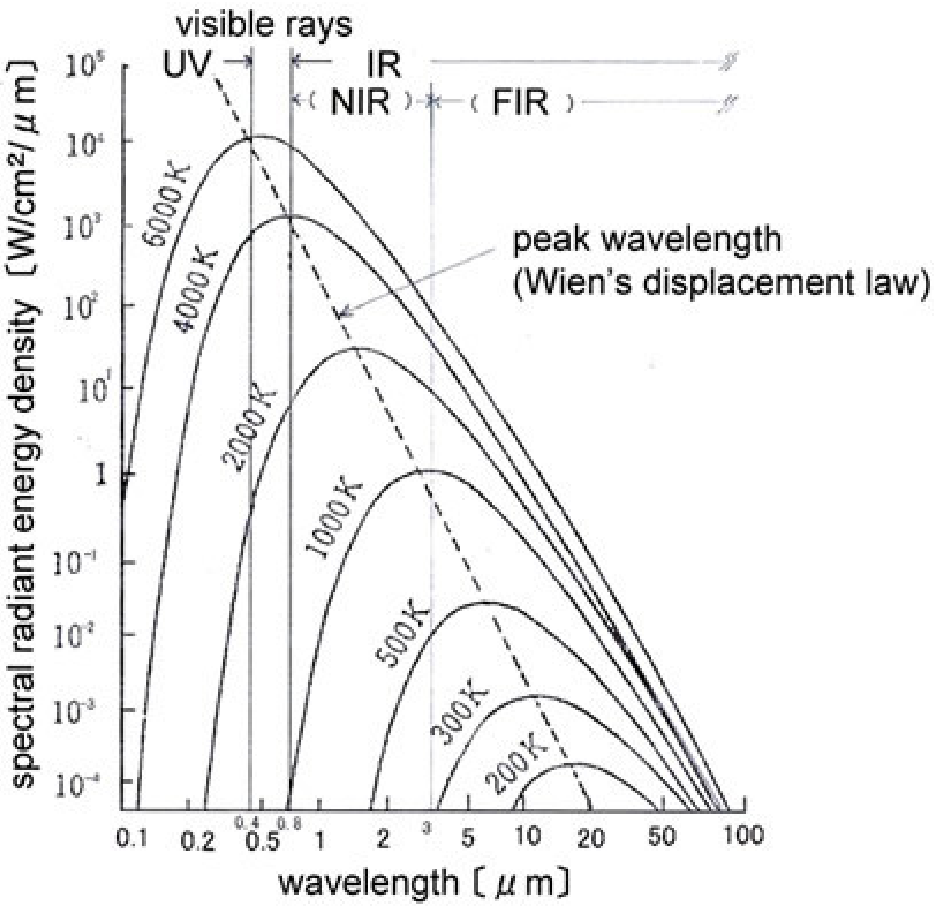


Figure 15.6: The spectra of blackbodies always have the same shape, but the wavelength where the *peak emission* occurs depends on temperature, and can be calculated using the "Wien displacement law" (since Wien is a German name, it is properly pronounced "Veen"). In this particular plot the unit of wavelength is the micrometer, 10^{-6} meter, symbolized by "μm." Note also that the x-axis is plotted as the *log* of wavelength, and the y-axis is the *log* of the radiant energy. We have to use this type of "log-log" plot since blackbodies cover a large range in radiant energy and wavelength, and we need an efficient way to compress the axes to make compact plots. We will be using these types of plots for the volcanoes of Io.

$(-10)^4 = 10{,}000$, because every time you multiply two negative numbers together, the result is a positive number.

If we were to use the Fahrenheit or Celsius temperature scales, our equation would produce nonsensical answers, since it is obvious that a hotter object has more energy than a colder one. Thus, scientists use a scale that has no negative numbers, the "Kelvin" scale. On the Kelvin scale, the temperature at which water freezes is 273 K, and it boils at 373 K (Kelvin has the same size degrees as the Celsius scale, and note also that the little degree symbol, "^{o}", is not used with Kelvin). In our example, 3^{o} C = 276 K, and 0^{o} C = 273 K. Now, a drop in temperature by 3 degrees does not cause the emitted energy to go from positive to zero, the energy simply decreases. There is a 0 K, but that temperature is so cold that any object with that temperature *would* emit zero energy (that, in fact, is the definition of 0 K!).

Working with the Stefan-Boltzmann Law

An equation like the Stefan-Boltzmann law is scary to many Astronomy 105 students. Nearly all of you have heard about "squares", such as the area of a circle being πR^2. But, there are many equations in science when the exponent is larger than 2. All an exponent says is that you must multiply the number by itself that many times: $R^2 = R \times R$. Or, $R^5 = R \times R \times R \times R \times R$. Other than the large numbers that come out of the Stefan-Boltzmann law (it is astronomy after all!), there is nothing difficult about understanding how to deal with T^4.

Ok, let's see how to use equation (1) so we can compare the energy emitted by *each square meter* of the surface of two different objects, A and B. We will construct the ratio so we do not have to worry about the value of the Stefan-Boltzmann constant:

$$\frac{E_A}{E_B} = \frac{sT_A^4}{sT_B^4} = \left(\frac{T_A}{T_B}\right)^4 \tag{17}$$

Do you understand what happened? We had an s on the top and bottom of our equation, but $s = s$, so it cancels out! We also use the property where $T_A^4 \div T_B^4 = (T_A/T_B)^4$ (in math this is called the "Power of a Quotient property").

Let's work an example. Object P has a temperature of 43 K, and object Q has a temperature of 33 K. The objects have the same area. How many times greater is the energy emitted by P compared to the energy emitted by Q? Set-up the equation:

$$\frac{E_P}{E_Q} = \frac{s(43)^4}{s(33)^4} = \left(\frac{43}{33}\right)^4 = (1.3)^4 = 1.3 \times 1.3 \times 1.3 \times 1.3 = 2.86 \tag{18}$$

Now it is your turn:

1. Assume that T_A, the surface temperature of Object A, is 200 K, and T_B, the surface temperature of Object B, is 100 K. The objects have the same area. How many times greater is the energy emitted by A compared to the energy emitted by B? (**2 points**)

2. Object R and Object S have the same temperature. But object R has an area of 4 square meters, and object S has an area of 2 square meters. How much more energy does object R emit compared to Object S? (**2 points**)

3. Now we are going to go backwards (much harder!): assume that we receive 81 times more energy from Object X than from Object Y. Object X and Y have the same areas. How many times hotter is the surface of X compared to the surface of Y? [Hint: what number multiplied by itself 4 times = 81?] (**2 points**)

We know that the last problem was hard! How does one solve such equations? The key to understanding this is to realize that for every mathematical operation that uses exponents, there is the reverse process of "taking the root". For example, two squared: $2^2 = 4$. What is the square root of 4? $\sqrt{4} = 2$. The square root can also be written as a fractional exponent: $(4)^{1/2} = 2$. This is how we solve the problem above. Here is an example: What is Q, if $Q^4 = 6561$? On a fancy scientific calculator, we just enter this: $(6561)^{1/4} = 9$. But the fourth root is really just two *successive* square roots: $\sqrt{6561} = 81$, $\sqrt{81} = 9 = (6561)^{1/4}$. So you do not need a fancy calculator, got it?

Working with Wien's Law

Unlike the Stefan-Boltzmann law, Wien's Law is very simple. So simple we do not think you need an example on how to use it! [Here is Wien's law again: $\lambda_{\rm max} \times$ T = 3670]

4. If the temperature of a black body is 1000 K, at what wavelength ($\lambda_{\rm max}$) does it emit its peak amount of energy? (Remember to include the wavelength unit!) (**2 points**)

5. An object is observed to have a blackbody spectrum that peaks at $\lambda_{\rm max} = 37\ \mu$m, what temperature is this object? (Remember to include the temperature unit!) (**2 points**)

15.5 Simulating Tidal Heating

As we noted above, the process of tidal heating is what causes Io to be covered in active volcanoes. In this exercise we are going to simulate tidal heating, where *you* are the source of the energy input. First off, however, have you ever tried to break a piece of wire with your hands? You cannot simply pull it apart with your hands, it is too strong. But we can break it by adding heat. We do this by first folding the wire to create a kink, and then rapidly bending the wire back and forth. The wire becomes very, very hot at the kink, and will eventually snap. What you have done is transfer energy your body generates and focused it on a tiny region of the wire. The intense heat weakens the wire and it snaps (you should try this with a paper clip). This process is what is going on in Io, a stretching/bending of the rock that generates heat.

Exercise #1:

Io is not a wire, it is a sphere! While the repeated bending of a wire is *exactly* like the process that is heating Io, it is not very realistic. Let's take this concept to a slightly more realistic level by "stretching" a sphere. Among the materials you were given were two, small exercise squeeze balls and a digital thermometer. We will now use these. To start this experiment, insert the thermometer into each of the balls and record the **Start Temperature**. Make sure the tip of the metal probe reaches the center of the ball (and no further!). Note that it also takes a certain amount of time for the temperature to stabilize at the correct value. Enter these values into Table 15.1.

Now, one member of your group should take a ball in each hand. One of these will be the "control ball", let's call that Ball #1. You will not do anything to Ball #1, except hold it in your hand. But for Ball #2, repeatedly, as rapidly as possible, squeeze this ball as tightly as possible, release, and repeat. *Do this for four straight minutes (one group member needs to be the time keeper!).* At the end of four minutes, as quickly as you can, insert the thermometer into the ball you have been squeezing and record the temperature. Note that it takes quite a few seconds for the temperature to read the correct value, continue to squeeze this ball *with* the thermometer inserted, until the temperature no longer rises. Record this value in the "End Temperature" column for Ball #2. Now, do the same for Ball #1, but do not squeeze, simply continue to quietly hold it in your hand while the thermometer rises to its maximum temperature. Put this value in Table 15.1. [If you cannot repeatedly squeeze Ball #2 for four straight minutes in one hand, go ahead and switch hands, as long as the same ball is the one that continues to get squeezed.]

Take the difference between the End and Start temperatures and enter it into the final column of Table 15.1. (**6 points**)

Table 15.1: Exercise Ball Temperatures

	Start Temperature	**End Temperature**	**Change in Temperature**
Ball #1			
Ball #2			

Answer the following questions: Are the start and end temperatures for both balls different? Why do you think we had you hold onto Ball #1 the entire time you were squeezing Ball #2? Which ball showed the greater temperature rise? Why did this happen, and where did this energy come from? (**6 points**)

15.6 Investigating the Volcanoes of Io

Now to the main part of today's lab, the volcanoes of Io. Along with the other lab materials, we have supplied you with a three ring binder containing images of Io, along with a large laminated map of Io. Please do not write on any of these items! The first section contains some images of Io taken with the Galileo spacecraft. Just page through them to get familiar with Io (including color versions of the Figures in the introduction of this lab). Io is an unusual place!

Today we are going to look at images and data obtained with three different instruments of the Galileo spacecraft: the Solid State Imager (SSI), the Near-Infrared Mapping Spectrometer (NIMS), and the Photopolarimeter-Radiometer (PPR). The SSI is simply a ("0.6 megapixel") digital camera not unlike the one in your smart phone, and only can detect visible light (technically wavelengths from 0.4 to 1.1 μm). NIMS is also an imager, but it detects near-infrared light, having wavelengths from 0.7 to 5.2 μm (your TA will demonstrate a version of this type of infrared camera during lab). The PPR measures the heat output of objects (not really an imager, though you could make coarse pictures with it), and could detect light with wavelengths from 17 to 110 μm.

Let's go back and look at Fig. 15.6. Do you understand why these instruments were included on a mission to Jupiter? The Sun has a blackbody temperature of about 6,000 K, what is the wavelength of peak emission for such a blackbody? This is the light that illuminates the Earth during the day, and all of the other objects in our solar system. Thus, to see these objects, we only need a regular camera (the SSI). But Jupiter is very far from the Sun, and thus it is very cold place. For example, at the surfaces of the Galilean satellites, the temperatures are about 100 K. To measure such cold objects, we need an instrument like the PPR. If there are hot spots on Jupiter or any of its moons (like Io!), they might have temperatures between 500 and 2000 K, and we will need a "near-infrared" camera like NIMS to detect this light.

In the second section of the three ring binder are some NIMS images. The first set of images shows a color picture of Io obtained with the SSI, and two images obtained with NIMS (at 1.593 and 4.133 μm). Note that in the SSI image there are bright and dark regions all over Io. In the NIMS images, however, Io begins to look quite different. In image #5a, at 1.593 μm there is still *some* reflected sunlight (since this is a daytime NIMS image), but by 4.133 μm thermal (blackbody) emission from Io is now strong.

Exercise #2

6. In image #5a, we see that at 4.133 μm there are many bright spots. Returning to Fig. 15.6 (above), estimate the temperature of these bright spots. [Hint: can you see the bright spots at 1.593 μm? What is the hottest blackbody in this figure that has a lot of emission at 4.133 μm, but (almost) none at 1.593 μm?] (**4 points**)

7. In image #5b, around the dark spot near the center of the 1.3 μm image, there is a bright ring. But this ring is very dark at 4.2 μm, suggesting it is very cold. How can it be bright at 1.3 μm, and dark at 4.2 μm? These are daytime images. Can you explain this feature? [Hint: think about snow] (**4 points**)

8. In Fig. 15.7, below, are plotted two blackbodies (energy emitted in Watts vs. wavelength in micrometers). Using Wien's law, what are the approximate temperatures of each of these blackbodies (one **solid** line, one **dashed**) in "K"? Which one is emitting more total energy? How do you explain this? (**4 points**)

Exercise #3

In section 3 of the binder, we have some NIMS images of active regions on Io. On these images are some small, numbered boxes, we will be looking at the NIMS + PPR spectra of some of these boxed regions to determine their temperatures. The names of the features on Io are from a variety of mythologies that have to do with deities of fire, volcanoes, the Sun, thunder and characters and places from Dante's Inferno. Named mountains, plateaus, layered terrain, and shield volcanoes are given the terms mons, mensa, planum, and tholus, respectively. The term "Patera" (plural = Paterae) means a bowl, and brighter, whitish regions go by the name "Regio".

9. Region #1 (Image #6) is a night time NIMS image of a region on Io. In this image, you can see lines of longitude and latitude. It basically runs from 125°W to 132°W in longitude, and from +59° to +71° in latitude. Using the big map of Io, what is the name of this active region? [Note: an SSI image of this region is shown in binder image #4!] (**2 points**)

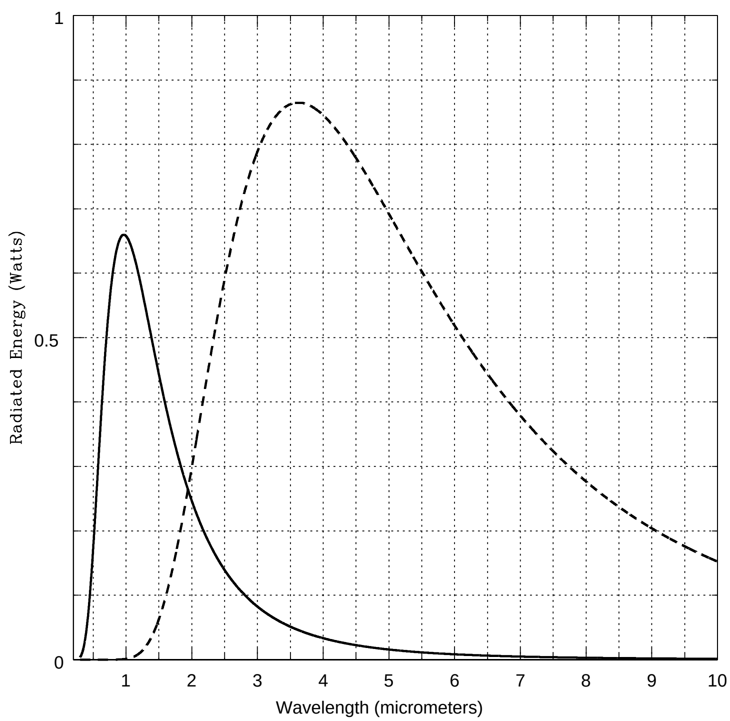


Figure 15.7: The energy vs. wavelength, the "spectra" (spectra is plural of spectrum), produced by two blackbodies with different temperatures.

11. It is clear the NIMS instrument does not make very pretty pictures, it has “poor resolution”. When this camera was built, infrared imaging technology was just becoming possible. The infrared camera that your TA has demonstrated today in class is as good, or better than NIMS! In these NIMS images, redder colors mean hot, and bluer colors mean cool. Compare the Region #1 NIMS image to Image #4 in the binder from the SSI (they have totally different orientations!!!). Can you figure out what is happening? Can you figure out which boxes in the NIMS image cover the hot, glowing lava feature in the SSI image? (**6 points**)

12. The NIMS image of Region #2 is shown as Image #7. Using the large map, what is the name of this region? (**2 points**)

13. In fact, the NIMS image of Region #2 does not cover all of this large feature, does it? In Fig. 15.8 we present the NIMS + PPR spectra of the six boxes shown identified in Image #7. Using the plastic blackbody overlay, measure the temperatures for *only* boxes 1 and 4. [If you are having trouble doing this, ask your TA for help.] (**4 points**)

Table 15.2: Region #2 Box Temperatures

Box	**Maximum Wavelength (μm)**	**Temperature (K)**
Box #1		
Box #4		

14. The radius of Io is 1,821.3 km, that means that the circumference of Io is ($C = 2\pi R$) 11,443.6 km. Since there are 360° in a circle, each degree of *latitude* represents 31.79 km. Assuming the northern half of this glowing ring has the same size as the southern

half, what is the total area covered by the hot material of this feature? [Hint: The latitude increases from the bottom to the top of the image (approximately the y-axis of the figure), while the horizontal (x-axis) direction is longitude. Note that the white grid lines are identical in size in the vertical and horizontal directions, thus you can measure both sides of the box in degrees of latitude (note that degrees of longitude only equal degrees of latitude at the equator, and this region is not at the equator!). The degrees of latitude are the small white numbers that run from 9 to 13.]

The area of a square is simply *side* × *side* = s^2. Calculate the area in square kilometers of one white grid box (not the tiny little boxes you measured the temperatures for!). Next, estimate the number of such grid squares *fully* covered by the "hot" reddish regions for the southern half of this feature (this will be a fraction of a grid box for some spots). The total area in square kilometers is the number of boxes covered times the area of one box—find this number. Multiply that result by two, and you have the approximate area of the entire feature. (**6 points**)

15. Now we want to figure out the total energy output of all of the volcanoes on Io. Step 1: In the large map of Io, the paterae are the brown regions. You can see that the volcano you just measured is just about the largest such feature on Io. The average patera appears to have about 5% (= 0.05) the area of this feature. Estimate the total area covered by *all of the paterae* on Io. [Hint: note what we said in the introduction about the estimated number of volcanoes on Io.] (**4 points**)

Total Volcano Area = Average area × number of volcanoes = ____ km^2

Total Volcano Area = ____ × ____ = ____ km^2

16. Step 2: Figure out the total area of Io. The area of a sphere is $4\pi R^2$. (**3 points**)

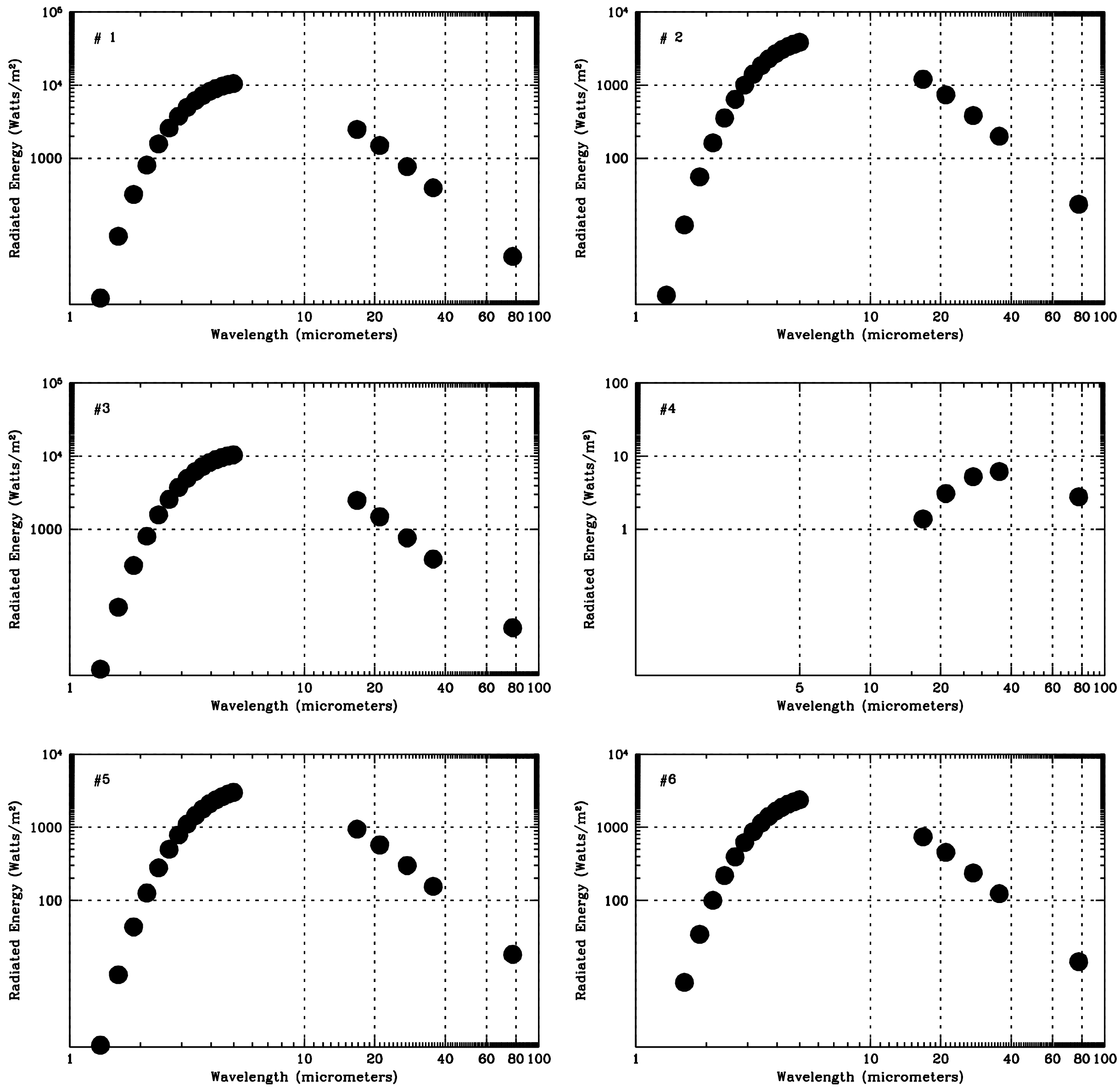


Figure 15.8: The blackbody spectra of the six boxes shown in Image #7. Be careful, these plots have *log* wavelength on the x-axis.

17. Step 3: We will assume that the average surface temperature of the non-volcanic regions on Io is the same as that of box #4 on Image #7 that you found above. We will assume that the average temperature of the paterae is the same as that of box #1 on Image #7 that you found above. Now, we are going to use the Stephan-Boltzmann law to calculate how much energy the volcanoes on Io put out compared to the rest of Io. Remember, the Stephan-Boltzmann law was the amount of energy output per unit area (m^2):

$$\frac{E_A}{E_B} = \frac{sT_A^4}{sT_B^4} = \left(\frac{T_A}{T_B}\right)^4 \tag{19}$$

Since in this problem we have two different emitting areas (total Io area, and area covered by volcanoes), we have to modify this law to explicitly include the area terms:

$$\frac{(Total\ Emitted\ Energy)_A}{(Total\ Emitted\ Energy)_B} = \frac{Area_A}{Area_B} \times \left(\frac{T_A}{T_B}\right)^4 \tag{20}$$

So,

$$\frac{(Total\ Emitted\ Energy)_{Volcano}}{(Total\ Emitted\ Energy)_{Io}} = \frac{(Area)_{Volcano}}{(Area)_{Io}} \times \left(\frac{T_{\#1}}{T_{\#4}}\right)^4 \tag{21}$$

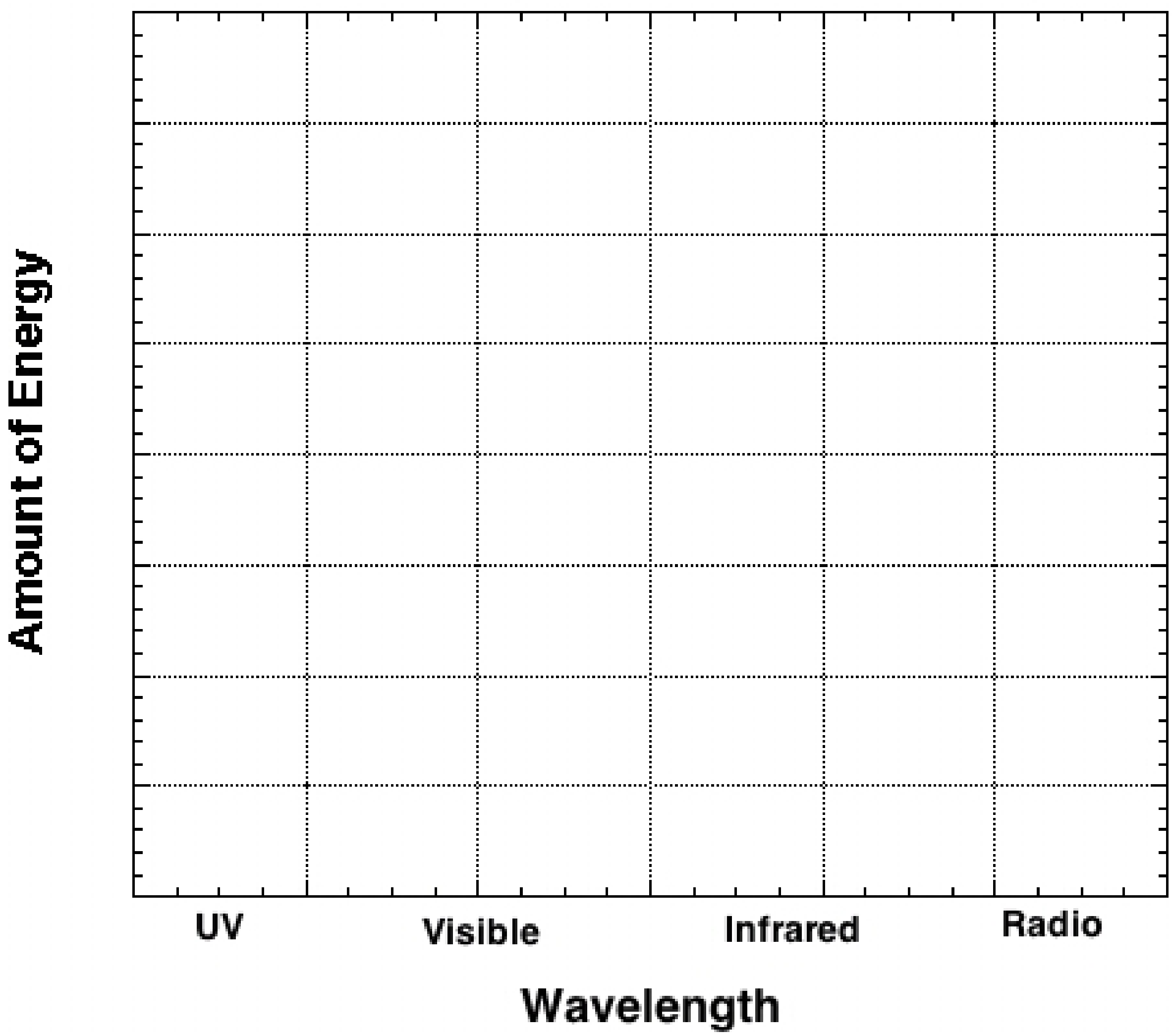
$$\frac{(Total\ Emitted\ Energy)_{Volcano}}{(Total\ Emitted\ Energy)_{Io}} = \tag{22}$$

The volcanoes on Io put out how much more energy than the total *for all of* Io? Do you find this surprising? Note that the Sun is far away (5.2 AU), and cannot heat-up Io very much. Thus, gravitational heating can be very important. This process is probably going on elsewhere in the solar system (such as with the moons of Saturn). What does this mean for the possibility of life existing on/inside these moons? (**4 points**)

Name:________________________________
Date:_________________________________

15.7 Take-Home Exercise (35 points total)

1. In the graph below, draw two curves indicating the blackbody curves (energy as a function of wavelength) emitted by i) a hot object (T = 6,000 K), and ii) a cool object (T = 1,000 K). Both objects have the same area. You will be graded on the *relative positions* of these two curves with respect to one another, as well as which one emits more energy. Label the y-axis with the appropriate numbers, and identify the blackbody curves! (**10 points**)



2. If Europa and Ganymede were further from Jupiter (had larger orbits), but Io remained where it is, would you still expect Io to experience volcanism? Explain. (**10 points**)

3. The colorful volcanic features we have studied in this lab involve the chemical element sulfur. It is not expected that molten sulfur gets any hotter than $\sim$ 350 Kelvin or so on Io's surface. As you have found out, however, many spots on Io's surface have been determined to possess temperatures that are much hotter, some as hot as 1800 K! It is believed that such regions must consist of molten rock (silicates, like lava here on Earth) and not molten sulfur.

   a) How many times greater would the flux from such a rock-lava region be compared to the flux emitted by the colder regions of Io (such as you measured in Exercise #3, question #13). (**3 points**)

   b) At what wavelength would the maximum (peak) energy emission occur from this 1,800 K region? (**2 points**)

c) Returning to Figure 15.6, would this very hot lava be detectable with the SSI? Explain. (**5 points**)

4. Jupiter has several moons that are much, much smaller than Io and that orbit even closer to Jupiter than Io. Give a brief explanation of why these moons do NOT show evidence of volcanism [Hint: think of a man-made satellite in Earth orbit, even a *big* one such as the International Space Station]. (**5 points**)

15.8 Possible Quiz Questions

1. Why does Io have volcanoes?

2. What does the term "orbital resonance" mean?

3. What is a "blackbody"?

4. What is Wien's law?

5. What does the term "patera" mean?

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

Orbital resonances are found elsewhere in the solar system. For example, the shaping of Saturn's ring system, or the relationship between Neptune and Pluto. Type-up a one page discussion of how orbital resonances affect the appearance of Saturn's rings, or how the Neptune-Pluto orbital resonance gives us insight into the processes that shaped the formation of our solar system.

Name:______________________________

Date:______________________________

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

16.1 Introduction

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

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

16.2 Asteroids and Comets

There are two main types of objects in the solar system that represent left over material from its formation: asteroids and comets. In fact, both objects are quite similar, their differences arise from the fact that comets are formed from material located in the most distant parts of our solar system, where it is very cold, and thus they have large quantities of frozen water and other frozen liquids and gases. Asteroids formed closer-in than comets, and are denser, being made-up of the same types of rocks and minerals as the terrestrial planets (Mercury, Venus, Earth, and Mars). Asteroids are generally just large rocks, as shown in the Figure 16.1.

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

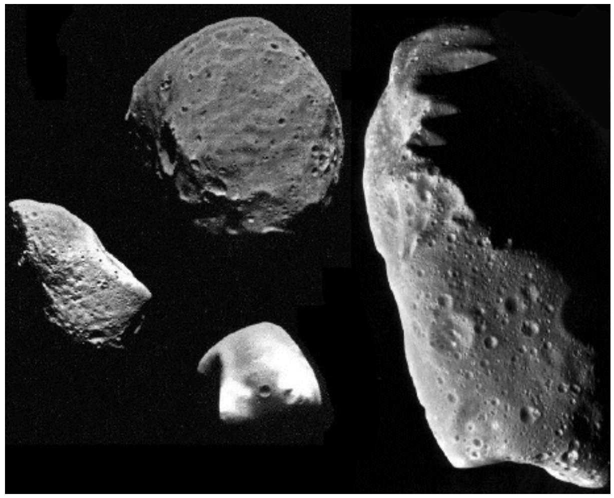


Figure 16.1: Four large asteroids. Note that these asteroids have craters from the impacts of even smaller asteroids!

3,476 km). There are now more than 40,000 asteroids that have been discovered, ranging in size from Ceres, all the way down to large rocks that are just a few hundred meters across. It has been estimated that there are at least 1 million asteroids in the solar system with diameters of 1 km or more. Most asteroids are harmless, and spend all of their time in orbits between those of Mars and Jupiter (the so-called "asteroid belt", see Figure 16.2). Some asteroids, however, are in orbits that take them inside that of the Earth, and could

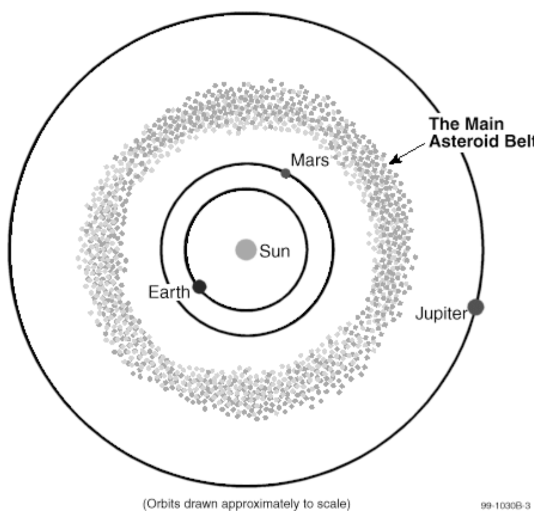


Figure 16.2: The Asteroid Belt.

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.

16.3 Comets

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

16.4 Composition and Components of a Comet

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

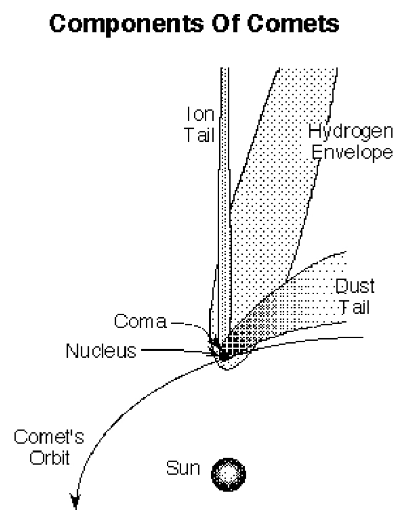


Figure 16.3: The main components of a comet.

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

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

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

These various components of a comet are shown in Figure 16.3.

16.5 Types of Comets

Comets originate from two primary locations in the solar system. One class of comets, called the **long-period comets**, have long orbits around the sun with periods of > 200 years. Their orbits are random in shape and inclination, with long-period comets entering the inner solar system from all different directions. These comets are thought to originate in the **Oort cloud**, a spherical cloud of icy bodies that extends from $\sim$ 20,000 – 150,000 AU from the Sun (see Figure 16.4). Some of these objects might experience only one close approach to the Sun and then leave the solar system (and the Sun's gravitational influence) completely.

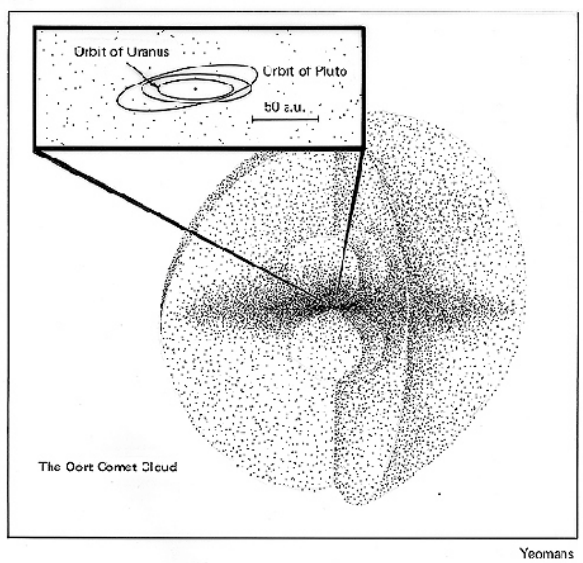


Figure 16.4: The Oort cloud.

In contrast, the **short-period comets** have periods less than 200 years, and their orbits are all roughly in the plane of the solar system. Comet Halley has a 76-year period, and therefore is considered a short-period comet. Comets with orbital periods < 100 years do not get much beyond Pluto's orbit at their farthest distance from the Sun. Short-period comets cannot survive many orbits around the Sun before their ices are all melted away. It is thought that these comets originate in the **Kuiper Belt,** a belt of small icy bodies beyond the large gas giant planets and in the plane of the solar system (see Fig. 16.5). Quite a few large Kuiper Belt objects have now been discovered, including one (Eris) that is about the same size as Pluto.

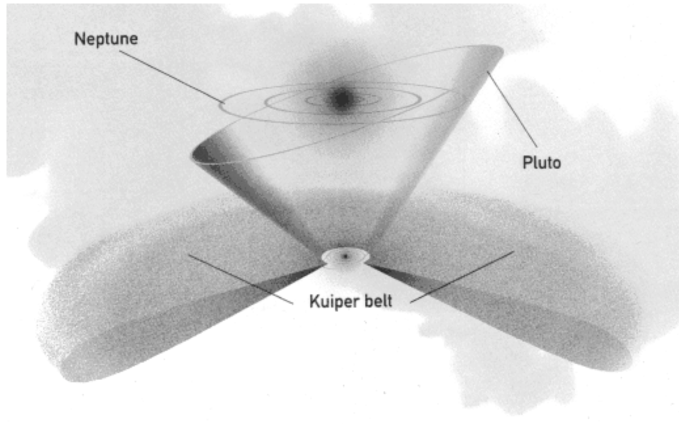


Figure 16.5: The Kuiper Belt.

16.6 The Impacts of Asteroids and Comets

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

16.7 Exercise #1: Creating Impact Craters

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

1. Have one member of your lab group take the meter stick, while another takes the smaller ball bearing.

2. Take the plastic tub that is filled with flour, and place it on the floor.

3. Make sure the flour is uniformly level (shake or comb the flour smooth)

4. Carefully hold the meter stick so that it is just touching the top surface of the flour.

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

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

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

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

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

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

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

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

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

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

16.7.1 Impact crater questions

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

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

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

16.8 Crater Illumination

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

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

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

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

16.9 Exercise #2: Building a Comet

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

1. Put a freezer bag in your bucket.
2. Place about 1/3 cup of water in the bag/bucket.
3. Add 2 spoonfuls of sand, stirring well. (**NOTE:** Do not stir so hard that you rip the freezer bag!)
4. Add a dash of ammonia.
5. Add a dash of organic material (potting soil). Stir until well-mixed.
6. Your TA will place a block or chunk of dry ice inside a towel and crush the block with the mallet and give you some crushed dry ice.
7. Add about 1 cup of crushed dry ice to the bucket, while stirring vigorously. (**NOTE:** Do not stir so hard that you rip the freezer bag!!)
8. Continue stirring until mixture is almost frozen.
9. Lift the comet out of the bucket, keeping it in the freezer bag, and shape it for a few seconds as if you were building a snowball (wear gloves!).

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

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

16.9.1 Comets and Light

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

- shape
- color
- smell

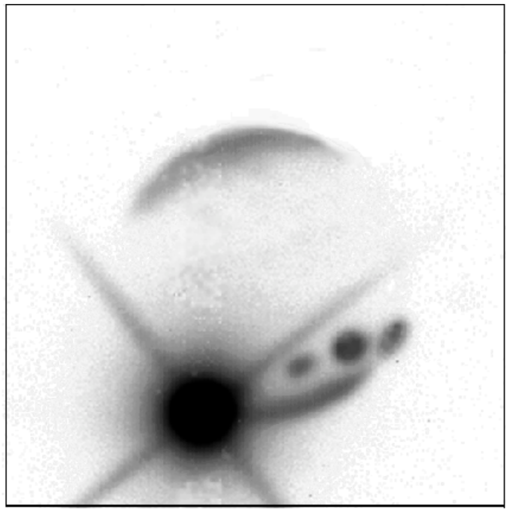
Now bring the comet over to a high intensity light source (overhead projector), or heat source (hairdryer) and place it on top. Observe what happens.

16.9.2 Comet Strength

Comets, like all objects in the solar system, are held together by their internal strength. If they pass too close to a large body, such as Jupiter, their internal strength is not large enough to compete with the powerful gravity of the massive body. In such encounters, a comet can be broken apart into smaller pieces. In 1994, we saw evidence of this when Comet Shoemaker-Levy/9 impacted into Jupiter. In 1992, that comet passed very close to Jupiter and was fragmented into pieces. Two years later, more than 21 cometary fragments crashed into Jupiter's atmosphere, creating spectacular (but temporary) "scars" on Jupiter's cloud deck (see Fig. 16.6).

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

Exercise: After everyone in your group has carefully examined your comet, it is time to say goodbye. Take a sample rock and your comet, go outside, and drop them both on the sidewalk. What happened to each object? (**2 points**)



Impact of Fragment K of Comet Shoemaker-Levy on Jupiter.
The scars of three previous impacts can be seen on the planetary disk.

Image from Peter McGregor and Mark Allen, ANU 2.3m telescope.
Instrument: CASPIR at 2.34μm. Colour Image Mt Stromlo Observatories.

Figure 16.6: The Impact of "Fragment K" of Comet Shoemaker-Levy/9 with Jupiter.

16.9.3 Comet Questions

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

2. What are some differences between long-period and short-period comets? Does it make sense that they are two distinct classes of objects? Why or why not? (**5 points**)

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

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

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

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

16.10 Summary

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

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

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

16.11 Possible Quiz Questions

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

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

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

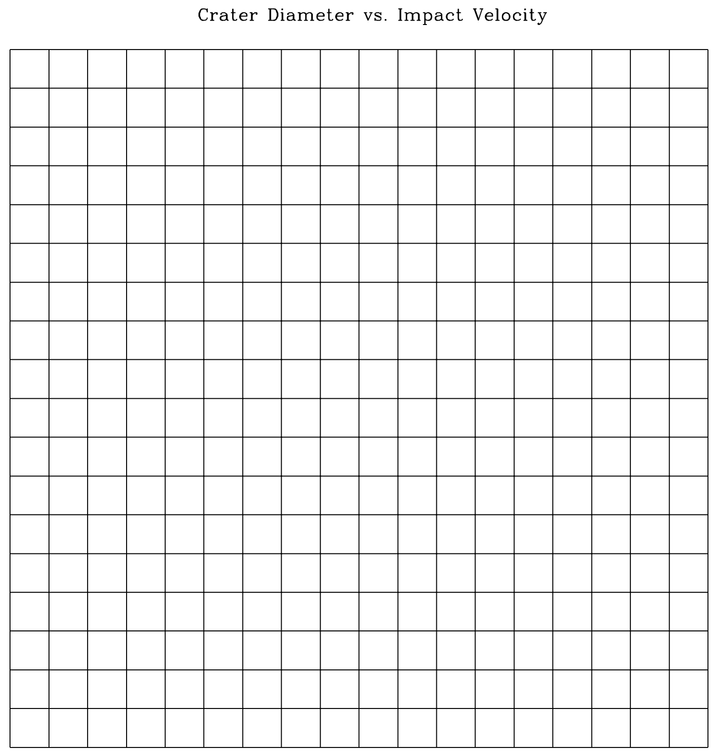


Figure 16.7: Plot your impact crater data here.

Name:____________________________________

Date:____________________________________

17 Our Sun

17.1 Introduction

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

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

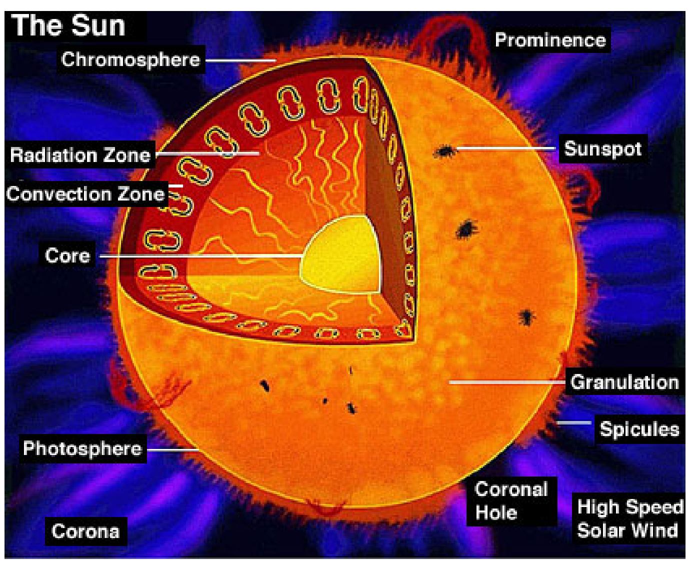


Figure 17.1: A diagram of the various layers/components of the Sun, as well as the appearance and location of other prominent solar features.

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

17.2 Layers of the Sun

One of the things we know best about the Sun is its overall structure. Figure 17.1 is a schematic of the layers of the Sun's interior and atmosphere. The interior of the Sun is made up of three distinct regions: the core, the radiative zone, and the convective zone. The *core* of the Sun is very hot and dense. This is the only place in the Sun where the temperature and pressure are high enough to support nuclear reactions. The *radiative zone* is the region of the sun where the energy is transported through the process of radiation. Basically, the photons generated by the core are absorbed and emitted by the atoms found in the radiative zone like cars in stop and go traffic. This is a very slow process. The *convective zone* is the region of the Sun where energy is transported by rising "bubbles" of material. This is the same phenomenon that takes place when you boil a pot of water. The hot bubbles rise to the top, cool, and fall back down. This gives the the surface of the Sun a granular look. Granules are bright regions surrounded by darker narrow regions. These granules cover the entire surface of the Sun.

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

17.3 Sunspots

Sunspots appear as dark spots on the photosphere (surface) of the Sun (see Figure 17.2). They last from a few days to over a month. Their average size is about the size of the Earth, although some can grow to many times the size of the Earth! Sunspots are commonly found in pairs. How do these spots form?

The formation of sunspots is attributed to the Sun's *differential rotation.* The Sun is a ball of gas, and therefore does not rotate like the Earth, or any other solid object. The Sun's equator rotates faster than its poles. It takes roughly 25 days for material to travel once around the equator, but about 35 days for it to travel once around near the north or south poles. This differential rotation acts to twist up the magnetic field lines inside the

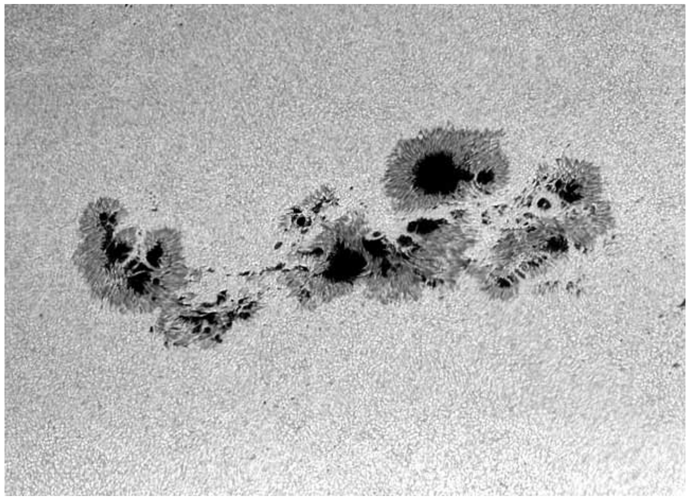


Figure 17.2: A large group of Sunspots. The "umbra" is the darker core of a sunspot, while the "penumbra" is its lighter, frilly edges.

Sun. At times, the lines can get so twisted that they pop out of the photosphere. Figure 17.3 illustrates this concept. When a magnetic field loop pops out, the places where it leaves and re-enters the photosphere are cooler than the rest of the Sun's surface. These cool places appear darker, and therefore are called "sunspots".

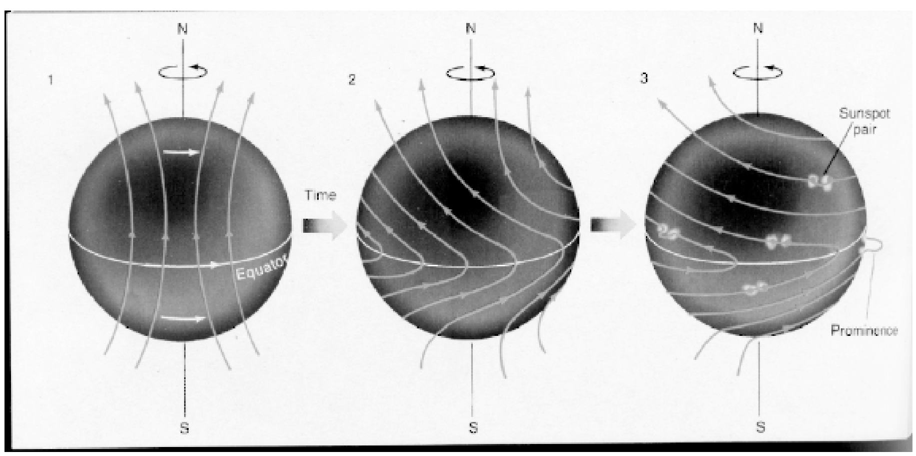


Figure 17.3: Sunspots are a result of the Sun's differential rotation.

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

17.4 Solar Phenomenon

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

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

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

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

17.5 Lab Exercises

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

17.5.2 Exercise #2: Exploring Magnetic Fields

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

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

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

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

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

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

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

- The iron filings trace the magnetic field lines of the bar magnet. The field lines surround the magnet in all dimensions (though we can only easily show them in two dimensions). Your TA will show you a device that has a bar magnet inside a plastic case to demonstrate the three dimensional nature of the field. Compare the pattern of the iron filings around the bar magnet to the picture of the sunspot shown in Figure 17.4. They are similar! What does this imply about sunspots? **(3 points)**

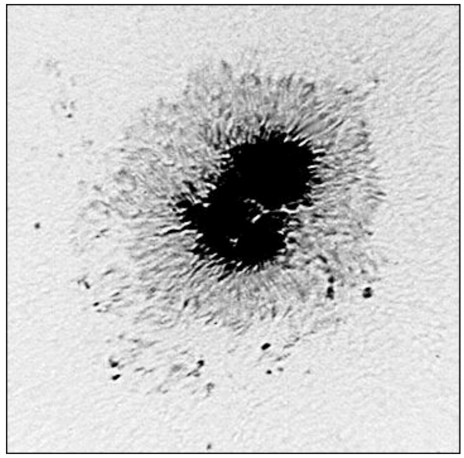


Figure 17.4: The darker region of this double sunspot is called the "umbra", while the less dark, filamentary region is called the "penumbra". For this sunspot, one umbra has a "North polarity", while the other has a "South polarity".

- Now, lets imagine what a fully three dimensional magnetic field looks like. The pattern of the iron filings around the bar magnet would also exist into the space *above* the bar magnet, but we cannot suspend the iron filings above the magnet. Complete Figure 17.5 by drawing-in what you imagine the magnetic field lines look like *above* the bar magnet. **(3 points)**

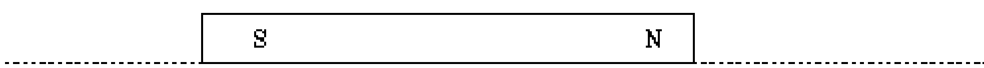


Figure 17.5: Draw in the field lines above this bar magnet.

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

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

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

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

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

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

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

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

- Take the two ends of the wire that is wound around the bolt and hook them to the terminals of the lantern battery (or 6V transformer). You now have an electromagnet.

Move the compass slowly around the electromagnet. Describe its behavior, does it act like the bar magnet? **(2 points)**

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

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

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

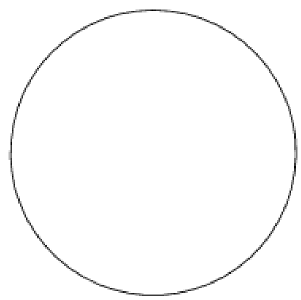
17.5.4 Exercise #3: Looking at the Sun

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

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

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

Solar Observation Worksheet



Name: ____________________ Lab Sec.: __________

Date: ____________________ TA: ______________

17.6 Summary (35 points)

Please summarize the important concepts discussed in this lab.

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

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

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

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

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

Name:______________________________
Date:_______________________________

18 Characterizing Exoplanets

18.1 Introduction

Exoplanets are a hot topic in astronomy right now. As of January, 2015, there were over 1500 known exoplanets with more than 3000 candidates waiting to be confirmed. These exoplanets and exoplanet systems are of great interest to astronomers as they provide information on planet formation and evolution, as well as the discovery of a variety of types of planets not found in our solar system. A small subset of these planetary systems are of interest for another reason: They may support life. In this lab you will analyze observations of exoplanets to fully characterize their nature. At the end, you will then compare your results with simulated images of these exoplanets to see how well you performed. Note that the capabilities required to intensely study exoplanets have not yet been built and launched into space. But we know enough about optics that we can envision a day when advanced space telescopes, like those needed for the conclusion of today's lab, will be in Earth orbit and will directly image these objects, as well as obtain spectra to search for the chemical signatures of life.

18.2 Types of Exoplanets

As you have learned in class this semester, our solar system has two main types of planets: Terrestrial (rocky) and Jovian (gaseous). Because these were the only planets we knew about, it was hard to envision what other kinds of planets might exist. Thus, when the first exoplanet was discovered, it was a shock for astronomers to find out that this object was a gas giant like Jupiter, but had an orbit that was even smaller than that of Mercury! This lead to a new kind of planet called "Hot Jupiters". In the two decades since the discovery of that first exoplanet, several other new types of planets have been recognized. Currently there are six major classes that we list below. We expect that other types of planets will be discovered as our observational techniques improve.

18.2.1 Gas Giants

Gas giants are planets similar to Jupiter, Saturn, Uranus, and Neptune. They are mostly composed of hydrogen and helium with possible rocky or icy cores. Gas giants have masses greater than 10 Earth masses. Roughly 25 percent of all discovered exoplanets are gas giants.

18.2.2 Hot Jupiters

Hot Jupiters are gas giants that either formed very close to their host star or formed farther out and "migrated" inward. If there are multiple planets orbiting a star, they can interact through their gravity. This means that planets can exchange energy, causing their orbits to expand or to shrink. Astronomers call this process migration, and we believe it happened early in the history of our own solar system. Hot Jupiters are found within 0.05-0.5 AU of their host star (remember that the Earth is at 1 AU!). As such, they are extremely hot (with temperatures as high as 2400 K), and are the most common type of exoplanet found; about 50 percent of all discovered exoplanets are Hot Jupiters. This is due to the fact that the easiest exoplanets to detect are those that are close to their host star and very large. Hot Jupiters are both.

18.2.3 Water Worlds

Water worlds are exoplanets that are completely covered in water. Simulations suggest that these planets actually formed from debris rich in ice further from their host star. As they migrated inward, the water melted and covered the planet in a giant ocean.

18.2.4 Exo-Earths

Exo-Earths are planets just like the Earth. They have a similar mass, radius, and temperature to the Earth, orbiting within the "habitable zone" of their host stars. Only a very small number of Exo-Earth candidates have been discovered as they are the hardest type of planet to discover.

18.2.5 Super-Earths

Super-Earths are potentially rocky planets that have a mass greater than the Earth, but no more than 10 times the mass of the Earth. "Super" only refers to the mass of the planet and has nothing to do with anything else. Therefore, some Super Earths may actually be gas planets similar to (slightly) smaller versions of Uranus or Neptune.

18.2.6 Chthonian Planets

"Chthonian" is from the Greek meaning "of the Earth." Chthonian Planets are exoplanets that used to be gas giants but migrated so close to their host star that their atmosphere was stripped away leaving only a rocky core. Due to their similarities, some Super Earths may actually be Chthonian Planets.

18.3 Detection Methods

There are several methods used to detect exoplanets. The most useful ones are listed below.

18.3.1 Transit Method/Light Curves

The transit method attempts to detect the "eclipse" of a star by a planet that is orbiting it. Because planets are tiny compared to their host stars, these eclipses are very small, requiring extremely precise measurements. This is best done from space, where observations can be made continuously, as there is no night or day, or clouds to get in the way. This is the detection method used by the *Kepler* Space Telescope. *Kepler* stared at a particular patch of sky and observed over a hundred thousand stars continuously for more than four years. It measured the amount light coming from each star. It did this over and over, making a new measurement every 30 minutes. Why? If we were looking back at the Sun and wanted to detect the Earth, we would only see one transit per year! Thus, you have to continuously stare at the star to insure you do not miss this event (as you need at least three of these events to determine that the exoplanet is real, and to measure its orbital period). The end result is something called a "light curve", a graph of the brightness of a star over time. The entire process is diagrammed in Figure 18.6. We will be exclusively using this method in lab today.

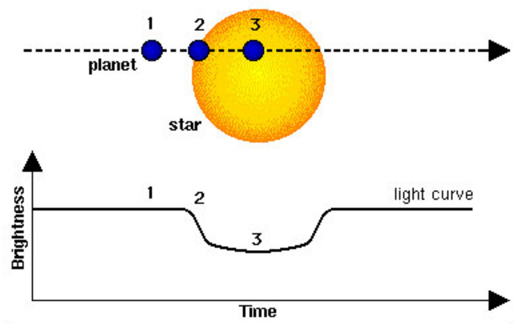


Figure 18.6: The diagram of an exoplanet transit. The planet, small, dark circle, crosses in front of the star as seen from Earth. In the process, it blocks out some light. The light curve, shown on the bottom, is a plot of brightness versus time, and shows that the star brightness is steady until the exoplanet starts to cover up some of the visible surface of the star. As it does so, the star dims. It eventually returns back to its normal brightness only to await the next transit.

In Figure 18.6, there is a dip in the light curve, signifying that an object passed between the star and our line of sight. If, however, *Kepler* continues to observe that star and sees the same sized dip in the light curve on a periodic basis, then it has probably detected an exoplanet (we say "probably" because a few other conditions must be met for it to be a confirmed exoplanet). The amount of star light removed by the planet is very small, as all planets are much, much smaller than their host stars (for example, the radius of Jupiter is 11 times that of the Earth, but it is only 10% the radius of the Sun, *or 1% of the area = how much the light dims*). Therefore, it is much easier to detect planets that are larger because they block more of the light from the star. It is also easier to detect planets that are close to their host star because they orbit quickly so *Kepler* could observe several dips in the light curve each year.

18.3.2 Direct Detection

Direct detection is exactly what it sounds like. This is the method of imaging (taking a picture) of the planets around another star. But we cannot simply point a telescope at a star and take a picture because the star is anywhere from 100 million (10^8) to 100 billion (10^{11}) times brighter than its exoplanets. In order to combat the overwhelming brightness of a star, astronomers use what is called a "coronagraph" to block the light from the star in order to see the planets around it. You may have already seen images made with a coronagraph to see the "corona" of the Sun in the Sun lab.

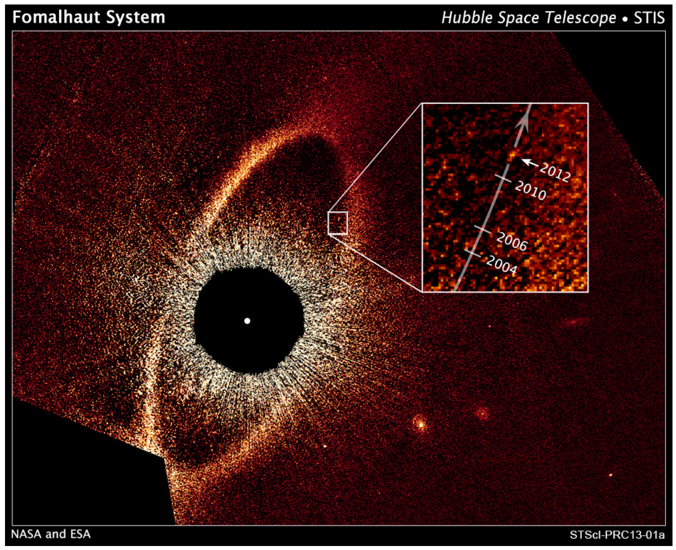


Figure 18.7: A coronagraphic image of an exoplanet orbiting the star Fomalhaut (inside the box, with the arrow labeled "2012"). This image was obtained with the Hubble Space Telescope, and the star's light has been blocked-out using a small metal disk. Fomalhaut is also surrounded by a dusty disk of material—the broad band of light that makes a complete circle around the star. This band of dusty material is about the same size as the Kuiper belt in our solar system. The planet, "Fomalhaut B", is estimated to take 1,700 years to orbit once around the star. Thus, using Kepler's third law ($P^2 \propto a^3$), it is roughly about 140 AU from Fomalhaut (remember that Pluto orbits at 39.5 AU from the Sun).

So if astronomers can block the light from the Sun to see its corona, they should be able to block the light from distant stars to see the exoplanets right? While this is true, directly seeing exoplanets is difficult. There are two problems: the exoplanet only shines by reflected light, and it is located very, very close to its host star. Thus, it takes highly specialized techniques to directly image exoplanets. However, for some of the closest stars this can be done. An example of direct exoplanet detection is shown in Figure 18.7. A new generation of space-based telescopes that will allow us to do this for many more stars is planned. Eventually, we should be able to take both spectra (to determine their composition) and direct images of the planets themselves. We will pretend that we can obtain good images of exoplanets later in lab today.

18.3.3 Radial Velocity (Stellar Wobble)

The radial velocity or "stellar wobble" method involves measuring the Doppler shift of the light from a particular star and seeing if the lines in its spectrum oscillate periodically between a red and blue shift. As a planet orbits its star, the planet pulls on the star gravitationally just as the star pulls on the planet. Thus, as the planet goes around and around, it slightly tugs on the star and makes it wobble, causing a back and forth shift in its radial velocity, the motion we see towards and away from us. Therefore, if astronomers see a star wobbling back and forth on a repeating, periodic timescale, then the star has at least one planet orbiting around it. The size of the wobble allows astronomers to calculate the mass of the exoplanet.

18.4 Characterizing Exoplanets from Transit Light Curves

Quite a bit of information about an exoplanet can be gleaned from its transit light curve. Figure 18.8 shows how a little bit of math (from Kepler's laws), and a few measurements, can tell us much about a transiting exoplanet.

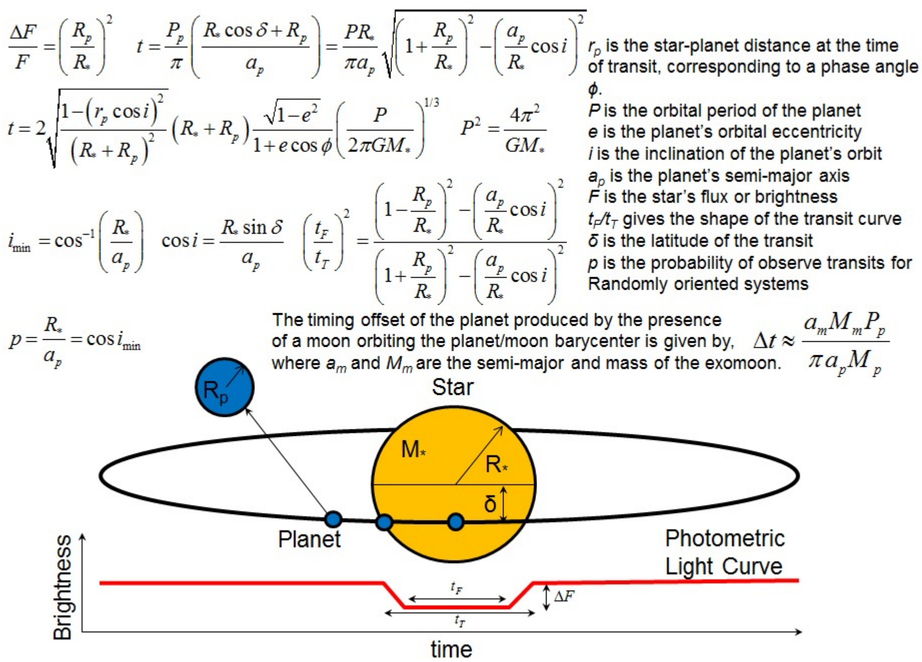


Figure 18.8: An exoplanet transit light curve (bottom) can provide a useful amount of information. The most important attribute is the radius of the exoplanet. But if you know the mass and radius of the exoplanet host star, you can determine other details about the exoplanet's orbit. As the figure suggests, by observing multiple transits of an exoplanet, you can actually determine whether it has a moon! This is because the exoplanet and its moon orbit around the center of mass of the system ("barycenter"), and thus the planet appears to wobble back and forth relative to the host star.

The equations shown in Figure 18.8 are complicated by the fact that exoplanets do not orbit their host stars in perfect circles, and that the transit is never exactly centered. Today we are going to only study planets that have circular orbits, and whose orbital plane is edge-on. Thus, all of the terms with "cos$i$" ("i" is the inclination of the orbit to our sight line, and $i = 0°$ for edge on), cosδ or sinδ (δ is the transit latitude, here $\delta = 90°$), and "e" (which is the eccentricity, the same orbital parameter you have heard about in class for our solar system planets, or in the orbit of Mercury lab, for circular orbits e= 1.0) are equal to "1" or "0".

First, let's remember Kepler's third law $P^2 \propto a^3$, where P is the orbital period, and a is the semi-major axis. For Earth, we have P = 1 yr, a = 1 AU. By taking ratios, you can figure out the orbital periods and semi-major axes of other planets in *our* solar system. Here we cannot do that, and we need to use Isaac Newton's reformulation of Kepler's third law:

$$P^2 = \frac{4\pi^2 a^3}{G(M_{star} + M_{planet})} \tag{1}$$

"G" in this equation is the gravitational constant (G = 6.67 x 10^{-11} Newton-m^2/kg^2), and $\pi = 3.14$.

We also have to estimate the size of the planet. As detailed in Fig. 18.8, the depth of the "eclipse" gives us the ratio of the radius of the planet to that of the star:

$$\frac{\Delta F}{F} = \left(\frac{R_{planet}}{R_{star}}\right)^2 \tag{2}$$

Now we have everything we need to use transits to characterize exoplanets. We will have to re-arrange equations 1 and 2 so as to extract unknown parameters where the other variables are known from measurements.

18.5 Deriving Parameters from Transit Light Curves

The orbital period of the exoplanet is the easiest parameter to measure. In Figure 18.9 is the light curve of "Kepler 1b", the first of the exoplanets examined by the *Kepler* mission. Kepler 1b is a Hot Jupiter, so it has a deep transit. You can see from the figure that transits recur every 2.5 days. That is the orbital period of the planet. It is very easy to figure out orbital periods, so we will not be doing that in this lab today.

In the following eight figures are the light curves of eight different transiting exoplanets. Today you will be using these light curves to determine the properties of transiting exoplanets. To help you through this complicated process, the data for exoplanet #8 will be worked out at each step below. You will do the same process for one of the other seven transiting exoplanets. Your TA might assign one to you, or you will be left to choose one. Towards the end of today's exercise your group will classify both of these exoplanets. Each panel lists the orbital period of the exoplanets ("xxx day orbit"), ranging from 3.89 days for exoplanet #3, to 3.48 years for exoplanet #2. You should be able to guess what that means already: one is close to its host star, the other far away. The other information contained in these figures is a measurement of "t", the total time of the transit ("eclipse takes xxx hours"). When working with the equations below, all time units must be in seconds! Remember, 3600 seconds per hour, 24 hours per day, 365 days per year (there are 3.15×10^7 seconds per year).

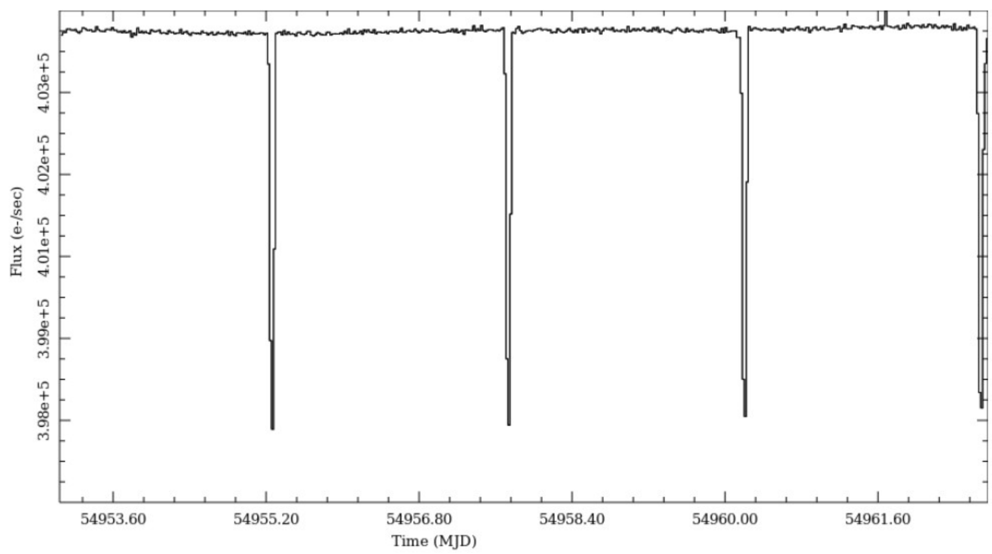


Figure 18.9: The light curve of Kepler 1b as measured by the *Kepler* satellite. The numbers on the y-axis are the total counts (how much light was measured), while the x-axis is "modified Julian days". This is a system that simply makes it easy to figure out periods of astronomical events since it is a number that increases by 1 every day (instead of figuring out how many days there were between June 6th and November 3rd). Thus, to get an orbital period you just subtract the MJD of one event from the MJD of the next event.

Exercise #1:

1. The first quantity we need to calculate is the size of the planet with respect to the host star. How do we do that? Go back to Figure 18.8. We need to measure "ΔF/F". The data points in the exoplanet light curves have been fit with a transit model (the solid line fit to the data points) to make it easy to measure the *minimum*. For both of the transits, take a ruler and determine the value on the y axis by drawing a line across the model fit to the light curve minimum. Estimate this number as precisely as possible, then subtract this number from 1, and you get ΔF/F. (**2 points**)

ΔF/F for transit # _________ = ________________________

ΔF/F for transit #8 = 0.00153

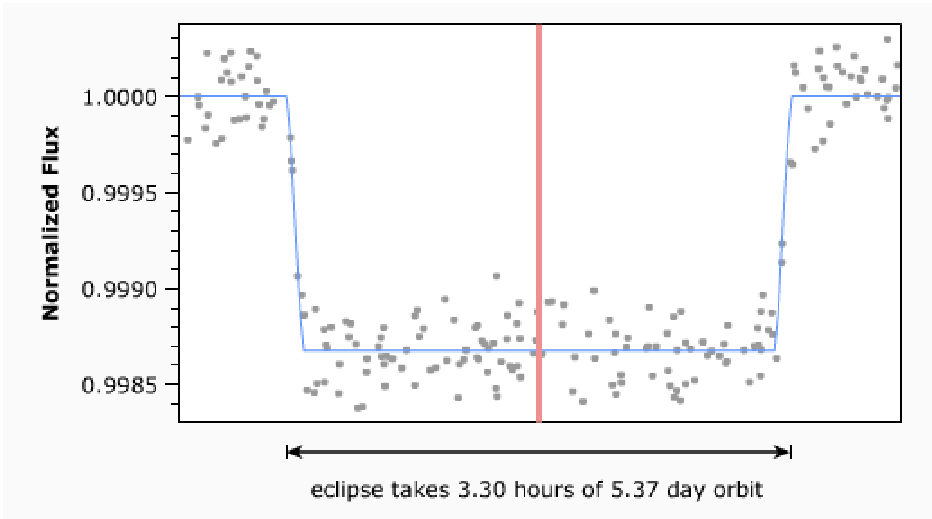


Figure 18.10: Transiting exoplanet #1. The vertical line in the center of the plot simply identifies the center of the eclipse.

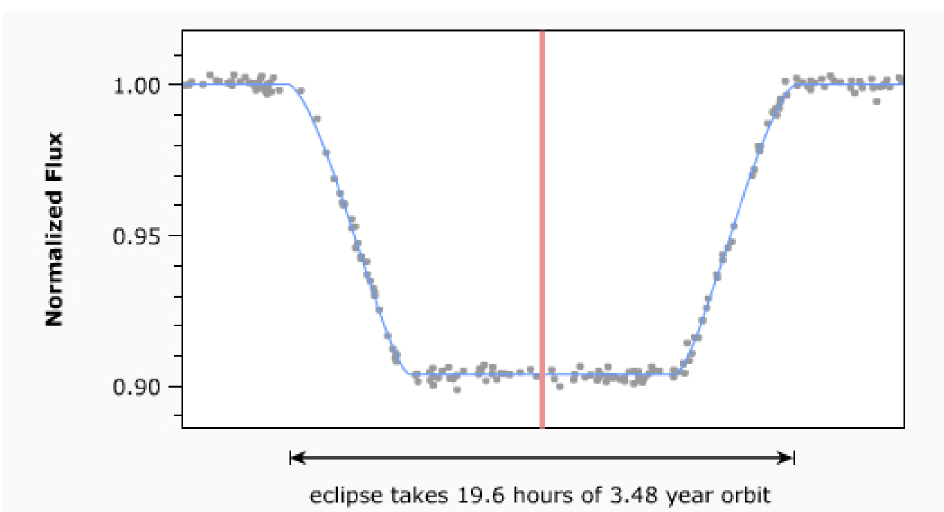


Figure 18.11: Transiting exoplanet #2.

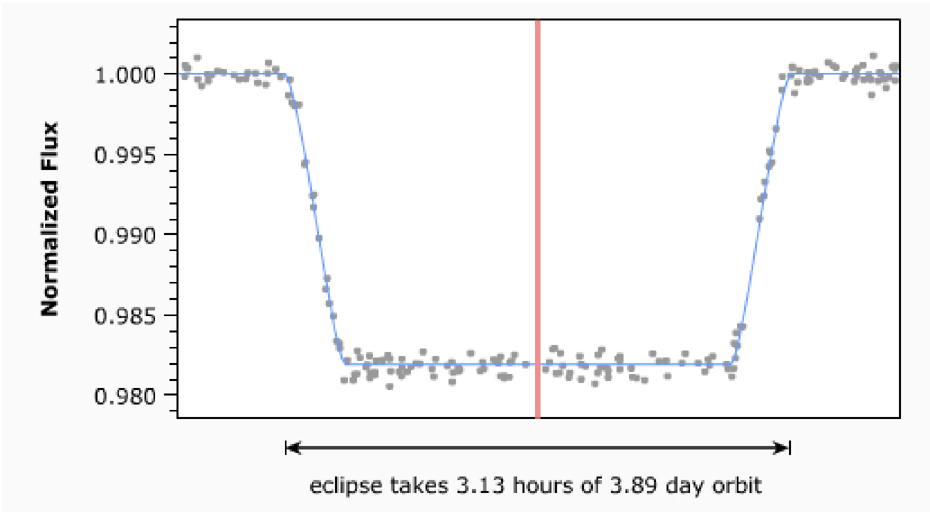


Figure 18.12: Transiting exoplanet #3.

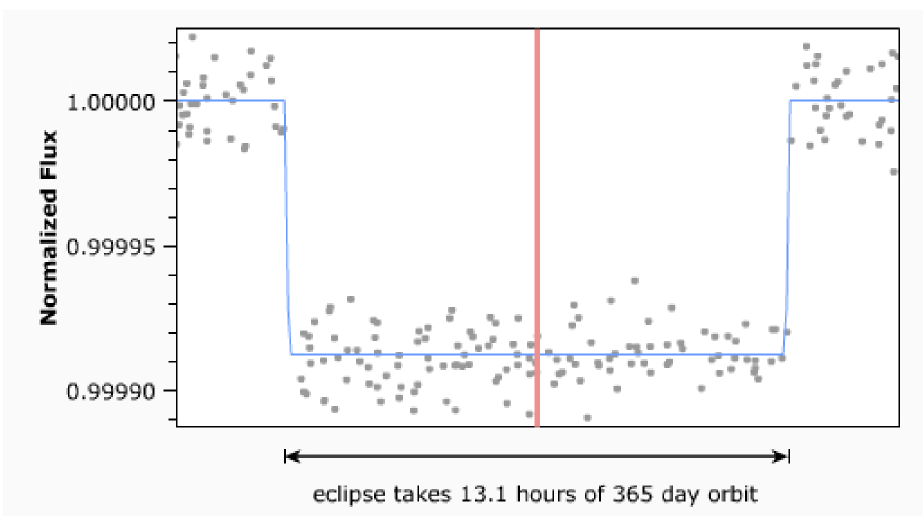


Figure 18.13: Transiting exoplanet #4.

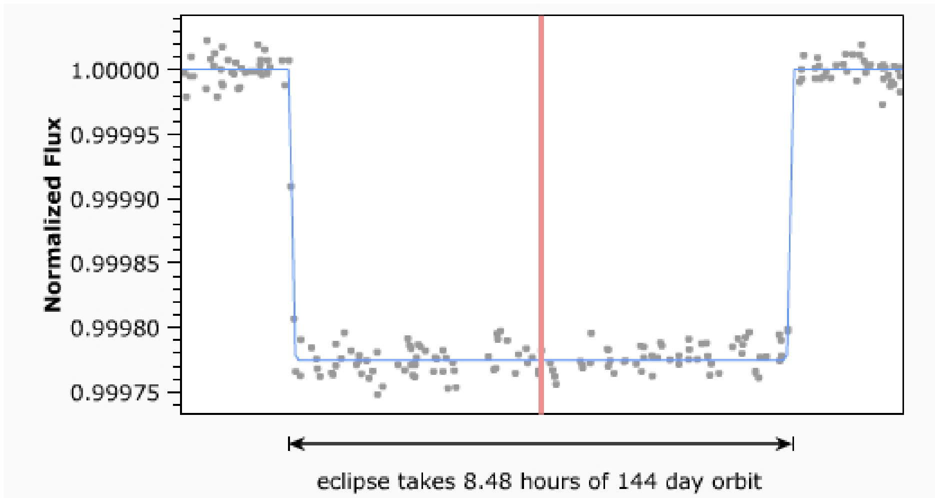


Figure 18.14: Transiting exoplanet #5.

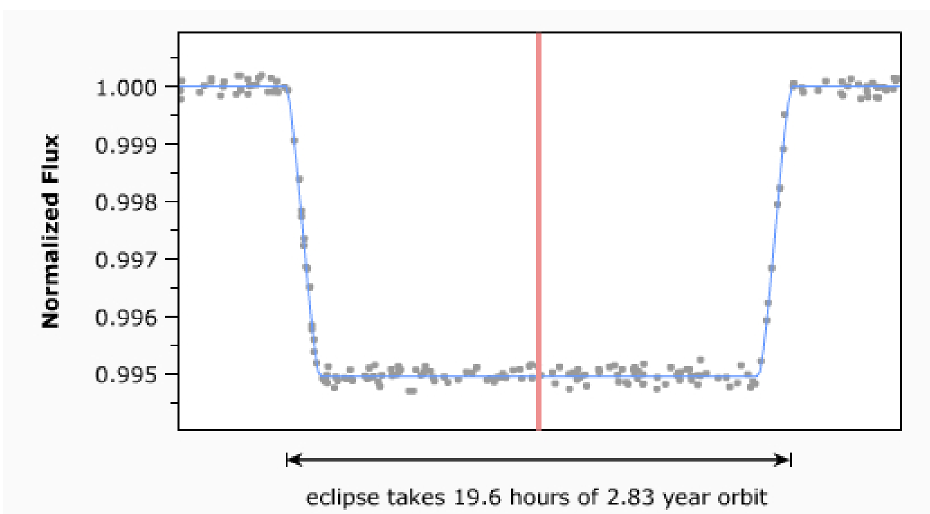


Figure 18.15: Transiting exoplanet #6.

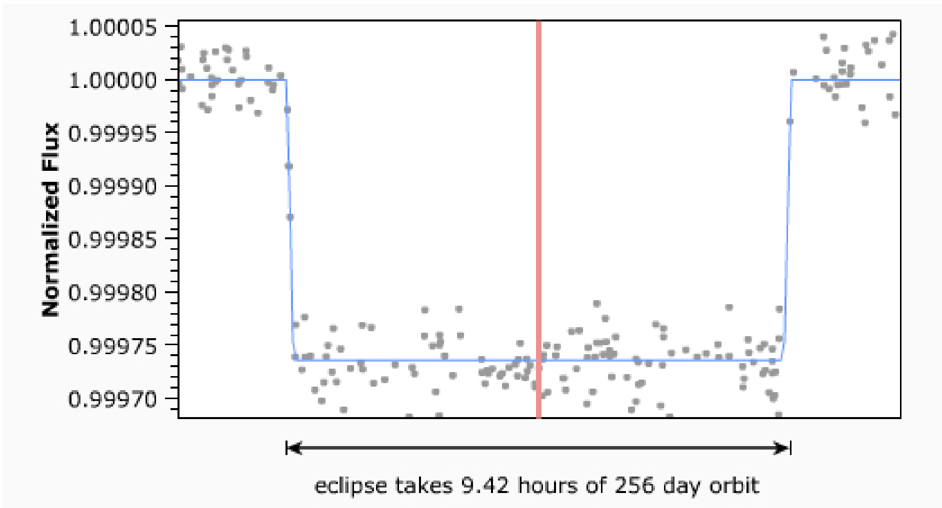


Figure 18.16: Transiting exoplanet #7.

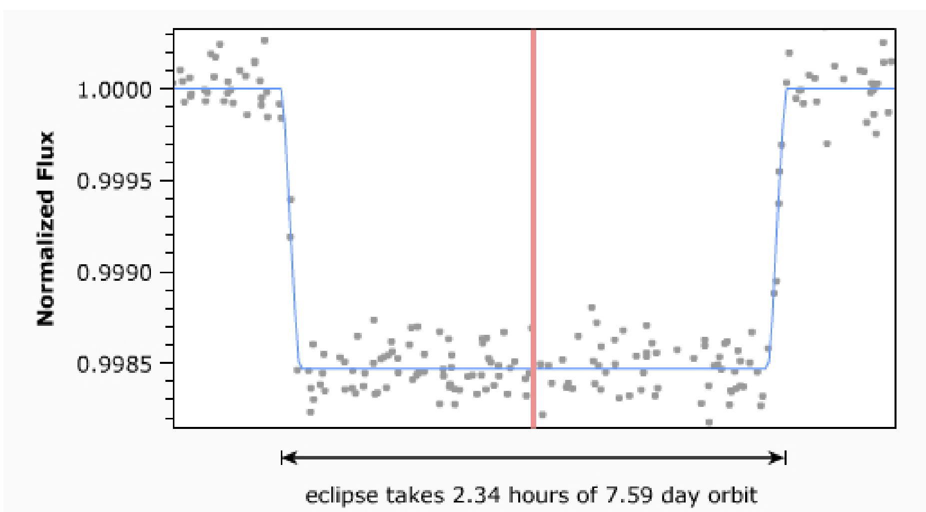


Figure 18.17: Transiting exoplanet #8.

Going back to equation #4, we have:

$$\frac{\Delta F}{F} = \left(\frac{R_{planet}}{R_{star}}\right)^2 \quad or \quad R_{planet} = \left(\frac{\Delta F}{F}\right)^{1/2} (\times\ R_{star})$$

2. Taking the square roots of the ΔF/F from above, fill in the following blanks (**4 points**):

R_{planet} for transit # __________ = _________________________($\times\ R_{star}$)

R_{planet} for transit ___#8___ = ______0.0391______($\times\ R_{star}$)

You just calculated the relative sizes of the planets to their host stars. To turn these into real numbers, we have to know the sizes of the host stars. Astronomers can figure out the masses, radii, temperatures and luminosities of stars by combining several techniques (photometry, parallax, spectroscopy, and interferometry). Note that stars can have dramatically different values for their masses, radii, temperatures and luminosities, and these directly effect the parameters derived for their exoplanets. The data for the eight exoplanet host stars are listed in Table 18.1. The values for our Sun are $M_\odot = 2 \times 10^{30}$ kg, $R_\odot = 7 \times 10^8$ m, $L_\odot = 4 \times 10^{26}$ Watts.

Table 18.1: Exoplanet Host Star Data

Object	**Mass** (kg)	**Radius** (meters)	**Temperature** (K)	**Luminosity** (Watts)
#1	2.0×10^{30}	7.00×10^{8}	5800	4.0×10^{26}
#2	1.3×10^{30}	4.97×10^{8}	4430	2.8×10^{25}
#3	2.2×10^{30}	7.56×10^{8}	6160	1.2×10^{27}
#4	2.0×10^{30}	7.00×10^{8}	5800	4.0×10^{26}
#5	1.6×10^{30}	5.88×10^{8}	5050	2.4×10^{26}
#6	2.0×10^{30}	7.00×10^{8}	5800	4.0×10^{26}
#7	1.4×10^{30}	5.25×10^{8}	4640	4.8×10^{25}
#8	1.0×10^{30}	3.99×10^{8}	3760	4.0×10^{24}

3. Now that you calculated the radius of the exoplanet with respect to the host star radius, use the data in Table 18.1 to convert the radii of your planet into meters, and put this value in the correct row and column in Table 18.2. (**5 points**)

4. Astronomer Judy, and her graduate student Bob, used the spectrograph on the Keck telescope in Hawaii to measure the masses of your planets using the radial velocity technique mentioned above. So we have entered their values for the masses for all of the exoplanets in Table 18.2. You need to calculate the density of your exoplanet and enter it in the correct places in Table 18.2. Remember that density = mass/volume,

Table 18.2: Exoplanet Data

Object	**Radius** (m)	**Semi-major axis** (m)	**Mass** (kg)	**Density** (kg/m^3)	**Temperature** (K)
#1			1.9×10^{26}		
#2			1.9×10^{28}		
#3			5.7×10^{27}		
#4			6.0×10^{24}		
#5			1.5×10^{25}		
#6			8.0×10^{26}		
#7			4.0×10^{24}		
#8	1.6×10^7	9.0×10^9	5.5×10^{25}	3205	555

and the volume of all of the planets is V = $4\pi R^3/3$, as we know that they all must be spherical. (**5 points**)

5. By calculating the density, you already know something about your planets. Remember that the density of Jupiter is 1326 kg/m^3 and the density of the Earth is 5514 kg/m^3. If you did the Density lab this semester, we used the units of gm/cm^3, where water has a density of 1.00 gm/cm^3. This is the "cgs" system of units. To get from kg/m^3 to gm/cm^3, you simply divide by 1000. Describe how the densities of your two exoplanets compare with the Earth and/or Jupiter. (**5 points**)

The next parameter we want to calculate is the semi-major axis "a". While we now know the size and densities of our planets, we do not know how hot or cold they are. We need to figure out how far away they are from their host stars. To do this we re-arrange equation #1, and we get this:

$$a = \left(\frac{P^2 G(M_{star} + M_{planet})}{4\pi^2}\right)^{1/3} = (1.69 \times 10^{-12} P^2 M_{star})^{1/3}$$

6. You must use seconds for P, and kg for the mass of the star (note: you can ignore the mass of the planet since it will be very small compared to the star). We have simplified the equation by bundling G and $4\pi^2$ into a single constant. Note that you have to take the cube root of the quantity inside the parentheses. We write the cube root as an exponent of "1/3". Ask your TA for help on this step. Fill in the column for semi-major axis in Table 18.2 for your exoplanet. (**5 points**)

18.6 The Habitable Zone

The habitable zone is the region around a star in which the conditions are just right for a planet to have liquid water on its surface. Here on Earth, all life must have access to liquid water to survive. Therefore, a planet is considered "habitable" if it has liquid water. This zone is also colloquially know as the "Goldilocks Zone".

To figure out the temperature of a planet is actually harder than you might think. We know how much energy the exoplanet host stars emit, as that is what we call their luminosities. We also know how far away your exoplanets are from this energy source (the semi-major axis). The formula to estimate the "equilibrium temperature" of an exoplanet with a semi-major axis of a around a host star with known parameters is:

$$T_{planet} = T_{star}(1.0 - A)^{1/4}\left(\frac{R_{star}}{2a}\right)^{1/2} \tag{3}$$

The "A" in this equation is the "Albedo", how much of the energy intercepted by a planet is reflected back into space. Equation #3 is not too hard to derive, but we do not have enough time to explain how it arises. You can ask your professor, or search Wikipedia using the term "Planetary equilibrium temperature" to find out where this comes from. The big problem with using this equation is that different atmospheres create different effects. For example, Venus reflects 67% of the visible light from the Sun, yet is very hot. The Earth reflects 39% of the visible light from the Sun and has a comfortable climate. It is how the atmosphere "traps heat" that helps determine the surface temperature. Alternatively, a planet might not even have an atmosphere and could be bright or dark with no heat trapping (for example, the Albedo of the moon is 0.11, as dark as asphalt, and the surface is boiling hot during the day, and extremely cold at night).

Let's demonstrate the problem using the Earth. If we use the value of A = 0.39 for Earth, equation #3 would predict a temperature of T_{Earth} = 247 K. But the mean temperature on the Earth is actually T_{Earth} = 277 K. Thus, the atmosphere on Earth keeps it warmer than the equilibrium temperature. This is true for just about any planet with a significant atmosphere. To account for this effect, let's go backwards and solve for "A". With $R_{\odot} = 7.0 \times 10^8$ m, $a = 1.50 \times 10^{11}$ m, T_{Earth} = 277 K, and $T_{\odot}$ = 5800 K, we find that A = 0.05. Thus, the Earth's atmosphere makes it seem like we absorb 95% of the energy from the Sun. We will presume this is true for all of our planets.

If we assume A = 0.05, equation #3 simplifies to:

$$T_{planet} = 0.70\left(\frac{R_{star}}{a}\right)^{1/2} T_{star} \tag{4}$$

[To understand what we did here, note that (1.0 − A) = 0.95. The fourth root of 0.95 = $0.95^{1/4}$ = 0.99 (remember the fourth root is two successive square roots: $\sqrt{0.95} = 0.95^{1/2}$ = 0.97, and $0.97^{1/2}$ = 0.99). We then divided 0.99 by $\sqrt{2}$ (= 1.41) to have a single constant out front.]

7. Calculate the temperature of your exoplanet using equation #4 and enter it into Table 18.2. (**5 points**)

As we said, the habitable zone is the region around a star of a particular luminosity where water might exist in a liquid form somewhere on a planet orbiting that star. The Earth (a = 1 AU) sits in the habitable zone for the Sun, while Venus is too close to the Sun (a = 0.67 AU) to be inside the habitable zone, while Mars (a = 1.52 AU) is near the outer edge. As we just demonstrated, the atmosphere of a planet can radically change the location of the habitable zone. Mars has a very thin atmosphere, so it is very cold there and all of its water is frozen. If Mars had the thick atmosphere of Venus, it would probably have abundant liquid water on its surface. As we noted, the mean temperature of Earth is 277 K, but the polar regions have average temperatures well below freezing (32°F = 273 K) with an average annual temperature at the North pole of 263 K, and 228 K at the South pole. The equatorial regions of Earth meanwhile have average temperatures of 300 K. So for just about every planet there will be wide ranges in surface temperature, and liquid water could exist somewhere on that planet.

8. Given that your temperature estimates are not very precise, we will consider your planet to be in the habitable zone if its temperature is between 200K and 350 K. Is either of your planets in the habitable zone? (**4 points)**

18.7 Classifying Your Exoplanets

At the beginning of today's lab we described the several types of exoplanet classes that currently exist. We now want you to classify your exoplanet into one of these types. To help you decide, in Table 18.3 we list the parameters of the planets in our solar system. After you have classified them, you will ask your TA to see "images" of your exoplanets to check to see how well your classifications turned out.

9. Compare the radii, the semi-major axes, the masses, densities and temperatures you found for your two exoplanets to the values found in our solar system. For example, if the radius of one of your exoplanets was 8×10^7, and its mass was 2.5×10^{27} it is similar in "size" to Jupiter. But it could have a higher or lower density, depending on composition, and it might be hotter than Mercury, or colder than Mars. Fully describe your two exoplanets. (**10 points**)

Table 18.3: Solar System Data

Object	**Radius** (m)	**Semi-major axis** (m)	**Mass** (kg)	**Density** (kg/m^3)	**Temperature** (K)
Mercury	2.44×10^6	5.79×10^{10}	3.3×10^{23}	5427	445
Venus	6.05×10^6	1.08×10^{11}	4.9×10^{24}	5243	737
Earth	6.37×10^6	1.49×10^{11}	5.9×10^{24}	5514	277
Mars	3.39×10^6	2.28×10^{11}	6.4×10^{23}	3933	210
Jupiter	6.99×10^7	7.78×10^{11}	1.9×10^{27}	1326	122
Saturn	6.03×10^7	1.43×10^{12}	5.7×10^{26}	687	90
Uranus	2.54×10^7	2.87×10^{12}	8.7×10^{25}	1270	63
Neptune	2.46×10^7	4.50×10^{12}	1.0×10^{26}	1638	50
Pluto	1.18×10^6	5.87×10^{12}	1.3×10^{22}	2030	43

As Table 18.3 shows you, there are two main kinds of planets in our solar system: the rocky Terrestrial planets with relatively thin atmospheres, and the Jovian planets, which are gas giants. Planets with high densities (> 3000 kg/m^3) are probably like the Terrestrial planets. Planets with low densities (< 3000 kg/m^3) are probably mostly gaseous or have large amounts of water (Pluto has a large fraction of its mass in water ice).

10. Given your discussion from the previous question, and the discussion of the types of exoplanets in the introduction, classify your two exoplanets into one of the following categories: 1) Gas giant, 2) Hot Jupiter, 3) Water world, 4) Exo-Earth, 5) Super-Earth, or 6) Chthonian. What do you expect them to look like? (**10 points**)

11. Your TA has images for all eight exoplanets of this lab obtained from NASA's "Exoplanet Imager" mission that was successfully launched in 2040. Were your predictions correct? Yes/no. If no, what went wrong? [The TA also has the data for all of the exoplanets to help track down any errors.] (**10 points**)

Name: ____________________
Date: ____________________

18.8 Take Home Exercise (35 points total)

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

- Discuss the different types of exoplanets and their characteristics.
- What are the measurements required for you to determine the most important parameters of an exoplanet?
- What requirement for an exoplanet gives it the possibility of harboring life?

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

18.9 Possible Quiz Questions

1. What are some of the different types of exoplanets?
2. What are some different exoplanet detection methods?
3. What is the habitable zone?

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

Your TA has the data for all of the exoplanets for today's lab. With that data, go back and answer questions #8 and #9 for all of the exoplanets.

Acknowledgement: This lab was made possible using the Extrasolar Planets Module of the Nebraska Astronomy Applet Project.

Name:________________________________
Date:_________________________________

19 Review for Final Exam

19.1 Introduction

This lab is designed to start preparing you for the final exam in this class. *You* **will** *be responsible for the material you learned in lab on the final exam!* Today you will revisit the most important points from each lab by answering these questions, which you will go over *at the end of today's lab.* Thus, by the end of lab today you should know what kind of questions to expect about the labs, as well as the answers to those questions. The questions are broken down by lab, so it should be clear where you can find the answers if you do not remember them. *Make the most of this class period by making sure you understand the important points from all of the labs!*

19.2 Lab Review Questions

Lab 2: Scale Model of the Solar System

1. Based on the scale model of the solar system that we built on the football field, describe the *spacing* of the planets relative to the Sun and to one another.

2. If the entire solar system were scaled down to 100 yards in size, how big would the Sun be? How about a giant planet (*e.g.* Jupiter)? How about a terrestrial planet (*e.g.* Earth)?

Lab 3: Phases of the Moon

1. What is the shape of the 3rd-quarter Moon's appearance, what time of day does it rise, and what time of day is this phase of the Moon at its highest point in the sky?

2. The Moon was most recently at its Full Moon phase on April 13th. When will/did the next New Moon occur? When will the next Full Moon occur?

Lab 4: Density

1. What is the definition of *density*?

2. List the following in order of **decreasing** density: lead, ice, styrofoam, silicate rock, iron

Lab 5: Reflectance Spectroscopy

1. Describe how the distinction between a red tee-shirt and a blue tee-shirt is different from a red star vs. a blue star. [Think about what causes a star to be red or blue; is this the same cause for a tee-shirt color?]

2. Describe the color difference between Mars and Venus in the context of this lab. Why does one (which one?) appear to be much redder in color?

Lab 6: Locating Earthquakes

1. How is the study of earthquakes used to learn about the interior of the Earth?

2. What causes earthquakes on the Earth?

3. Would you expect to detect earthquakes on any of the other terrestrial planets if you dropped seismometers on them today? Why or why not?

4. Describe how geologists use seismic measurements to determine the exact location of an earthquake's *epicenter*.

Lab 7: Surface of the Moon

1. By looking at images of the Moon's surface, how can you tell which area is older and which area is younger?

2. What caused the *highlands* and the *maria* to look as they do today?

3. Do you think it is a coincidence that the average density and composition of the Moon is a very close match to that of the Earth's mantle? Why or why not?

Lab 8: Heating and Cooling of Planets/Daytime Observations

1. Explain how the following factors can affect a planet's average surface temperature: axial tilt, ellipticity of a planet's orbit, and the rotation rate of a planet.

2. How does the presence of greenhouse gases in an atmosphere affect a planet's surface temperature?

3. If you spend a lot of time in your car in Las Cruces in the summer, would it be better to have light or dark color upholstery? Why?

4. Why does Venus have phases?

5. How did the observations of the phases of Venus help Galileo demonstrate the strength of the heliocentric model of the universe?

Lab 9: Surface Features on Mars

1. What is the evidence that Mars probably had liquid water on its surface in the past?

2. Mars certainly does not have water on its surface today – where did it go?

Lab 10: Heat Loss from Io

1. What is the source of the internal heat that powers Io's volcanoes?

2. If Object 2 is twice as hot as Object 1, will it emit more or less radiation than Object 1? [Bonus question: how much more or less?]

Lab 11: Building a Comet

1. Draw a picture of a comet, labeling all of its parts.

2. What causes the tails of a comet, and are they always visible?

3. Describe the two reservoirs of comets. Where are they located?

4. How does the internal strength of a comet compare to that of an asteroid? Why are they different?

Lab 12: Extra-Solar Planets

1. Describe the technique that has been employed to detect the presence of nearly all of the extrasolar planets that we know to be orbiting other stars in our Galaxy.

2. Even if an Earth-like planet exists in orbit around another star, the technique described above would not currently indicate the presence of that Earth-type

planet. Why not?

Lab 13: The Sun

1. What are sunspots, and what leads to their formation?

2. List and describe the three interior regions of the Sun.

3. What is differential rotation?

Name:
Date:
Object:
Telescope:

Draw the object as it looks to you through the telescope

Name:
Date:
Object:
Telescope:

Draw the object as it looks to you through the telescope

Name:
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Draw the object as it looks to you through the telescope

Name:
Date:
Object:
Telescope:

Draw the object as it looks to you through the telescope

Name:______________________________
Date:______________________________

20 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 $y = 13$ ($y = 3\times 2 + 7 = 13$). Here are some additional examples:

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

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

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

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

20.1 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 $x = 11$:

$y^2 = 3\times 11 + 3 = 33 + 3 = 36$

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.