ASTR 105G Lab Manual

Astronomy Department
New Mexico State University

Contents

Name:______________________________
Date:______________________________

1 Tools for Success in ASTR 105G

1.1 Introduction

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

1.2 The Metric System

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

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

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

Table 1.1: Metric System Prefixes

Prefix Name	**Prefix Symbol**	**Prefix Value**
Giga	G	1,000,000,000 (one billion)
Mega	M	1,000,000 (one million)
kilo	k	1,000 (one thousand)
centi	c	0.01 (one hundredth)
milli	m	0.001 (one thousandth)
micro	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?

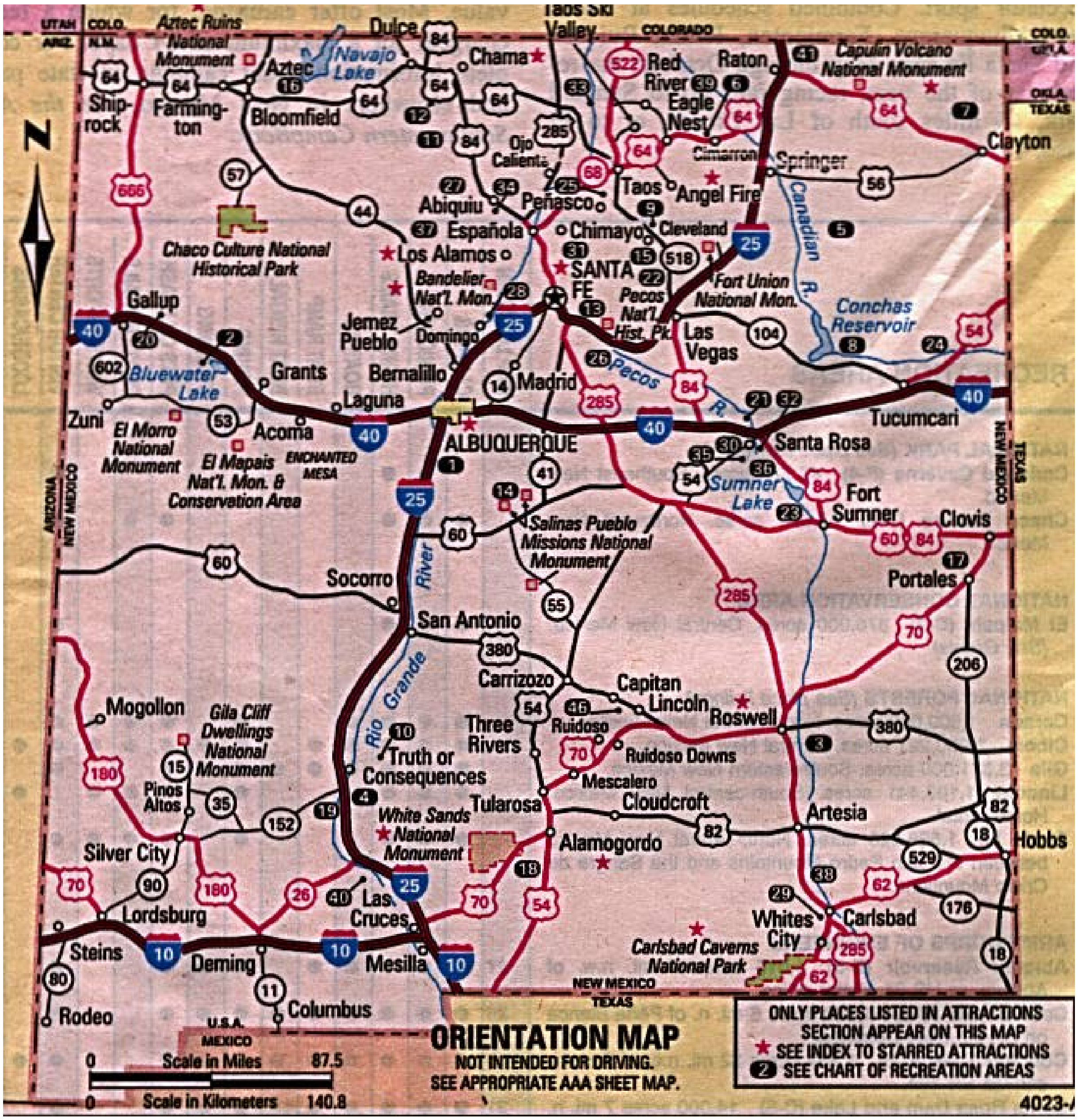


Figure 1.1: Map of New Mexico.

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.

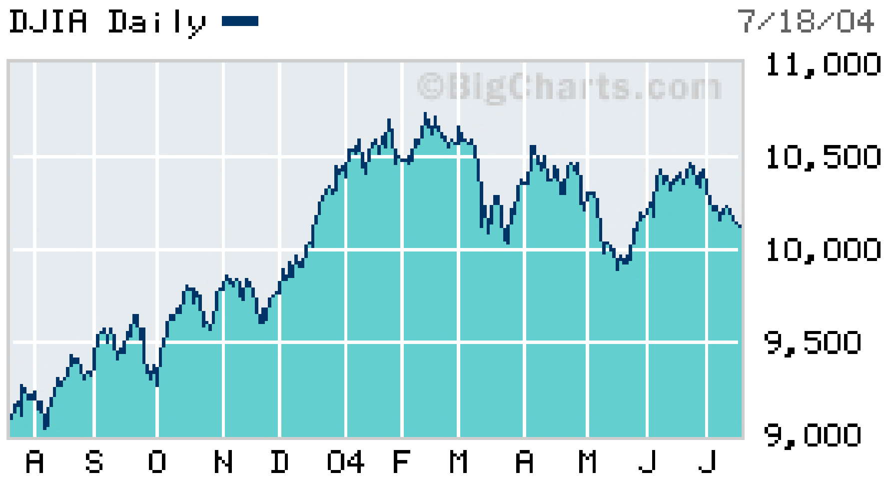


Figure 1.2: The change in the Dow Jones stock index over one year (from April 2003 to July 2004).

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.

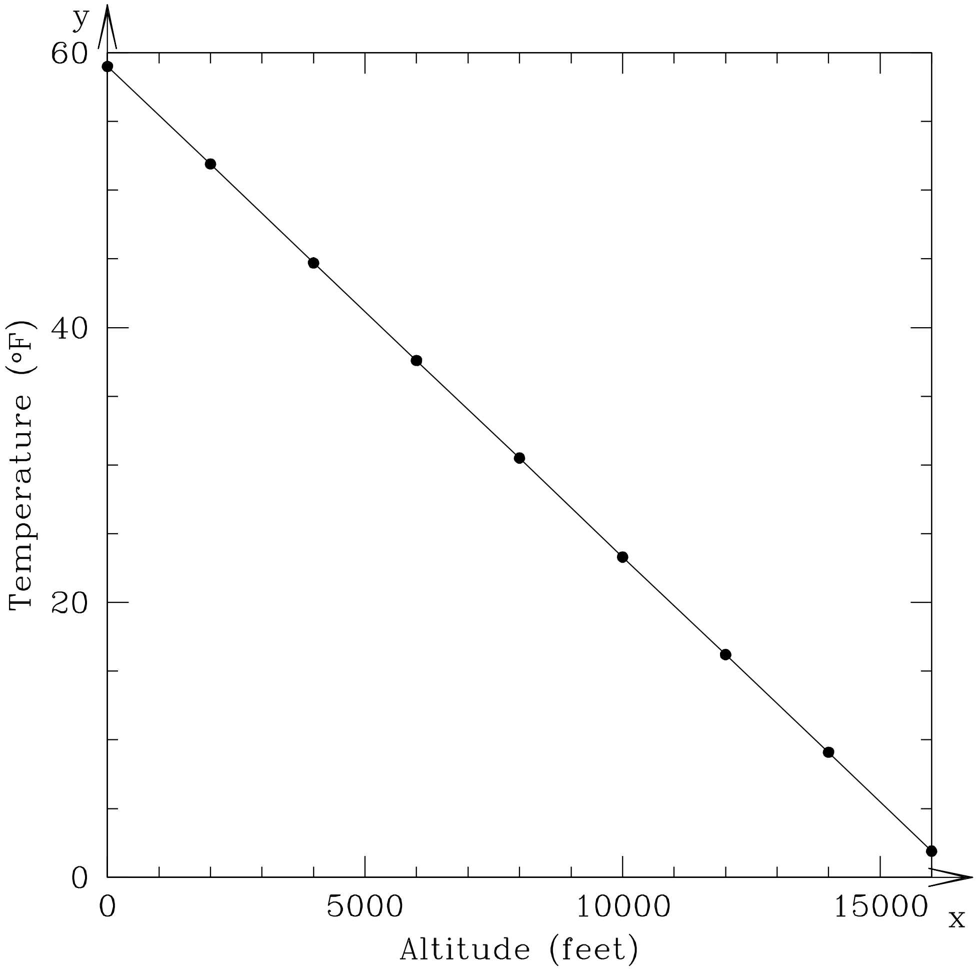


Figure 1.3: The change in temperature as you climb in altitude with the data from Table 1.2. At sea level (0 ft altitude) the surface temperature is 59°F. As you go higher in altitude, the temperature goes down.

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 Scale Model of the Solar System

2.1 Introduction

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

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

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

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

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

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

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

2.2 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 2.1: 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.

2.3 Sizes of Planets

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

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

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

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

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:

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

Using this equation, fill in the values in Table 6.2 **(8 points)**.

Now we have all the information required to create a scaled model of the Solar System. Using any of the items listed in Table 6.3 (spheres of different diameter), select the ones that most closely approximate the sizes of your scaled planets, along with objects to represent both the Sun and the Moon.

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

Observations:

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

Table 2.2: Planets' diameters in a football field scale model.

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

Table 2.3: Objects that Might Be Useful to Represent Solar System Objects

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

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

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

2.4 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. Calculate which planets will be swallowed-up by the Sun (**5 points**).

Name:________________________________
Date:_________________________________

2.5 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)**

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

Table 2.4: 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 2.5: Planets' diameters in a New Mexico scale model.

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


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

2.6 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"?

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

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

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

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

Name(s):______________________________
Date:______________________________

3 The Origin of the Seasons

3.1 Introduction

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

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

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

3.2 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 3.1 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 3.1, the "N" following the latitude means the city is in the northern hemisphere of the Earth (as is all of the United States and Europe) and thus *North* of the equator. An "S" following the latitude means that it is in the southern hemisphere, *South* of the Earth's

Table 3.1: **Season Data for Select Cities**

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

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

Now, if you were to walk into the Mesilla Valley Mall and ask a random stranger "why do we have seasons"? The most common answer you would get is "because we are closer to the Sun during Summer, and further from the Sun in Winter". This answer suggests that the general public (and most of your classmates) correctly understand that the Earth orbits the Sun in such a way that at some times of the year it is closer to the Sun than at other times of the year. As you have (or will) learn in your lecture class, the orbits of all planets around the Sun are ellipses. As shown in Figure 3.1 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.

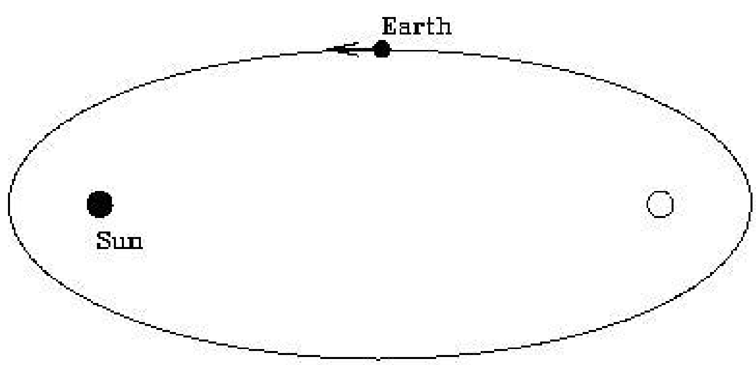


Figure 3.1: An ellipse with the two "foci" identified. The Sun sits at one focus, while the other focus is empty. The Earth follows an elliptical orbit around the Sun, but not nearly as exaggerated as that shown here!

Exercise #1. In Figure 3.1, we show the locations of the two "foci" of an ellipse (foci is the plural form of focus). We will ignore the mathematical details of what foci are for now, and simply note that the Sun sits at one focus, while the other focus is empty (see the Kepler Law lab for more information if you are interested). A planet orbits around the Sun in an elliptical orbit. So, there are times when the Earth is closest to the Sun ("perihelion"), and times when it is furthest ("aphelion"). When closest to the Sun, at perihelion, the distance from the Earth to the Sun is 147,056,800 km ("147 million kilometers"). At aphelion, the distance from the Earth to the Sun is 152,143,200 km (152 million km).

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

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

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

Given that *we know* objects appear bigger when we are closer to them, let's take a look at the two pictures of the Sun you were given as part of the materials for this lab. One image was taken on January 23$^{\text{rd}}$, 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, if an object appears bigger when we get closer to it, in what month is the Earth

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

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

Exercise #2. Characterizing the nature of the seasons at different locations. For this exercise, we are going to be exclusively using the data contained in Table 3.1. First, let's look at Las Cruces. Note that here in Las Cruces, our latitude is +32.5°. That is we are about one third of the way from the equator to the pole. In January our average high temperature is 57°F, and in July it is 96°F. It is hotter in Summer than Winter (duh!). Note that there are about 10 hours of daylight in January, and about 14 hours of daylight in July.

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

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

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

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

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

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

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

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

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

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

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

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

17) From Table 3.1, I conclude that the times of the seasons in the Northern hemisphere are exactly _______________ to those in the Southern hemisphere. (**1 point**)

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

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

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

3.3 The Spinning, Revolving Earth

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

Figure 3.2: Pointing a camera to the North Star (Polaris, the bright dot near the center) and exposing for about one hour, the stars appear to move in little arcs. The center of rotation is called the "North Celestial Pole", and Polaris is very close to this position. The dotted/dashed trails in this photograph are the blinking lights of airplanes that passed through the sky during the exposure.

What is going on in these photos? The easiest explanation is that the Earth is spinning, and as you keep your camera shutter open, the stars appear to move in "orbits" around the North Pole. You can duplicate this motion by sitting in a chair that is spinning—the objects in the room appear to move in circles around you. The further they are from the "axis of rotation", the bigger arcs they make, and the faster they move. An object straight above you, exactly on the axis of rotation of the chair, does not move. As apparent in Figure 3.3, the "North Star" Polaris is not perfectly on the axis of rotation at the North Celestial Pole, but it is very close (the fact that there is a bright star near the pole is just random chance). Polaris has been used as a navigational aid for centuries, as it allows you to determine the direction of North.

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

Figure 3.3: Here is a composite of many different exposures (each about one hour in length) of the night sky over Vienna, Austria taken throughout the year (all four seasons). The images have been composited using a software package like Photoshop to demonstrate what would be possible if it stayed dark for 24 hrs, and you could actually obtain a 24 hour exposure (which can only be truly done north of the Arctic circle). Polaris is the smallest circle at the very center.

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

Now, as shown back in Figure 3.1, we said the Earth orbits ("revolves" around) the Sun on an ellipse. We could discuss the evidence for this, but to keep this lab brief, we will just assume this fact. So, now we have two motions: the spinning and revolving of the Earth. It is the combination of these that actually give rise to the seasons, as you will find out in the next exercise.

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

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

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

Table 3.2: Total Arc Length

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

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

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

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

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

Table 3.3: Position #1: Equinox Data Table

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

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

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

Table 3.4: Position #1: Length of Night and Day

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

18) The caption for Table 3.3 was "Equinox data". The word Equinox means "equal nights", as the length of the nighttime is the same as the daytime. While your numbers in Table 3.4 may not be exactly perfect, what do you conclude about the length of the nights and days for *all* latitudes on Earth in this experiment? Is this result consistent with the term Equinox? (**3 points**)

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

19) Compare your results in Table 3.6 for +45° latitude with those for Minneapolis in Table 3.1. Since Minneapolis is at a latitude of +45°, what season does this orientation of the globe correspond to? (**2 points**)

Table 3.5: Position #2: Solstice Data Table

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

Table 3.6: Position #2: Length of Night and Day

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

20) What about near the poles? In this orientation what is the length of the nighttime at the North pole, and what is the length of the daytime at the South pole? Is this consistent with the trends in Table 3.1, 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 3.7: Position #3: Solstice Data Table

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

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

Table 3.8: Position #3: Length of Night and Day

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

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

22) What about near the poles? In this orientation, how long is the daylight at the North pole, and what is the length of the nighttime at the South pole? Is this consistent with the trends in Table 3.1, 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 3.1 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 3.4). *But the spin axis always points to the same place in the sky* (towards Polaris). Thus, as the Earth orbits the Sun, the amount of sunlight seen at a particular latitude varies: the amount of daylight and nighttime hours change with the seasons. In Northern Hemisphere Summer (approximately June 21^{st}) there are more daylight hours, at the start of the Autumn ($\sim$ Sept. 20^{th}) and Spring ($\sim$ Mar. 21^{st}) the days are equal to the nights. In the Winter (approximately Dec. 21^{st}) the nights are long, and the days are short. We have also discovered that the seasons in the Northern and Southern hemispheres are exactly opposite. If it is Winter in Las Cruces, it is Summer in Sydney (and vice versa). This was clearly demonstrated in our experiments, and is shown in Figure 3.4.

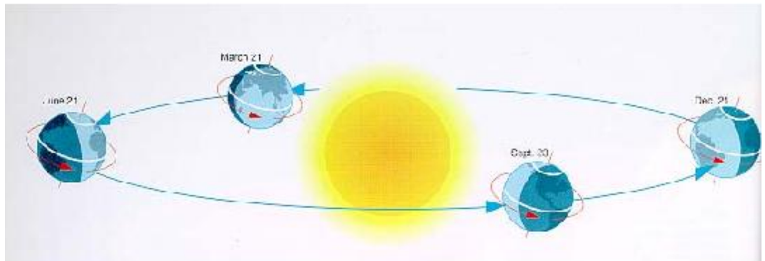


Figure 3.4: The Earth's spin axis always points to one spot in the sky, *and* it is tilted by 23.5° to its orbit. Thus, as the Earth orbits the Sun, the illumination changes with latitude: sometimes the North Pole is bathed in 24 hours of daylight, and sometimes in 24 hours of night. The exact opposite is occurring in the Southern Hemisphere.

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

3.4 Elevation Angle and the Concentration of Sunlight

We have found out part of the answer to why it is warmer in summer than in winter: the length of the day is longer in summer. But this is only part of the story–you would think that with days that are 22 hours long during the summer, it would be hot in Alaska and Canada during the summer, but it is not. The other affect caused by Earth's tilted spin axis is the changing height that the noontime Sun attains during the various seasons. Before we discuss why this happens (as it takes quite a lot of words to describe it correctly), we want to explore what happens when the Sun is higher in the sky. First, we need to define two new terms: "altitude", or "elevation angle". As shown in the diagram in Fig. 3.5.

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

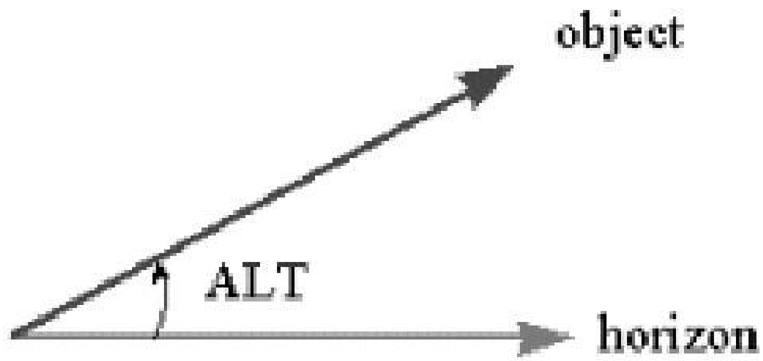


Figure 3.5: Altitude ("Alt") is simply the angle between the horizon, and an object in the sky. The smallest this angle can be is 0°, and the maximum altitude angle is 90°. Altitude is interchangeably known as elevation.

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

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

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

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

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

The radius of the illuminated circle is __________________ cm.

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

Now, as you should have noticed at the beginning of this exercise, as you move the flashlight to lower and lower elevations, the circle changes to an ellipse. Now adjust the elevation angle to be 45°. Ok, time to introduce you to two new terms: the major axis and minor axis of an ellipse. Both are shown in Fig. 3.6. The minor axis is the smallest diameter, while the major axis is the longest diameter of an ellipse.

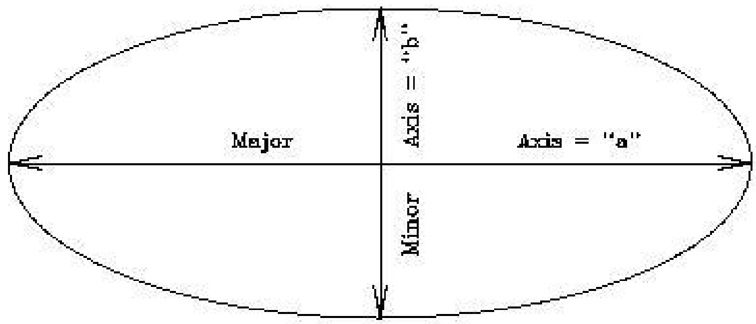


Figure 3.6: An ellipse with the major and minor axes defined.

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

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

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

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

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

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

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

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

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

You are now finished with the in-class portion of this lab. To understand why the Sun appears at different heights at different times of the year takes a little explanation (and the following can be read at home unless you want to discuss it with your TA). Let's go back and take a look at Fig. 3.3. Note that Polaris, the North Star, barely moves over the course of a night or over the year—it is always visible. If you had a telescope and could point it accurately, you could see Polaris during the daytime too. Polaris never sets for people in the Northern Hemisphere since it is located very close to the spin axis of the Earth. Note that as we move away from Polaris the circles traced by other stars get bigger and bigger. But all of the stars shown in this photo are *always* visible—they never set. We call these stars "circumpolar". For every latitude on Earth, there is a set of circumpolar stars (the number decreases as you head towards the equator).

Now let us add a new term to our vocabulary: the "Celestial Equator". The Celestial Equator is the projection of the Earth's Equator onto the sky. It is a great circle that spans the night sky that is directly overhead for people who live on the Equator. As you have now learned, the lengths of the days and nights at the equator are nearly always the same: 12 hours. But we have also learned that during the Equinoxes, the lengths of the days and the nights *everywhere* on Earth are also twelve hours. Why? Because during the equinoxes, the Sun is *on the Celestial Equator*. That means it is straight overhead (at noon) for people who live in Quito, Ecuador (and everywhere else on the equator). Any object that is on the Celestial Equator is visible for 12 hours per night from everywhere on Earth. To try to understand this, take a look at Fig. 3.7. In this figure is shown the celestial geometry explicitly showing that the Celestial Equator is simply the Earth's equator projected onto the sky (left hand diagram). But the Earth is large, and to us, it appears flat. Since the objects in the sky are very far away, we get a view like that shown in the right hand diagram: we see one hemisphere of the sky, and the stars, planets, Sun and Moon rise in the east, and set in the west. But note that the Celestial Equator exactly intersects East and West. Only objects located on the Celestial Equator rise exactly due East, and set exactly due West. All other objects rise in the northeast or southeast and set in the northwest or the southwest. Note that in this diagram (for a latitude of 40°) all stars that have latitudes (astronomers call them "Declinations", or "dec") above 50° never set–they are circumpolar.

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

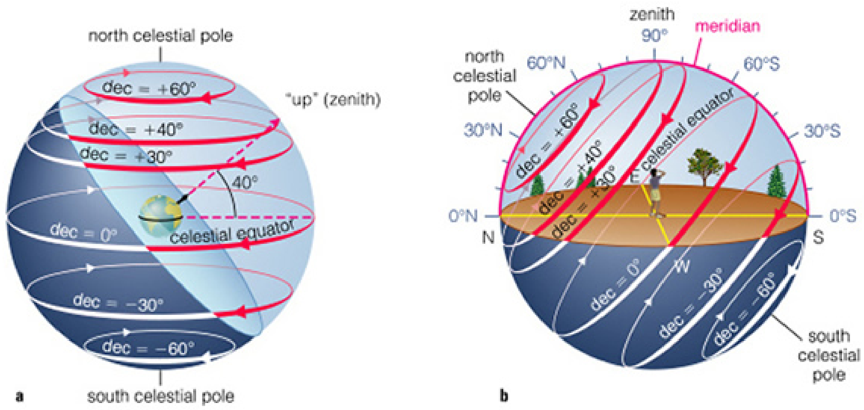


Figure 3.7: The Celestial Equator is the circle in the sky that is straight overhead ("the zenith") of the Earth's equator. In addition, there is a "North Celestial" pole that is the projection of the Earth's North Pole into space (that almost points to Polaris). But the Earth's spin axis is tilted by 23.5° to its orbit, and the Sun appears to move above and below the Celestial Equator over the course of a year.

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

3.5 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?

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

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

Name: _______________
Team Number: __________

Origin of the Seasons Take Home Exercise (35 points total)

1. Why does the Earth have seasons?

2. What is the origin of the term “Equinox”?

3. What is the origin of the term “Solstice”?

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

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

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

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

Name(s):______________________________
Date:________________________________

4 Earth's Moon

Part 1 - Phases of the Moon

4.1 Introduction

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

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

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

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

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

The objective of this lab is to improve your understanding of the Moon phases. 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.

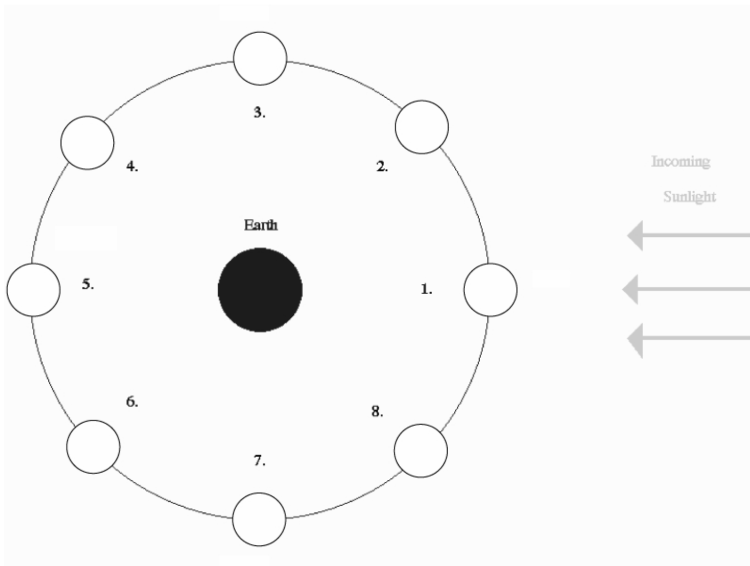
You will finish this lab by demonstrating to your instructor that you do clearly understand the concept of Moon phases, including an understanding of:

- 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

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].

4.2 Exercise 1 (6 points)

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



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

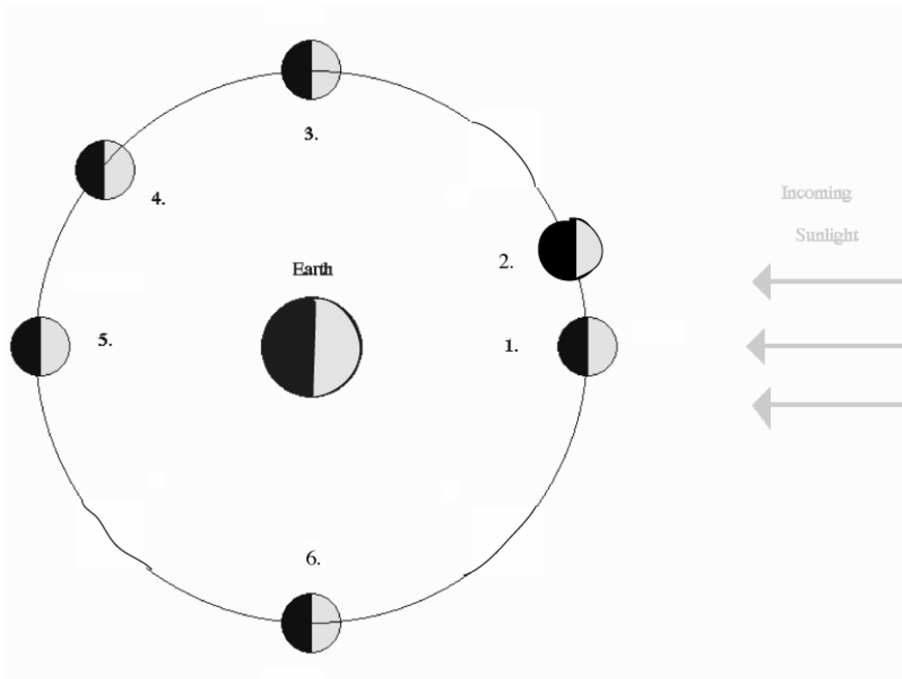
Ranking Order: Greatest A ____B ____C ____D ____E ____F ____G ____H ____Least

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

Carefully explain the reasoning for your result:

4.3 Exercise 2 (6 points)

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



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

Ranking Order: Greatest A ______B ______C ______D ______E ______F ______Least

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

Carefully explain the reasoning for your result:

4.4 Exercise 3 (10 points)

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

A B C D E

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

Ranking Order:

1) Waxing Gibbous

2) ____________________

3) ____________________

4) ____________________

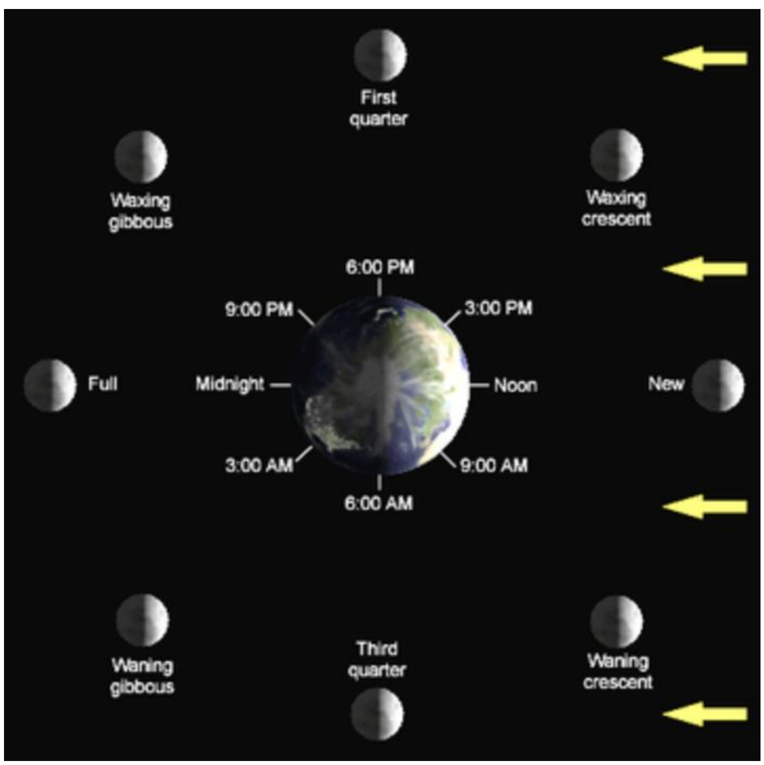
5) ____________________

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

4.5 Lunar Phases, and When They Are Observable

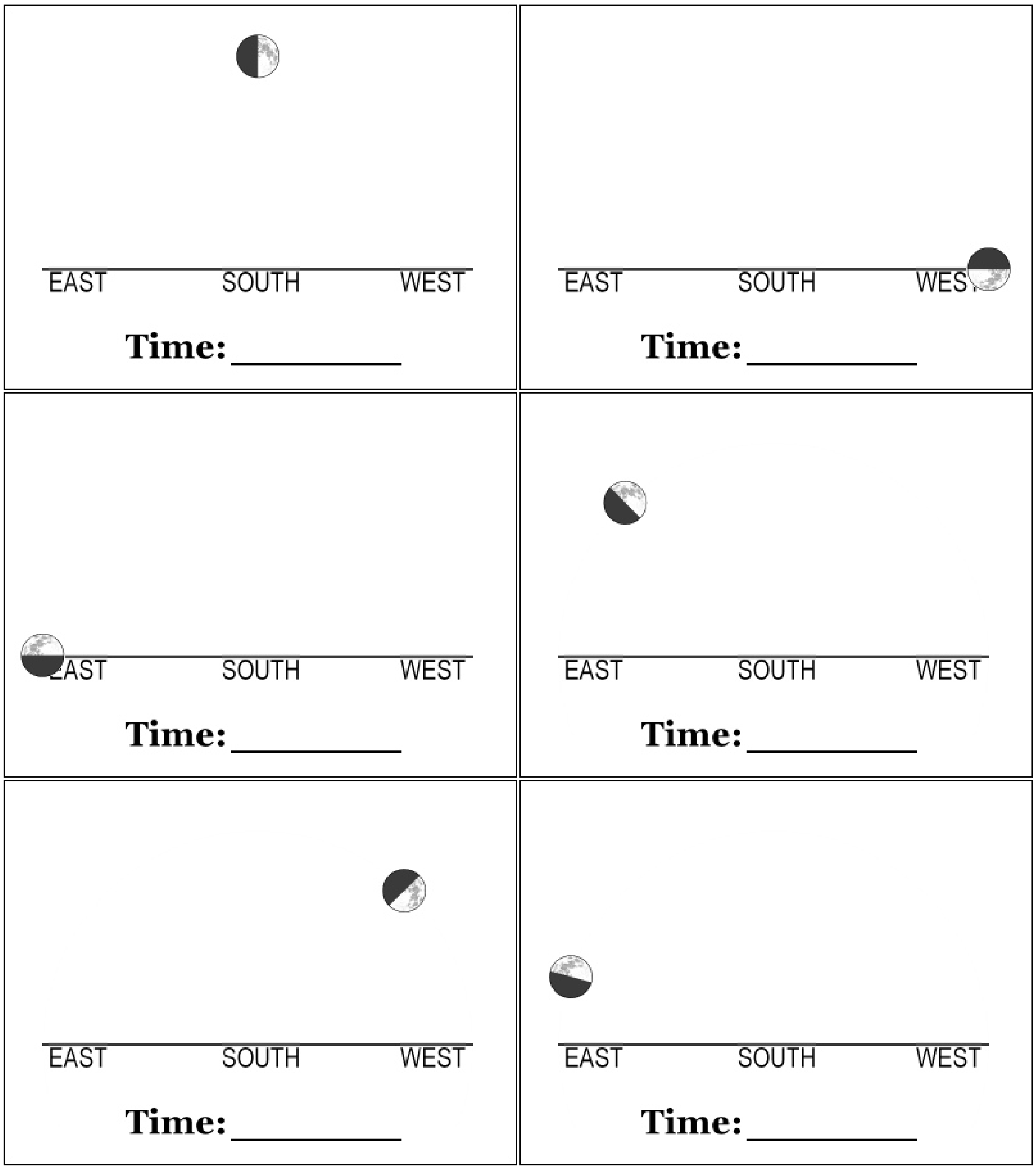
The next three exercises involve determining when certain lunar phases can be observed. Or, alternatively, determining the approximate time of day or night using the position and phase of the Moon in the sky.

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



4.6 Exercise 4 (6 points)

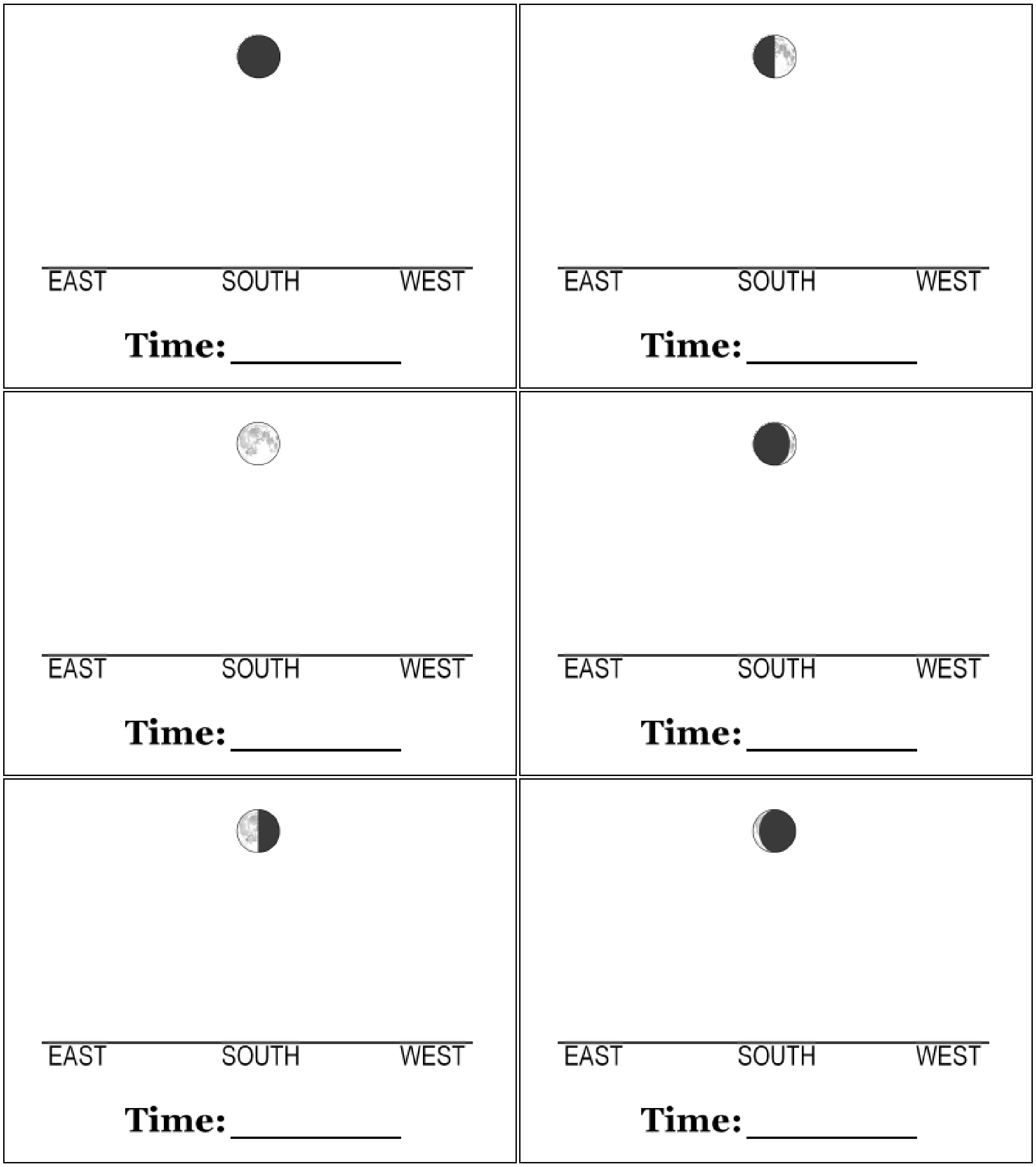
In the set of figures below, the Moon is shown in the first quarter phase at different times of the day (or night). Assume that sunset occurs at 6 p.m. and that sunrise occurs at 6 a.m.



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

4.7 Exercise 5 (6 points)

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



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

Part 2 - Surface of the Moon

4.8 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 4.1 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.

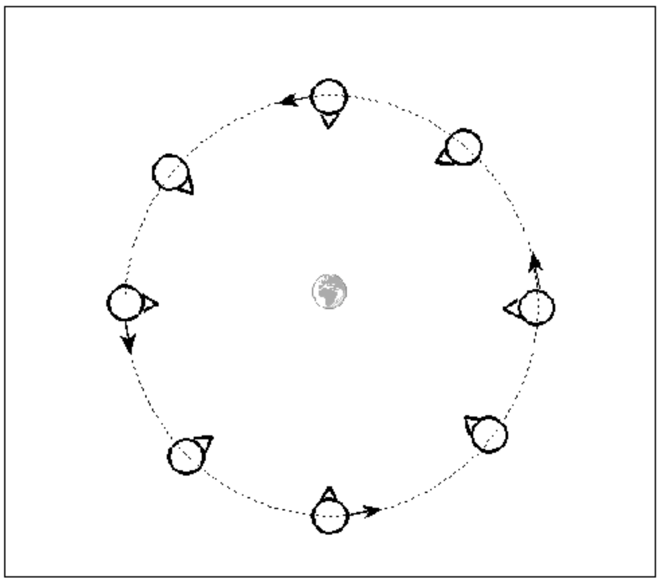


Figure 4.1: The Moon's synchronous orbit. (Not drawn to scale.)

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

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

4.9 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 4.2, 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 4.2 also shows that the rock beneath the crater becomes fractured (full of cracks).

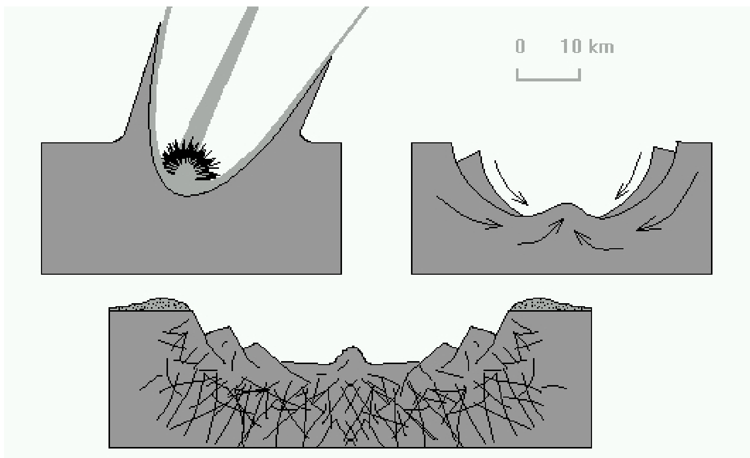


Figure 4.2: Formation of an impact crater.

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

4.10 Relative Ages on the Moon

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

4.11 Lab Stations

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

The binders contain separate sections, or "stations," with the photographs and/or images for each specific exercise. Each group must go through all the stations, and consider and discuss each question and come to a conclusion. **Remember to back up your answers with reasonable explanations, and be sure to answer *all* of the questions.** While you should discuss the questions as a group, be sure to write down the answer in your own words for each question.

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

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

1. Approximately how many craters can you see inside the dark circular region that defines Mare Imbrium? Compare the number of craters in Mare Imbrium to the brighter regions to the North (above) of Mare Imbrium. (**3 points**)

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

2. Using the diameters for the large craters noted above, and a ruler, what is the approximate diameters of the smallest craters you can clearly see in images #4 and #5? If the NMSU campus is about 1 km in diameter, compare the smallest crater you can see to the size of our campus. (**3 points**)

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

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

3. Compare the region around Clavius to Mare Imbrium. Scientists now know that the lunar highlands are older than the maria. What evidence do you have (using these photographs) that supports this idea? [Hint: review section 7.3 of the introduction.] (**3 points**)

Station 3: Comparing Apollo landing sites. **Images #10 and #11** are close-ups of the Apollo 11 landing site in Mare Tranquillitatis (the "Sea of Tranquility"). The actual spot where the "Eagle" landed on July 20, 1969, is marked by the small cross in image 11 (note that three small craters near the landing site have been named for the crew of this mission: Aldrin, Armstrong and Collins). [There are also quite a number of photographic defects in these pictures, especially the white circular blobs near the center of the image to the North of the landing site.] The landing sites of two other NASA spacecraft, Ranger 8 and Surveyor 5, are also labeled in image #11. NASA made sure that this was a safe place to explore! Recently, a new mission to map the Moon with better resolution called the "Lunar Reconnaissance Orbiter" (LRO) sent back images of the Apollo 11 landing site (**image 11B**). In this image LM is the base of the lunar module, LRRR and PSEP are two science experiments. You can even see the (faintly) disturbed soil where the astronauts walked!

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

4. 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? (**3 points**)

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

5. Do you agree with the theory that the crater floor has been recently flooded? Is the maria that forms the floor of this crater younger, older, or approximately the same age as the nearby region of Mare Imbrium located just to the South (below) of Plato? Explain your reasoning. (**3 points**)

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

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

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.

6. Does the Earth's surface have more craters or fewer craters than the surface of the Moon? Discuss two differences between the Earth and the Moon that could explain this. **(3 points)**

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

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

7. 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**)

Earth has 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 cubic centimeters or meters).

Water has a density of 1 gm/cm^3. The density of the Earth's crust is about 3 gm/cm^3, while the mantle has a density of 4.5 gm/cm^3. The core is very dense: 14 gm/cm^3 (this is partly due to its composition, and partly due to the great pressure exerted by the mass located above the core). The core of the Earth is almost pure iron, while the mantle is a mixture of magnesium, silicon, iron and oxygen. The average density of the Earth is 5.5 gm/cm^3.

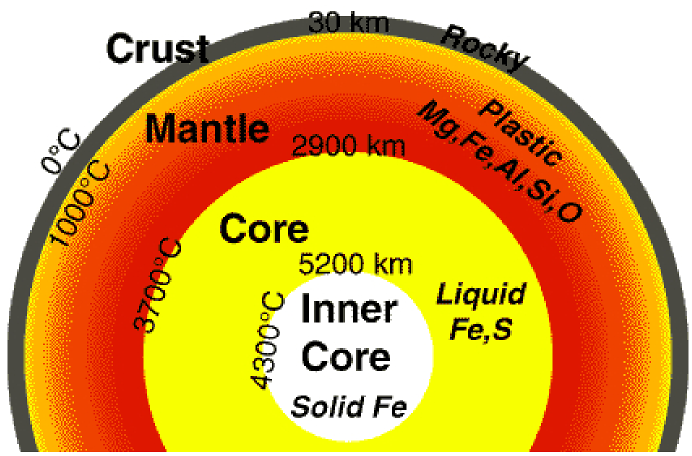


Figure 4.3: The internal structure of the Earth, showing the dimensions of the crust, mantle and core, as well as their composition and temperatures.

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

Table 4.1: 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%

8. Is the Moon composed of the same proportion of elements as the Earth? What are the biggest differences? Does this support a model where the Moon formed out of the same material as the Earth? (**3 points**)

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

9. Given this information, do you think it is likely that the Moon formed out near Mars? Why? (**3 points**)

The currently accepted theory for the formation of the Moon is called the "Giant Impact" theory. In this model, a large body (about the size of Mars) collided with the Earth, and the resulting explosion sent a large amount of material into space. This material eventually collapsed (coalesced) to form the Moon. Most of the ejected material would have come from the crust and the mantle of the Earth, since it is the material closest to the Earth's surface. Table 4.2 shows the composition of the Earth's crust and mantle compared to that of the Moon.

Table 4.2: Chemical Composition of the Earth (crust and mantle) and Moon.

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

10. Given the data in Table 4.2, present an argument for why the giant impact theory probably is now the favorite theory for the formation of the Moon. Can you think of a reason why the compositions might not be *exactly* the same? (**4 points**)

Name:__________________________________
Date:___________________________________

4.12 Take-Home Assignment - Earth's Moon (35 points)

Answer the following questions in the space provided:

1. Let's talk about Solar Eclipses.

   (a) What is a Solar Eclipse? **Draw a diagram** showing the relative positions of the Earth, Sun, and Moon to illustrate your answer. **(5 points)**

   (b) In order to see a Solar Eclipse, what phase must the moon be in? **(2 points)**

   (c) Why do we not see a Solar Eclipse during this phase of the moon each month? **(3 points)**

2. 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. (5 points)**

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

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

5. How can the Earth be older than the Moon, as suggested by the Giant Impact Theory of the Moon's formation, but the Moon's surface is older than the Earth's surface? What do we mean by 'old' in this context? (**10 points**)

Name:______________________________
Date:______________________________

5 Kepler's Laws

5.1 Introduction

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

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

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

Johannes Kepler (1571 − 1630) was the first person to truly understand how the planets in our solar system moved. Using the highly precise observations by Tycho Brahe (1546 −

1601) of the motions of the planets against the background stars, Kepler was able to formulate three laws that described how the planets moved. With these laws, he was able to predict the future motion of these planets to a higher precision than was previously possible. Many credit Kepler with the origin of modern physics, as his discoveries were what led Isaac Newton (1643 − 1727) to formulate the law of gravity. Today we will investigate Kepler's laws and the law of gravity.

5.2 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. 5.1. Here $F_{gravity}$ is the gravitational attractive force between two objects whose masses are M_1 and M_2. The distance between the two objects is "R". The gravitational constant G is just a small number that scales the size of the force. **The most important thing about gravity is that the force depends only on the masses of the two objects and the distance between them.** This law is called an Inverse Square Law because the distance between the objects is *squared*, and is in the denominator of the fraction. There are several laws like this in physics and astronomy.

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

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

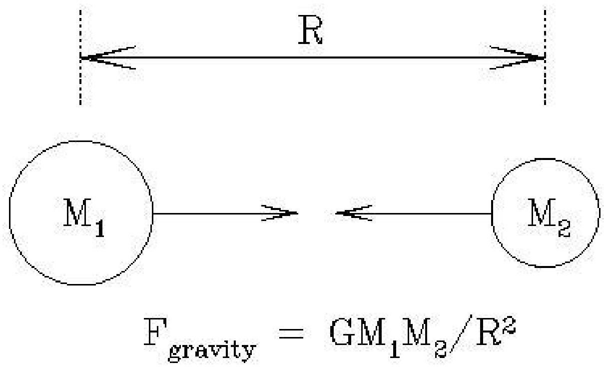


Figure 5.1: The force of gravity depends on the masses of the two objects (M_1, M_2), and the distance between them (R).

5.3 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. 5.2.

Before we describe an ellipse, let's examine a circle, as it is a simple form of an ellipse. As you are aware, the circumference of a circle is simply 2πR. The radius, R, is the distance between the center of the circle and any point on the circle itself. In mathematical terms, the center of the circle is called the "focus". An ellipse, as shown in Fig. 5.3, 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. 5.4 is an ellipse with the two foci identified, "F_1" and "F_2".

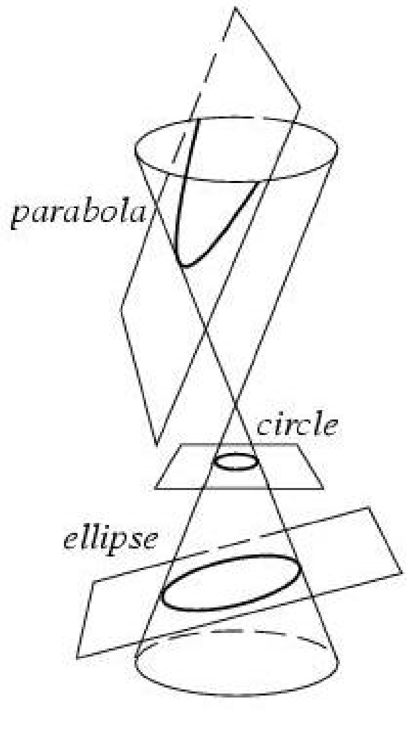


Figure 5.2: Four types of curves can be generated by slicing a cone with a plane: a circle, an ellipse, a parabola, and a hyperbola. Strangely, these four curves are also the allowed shapes of the orbits of planets, asteroids, comets and satellites!

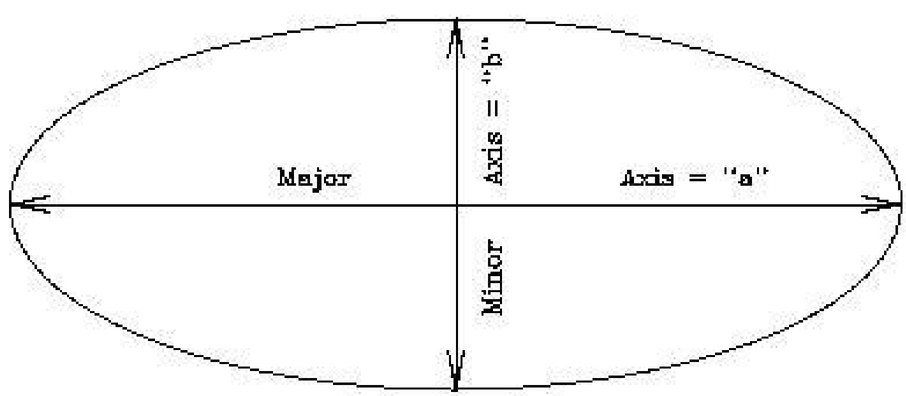


Figure 5.3: An ellipse with the major and minor axes identified.

Exercise #1: On the ellipse in Fig. 5.4 are two X's. Confirm that that sum of the distances between the two foci to any point on the ellipse is always the same by measuring the distances between the foci, and the two spots identified with X's. Show your work. (**2 points**)

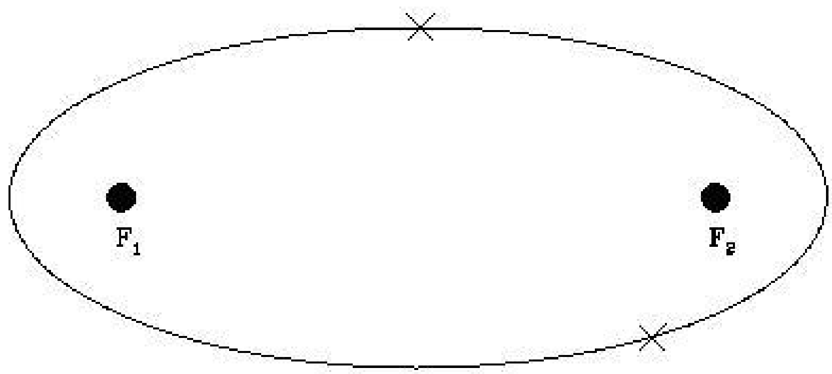


Figure 5.4: An ellipse with the two foci identified.

Exercise #2: In the ellipse shown in Fig. 5.5, two points ("P_1" and "P_2") are identified that are not located at the true positions of the foci. Repeat exercise #1, but confirm that P_1 and P_2 are not the foci of this ellipse. (**2 points**)

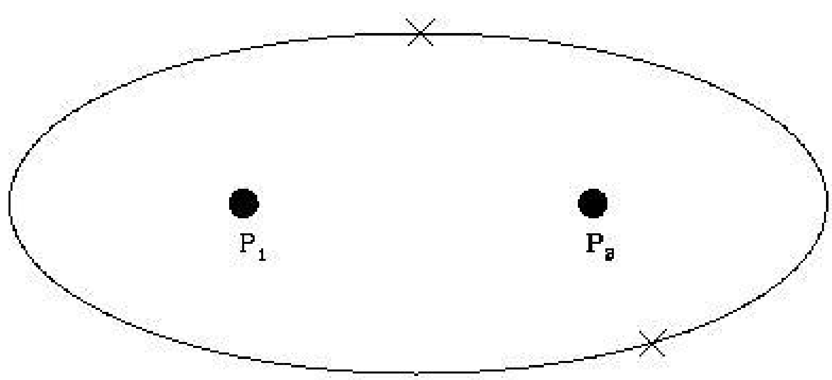


Figure 5.5: An ellipse with two non-foci points identified.

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

Exercise #3: Kepler's first law.

Click on the "Kepler's Law button" and then the "First Law" button inside the Kepler's Law box.

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

At the top of the panel is the program control bar. For now, simply hit the "Go" button.

You can clear and restart the simulation by hitting "Restart" (do this as often as you wish).

After hitting Go, note that the planet executes an orbit along the ellipse. The program draws the "vectors" from each focus to 25 different positions of the planet in its orbit. It draws a blue vector from the Sun to the planet, and a yellow vector from the other focus to the planet. The right hand panel sums the blue and yellow vectors. [Note: if your computer runs the simulation too quickly, or too slowly, simply adjust the "Slow down/Speed Up" slider for a better speed.]

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

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

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

Now let's put the Initial Velocity down to a value of 1.0. Run the simulation.

3. What is happening here? The orbit is now a circle. Where are the two foci located? In this case, what is a name that describes the distance between the focus point and the orbit? (**4 points**)

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

Exercise #4: Kepler's Second Law: "A line from a planet to the Sun sweeps out equal areas in equal intervals of time."

From the simulation window, click on the "Kepler's Law button" and then the "Second Law" button inside the Kepler's Law box.

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

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

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

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

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

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

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

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

3. Do you think the planet will move faster, or slower when it is closest to the Sun? Test this by assuming that r = 0.5a at perihelion, and r = 1.5a at aphelion, and that a=1! [Hint, simply set $G(M_{\text{sun}} + M_{\text{planet}}) = 1$ to make this comparison very easy!] Does this explain Kepler's second law? (**4 points**)

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

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

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

Exercise #5: Kepler's Third Law: "A planet's orbital period squared is proportional to its average distance from the Sun cubed: $P^2 \propto a^3$".

As we have just learned, the law of gravity states that the further away an object is, the weaker the force. We have already found that at aphelion, when the planet is far from the Sun, it moves more slowly than at perihelion. Kepler's third law is merely a reflection of this fact–the further a planet is from the Sun ("a"), the more slowly it will move. The more slowly it moves, the longer it takes to go around the Sun ("P"). The relation is $P^2 \propto a^3$, where P is the orbital period in years, while a is the average distance of the planet from the Sun, and the mathematical symbol for proportional is represented by "$\propto$". However, if we use units of 'years' for P and 'AU' for a we can replace the proportional sign with an equal sign:

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

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

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

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

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

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

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

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

2. Did your calculation agree with the simulation? Describe your results. (**2 points**)

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

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

Table 5.1: The Orbital Periods of the Planets

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

Notice that the further the planet is from the Sun, the slower it moves, and the longer it takes to complete one orbit around the Sun (its "year").

4. Neptune was discovered in 1846, and Pluto was discovered in 1930 (by Clyde Tombaugh, a former professor at NMSU). How many orbits (or what fraction of an orbit) have Neptune and Pluto completed since their discovery? (**3 points**)

5.4 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. 5.6 is a diagram explaining the center of mass. If you think of a teeter-totter, or a simple balance, the center of mass is the point where the balance between both sides occurs. If both objects have the same mass, this point is halfway between them. If one is more massive than the other, the center of mass/balance point is closer to the more massive object.

Most binary star systems have stars with similar masses ($M_1 \approx M_2$), but this is not always the case. In the first (default) binary star simulation, $M_1 = 2M_2$. The "mass ratio" ("q") in this case is 0.5.

Mass ratio is defined to be

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

Here, $M_2 = 1$, and $M_1 = 2$, so $q = M_2/M_1 = 1/2 = 0.5$. This is the number that appears in the "Mass Ratio" window of the simulation.

Exercise #6: Binary Star systems. We now want to set-up some special binary star orbits to help you visualize how gravity works. This requires us to access the "Input" window

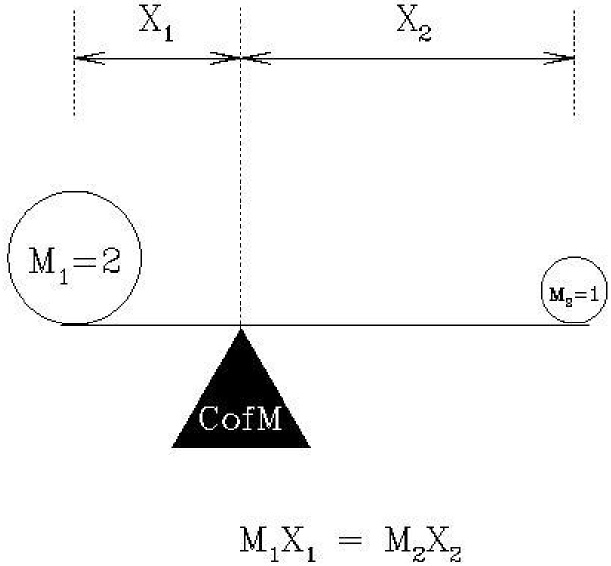


Figure 5.6: A diagram of the definition of the center of mass. Here, object one (M_1) is twice as massive as object two (M_2). Therefore, M_1 is closer to the center of mass than is M_2. In the case shown here, $X_2 = 2X_1$.

on the control bar of the simulation window to enter in data for each simulation.

Clicking on Input brings up a menu with the following parameters: Mass Ratio, "Transverse Velocity", "Velocity (magnitude)", and "Direction". Use the slide bars (or type in the numbers) to set Transverse Velocity = 1.0, Velocity (magnitude) = 0.0, and Direction = 0.0. For now, we simply want to play with the mass ratio.

Use the slide bar so that Mass Ratio = 1.0. Click "Ok". This now sets up your new simulation. Click Run.

1. Describe the simulation. What are the shapes of the two orbits? Where is the center of mass located relative to the orbits? What does $q = 1.0$ mean? (Remember Equation 6) Describe what is going on here. (**4 points**)

Ok, now we want to run a simulation where only the mass ratio is going to be changed.

2. Go back to Input and enter in the correct mass ratio for a binary star system with $M_1 = 4.0$, and $M_2 = 1.0$ (using Equation 6). Run the simulation. Describe what is happening in this simulation. How are the stars located with respect to the center of mass? Why? [Hint: see Fig. 5.6.] (**4 points**)

Finally, we want to move away from circular orbits, and make the orbit as elliptical as possible. You may have noticed from the Kepler's law simulations that the Transverse Velocity affected whether the orbit was round or elliptical. When the Transverse Velocity = 1.0, the orbit is a circle. Transverse Velocity is simply how fast the planet in an elliptical orbit is moving *at perihelion* relative to a planet in a circular orbit of the same orbital period. The maximum this number can be is about 1.3. If it goes much faster, the ellipse then extends to infinity and the orbit becomes a parabola.

3. Go back to Input and now set the Transverse Velocity = 1.3. Run the simulation. Describe what is happening. When do the stars move the fastest? The slowest? Does this make sense? Why/why not? (**4 points**)

The final exercise explores what it would be like to live on a planet in a binary star system–not so fun!

4. In the “Two-Body and Many-Body” simulations window, click on the “Dbl. Star and a Planet” button. Here we simulate the motion of a planet going around the less massive star in a binary system. Click Go. Describe the simulation—what happened to the planet? Why do you think this happened? (**4 points**)

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

5. Run simulations with $q = 0.4$ and 0.6. Compare them to the simulations with $q = 0.5$. What happens as q gets larger, and larger? What is increasing? How does this increase affect the force of gravity between the star and its planet? (**5 points**)

6. Ok, reset $q = 0.5$, and now let's adjust the Planet–Star Distance. In the Settings window, set the Planet–Star Distance = 0.1 and run a simulation. Note the outcome of this simulation. Now set Planet–Star Distance = 0.3. Run a simulation. What happened? Did the planet wander away from its parent star? Are you surprised? (**5 points**)

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

5.5 Possible Quiz Questions

1. Describe the difference between an ellipse and a circle.
2. List Kepler's three laws.
3. How quickly does the strength ("pull") of gravity get weaker with distance?
4. Describe the major and minor axes of an ellipse.

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

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

Name: ________________
Team Number: __________

Kepler's Laws Take Home Exercise (35 points total)

1. Describe the Law of Gravity in words and with the equation. **(6 points)**

2. What happens to the gravitational force as
    a. the masses increase?**(4 points)**
    b. the distance between the two objects increases? **(4 points)**

3. Describe Kepler's three laws in your own words, and describe how you tested each one of them in the lab. (1-2 complete sentences for each of Kepler's Laws) **(15 points)**

4. Astronomers think that finding life on planets orbiting binary systems is unlikely. Why do they think that? Use your simulation results to strengthen your argument. **(6 points)**

Name:________________________________

Date:________________________________

6 The Power of Light: Understanding Spectroscopy

6.1 Introduction

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

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

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

This lab is split into three main parts:

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

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

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

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

6.2 Blackbody Radiation

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

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

To study light, astronomers often split the light up into a spectrum. A spectrum shows the distribution of brightness at many different wavelengths. Thus, a spectrum can be shown using a graph of brightness vs. wavelength. A simple example of this is if you were to look at a rainbow and record how bright each of the separate colors were. Figure 6.1 shows what the brightness of the colors in a hot flame or hot star might look like. At each separate color, a brightness is measured. By fitting a curve to the data points, and finding the peak in the curve, we can determine the temperature of the blackbody source.

6.3 Absorption and Emission Lines

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

6.3.1 The Bohr Model of the Atom

In the early part of the last century, a group of physicists developed the *Quantum Theory of the Atom.* Among these scientists was a Danish physicist named Niels Bohr. His model

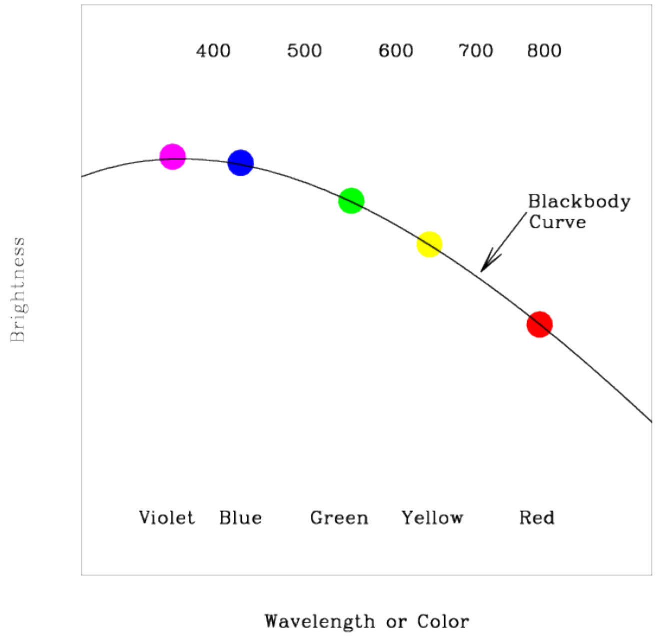


Figure 6.1: Astronomers measure the amount of light at a number of different wavelengths (or colors) to determine the temperature of a blackbody source. Every blackbody has the same shape, but the peak moves to the violet/blue for hot sources, and to the red for cool sources. Thus we can determine the temperature of a blackbody source by figuring out where the most light is emitted.

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

In the Bohr model, Figure 6.2, the electron is allowed to exist only at *certain* distances from the nucleus. This also means the electron is allowed to have *only certain orbital energies*. Often the terms *orbits*, *levels*, and *energies* are used interchangeably so try not to get confused. They all mean the same thing and all refer to the electrons in the Bohr model of the atom.

Now that our model is set up let's look at some situations of interest. When scientists

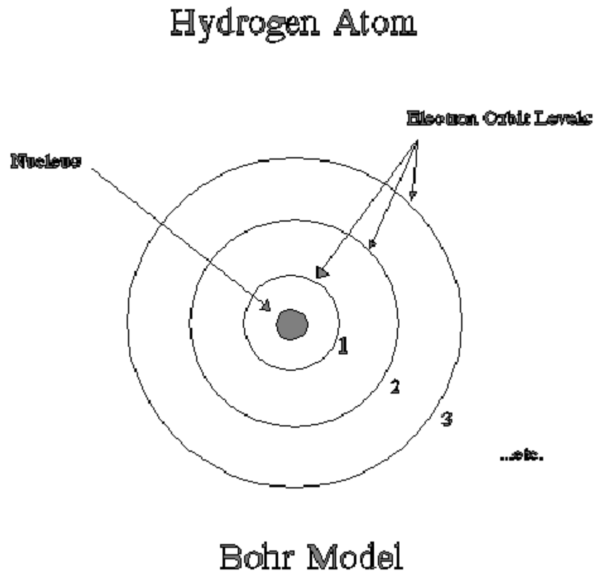


Figure 6.2: In the Bohr model, the negatively charged electrons can only orbit the positively charged nucleus in specific, "quantized", orbits.

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

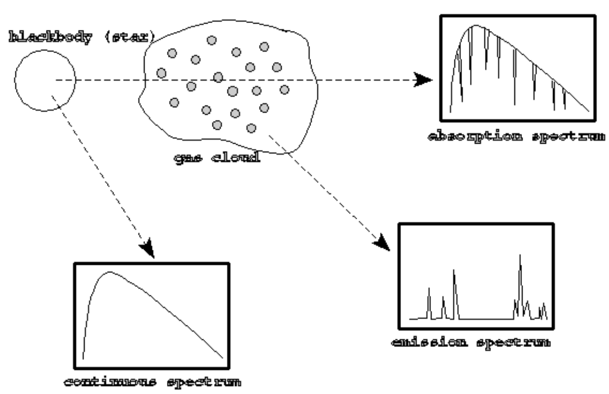
After much study, the physicists found out that the atom had taken-in energy from the collision or from the surrounding environment and that as it jumps downward in levels, it re-emits the energy as light. The light is a particular color because the electron really is allowed only to be in certain discrete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

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

6.3.2 Kirchoff's Laws

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

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



Kirchoff's Laws

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

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

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

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

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

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

6.4 Creating a Spectrum

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

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

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

6.5 Observing Blackbody Sources with the Spectrograph

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

1. First, get a spectroscope from your lab instructor. Study Figure 6.3 figure out which way the entrance slit should line up with the light source. **DO NOT TOUCH THE ENTRANCE SLIT OR DIFFRACTION GRATING!** Touching the plastic ends degrades the effectiveness and quality of the spectroscope.

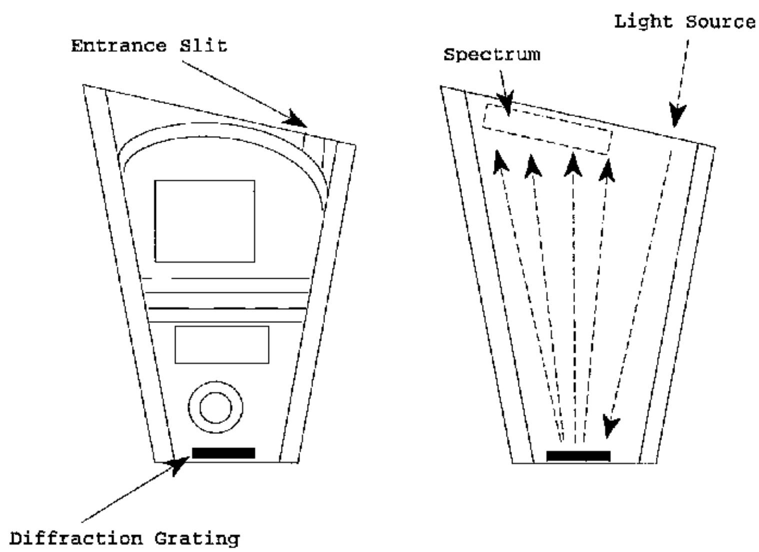


Figure 6.3:

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

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

4. Of all of the colors which you see in the spectrographs, which color appears the bright-

est?(**3 points**)

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

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

7. Betelgeuse is a Red Giant Star found in the constellation Orion. Sirius, the brightest star in the sky, is much hotter and brighter than Betelgeuse. Describe how you might expect the colors of these two stars to differ. (**4 points**)

6.6 Quantitative Behavior of Blackbody Radiation

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

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

`http://astro.unl.edu/naap/blackbody/animations/blackbody.html`

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

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

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

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

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

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

Temperature	Peak Wavelength
3000	
6000	
12000	
24000	

4. Can you see a pattern from your table? Describe how the peak wavelength changes as you increase the temperature. (**3 points**)

5. The peak wavelength and temperature are related by the equation:

$$\lambda_{\max} = \frac{2.898\text{x}10^6}{T} \tag{7}$$

where $\lambda_{\max}$ is the peak wavelength (in nanometers) and T is the temperature (in Kelvin). Where would the peak wavelength be for objects on Earth, at a temperature of about 300 degrees K? **(2 points)**

6.7 Spectral Lines Experiment

6.7.1 Spark Tubes

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

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

6.7.2 Emission-line Spectra Experiment

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

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

6.7.3 The Unknown Element

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

Table 6.1: Unknown Emission Line Source

Observed Wavelength (nm)	Color of Line

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

Table 6.2: Emission Line Wavelengths

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

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

6.8 Questions

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

2. What causes a spectrum to have more lines than another spectrum (for example,

Helium has more lines than Hydrogen)? **(4 points)**

3. Referring to Fig. 6.4, does the electron transition in the atom labeled "A" cause the emission of light, or require the absorption of light? **(2 points)**

4. Referring to Fig. 6.4, does the electron transition in the atom labeled "B" cause the emission of light, or require the absorption of light? **(2 points)**

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

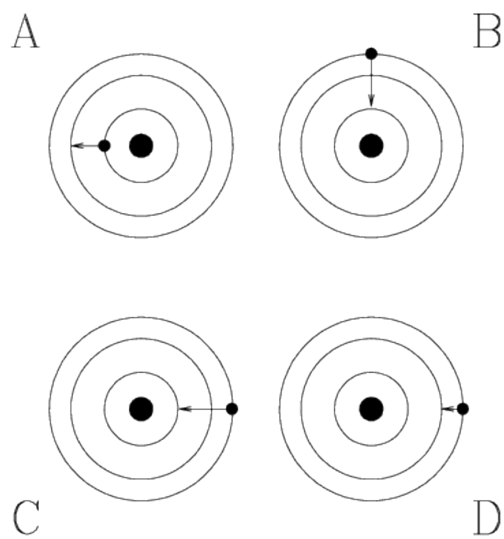


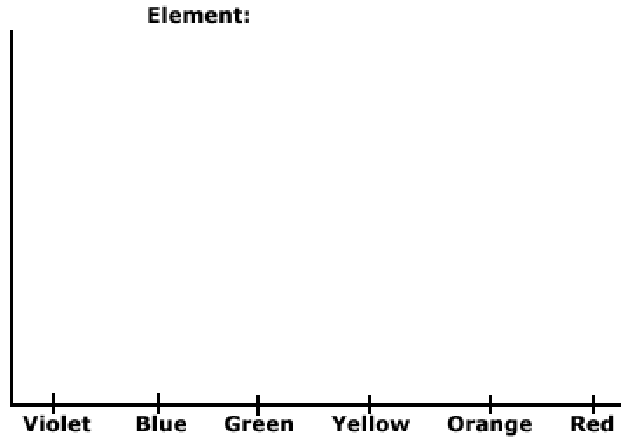
Figure 6.4: Electron transitions in an atom (the electrons are the small dots, the nucleus the large black dots, and the circles are possible orbits.

6.9 Possible Quiz Questions

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

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

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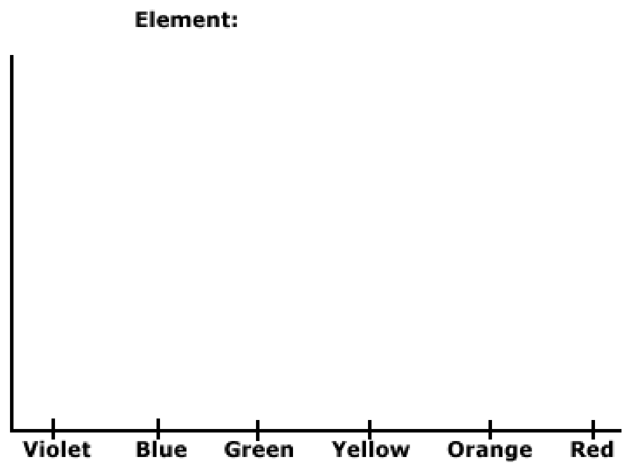
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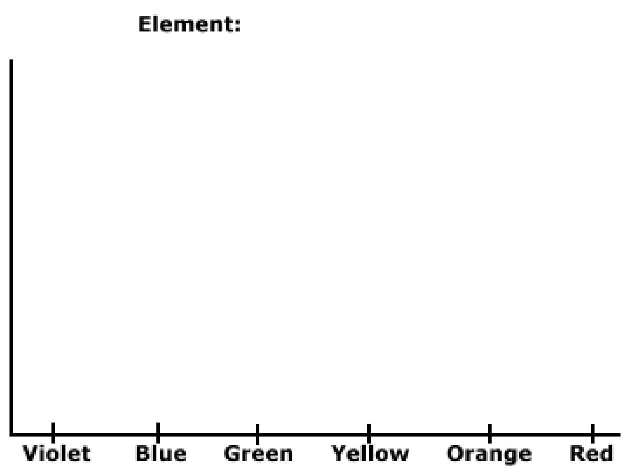
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Name: ________________
Team Number: __________

Spectroscopy Take Home Exercise (35 points total)

1. What information you can learn about a celestial object just by measuring the peak of its blackbody spectrum? (**5 points**)

2. What does a blackbody spectrum look like? Draw a blackbody spectrum on the plot below and make sure to label both axis! (**5 points**)

3. How does the peak wavelength change as the temperature of a blackbody changes? (**5 points**)

4. How can you quantitatively measure the color of an object? (**5 points**)

5. Do the color of items you see around you on Earth (e.g. a red and blue shirt) tell you something about the temperature of the object? Why or why not? (**5 points**)

6. What information can you learn about an astronomical object from its spectrum? How can you get this information from a spectrum? (**10 points**)

Name:________________________________
Date:_________________________________

7 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.

7.1 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 7.1: A dendritic drainage pattern in Yemen (left), and an anastomosing drainage in Alaska (right).

7.1.1 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 7.1. (**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!

7.1.2 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**)

7.2 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**)

7.3 Possible Quiz Questions

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

7.4 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: ________________
Team Number: __________

Water on Mars Take Home Exercise (35 points total)

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 are), then where has all of the water gone? Discuss two possible fates that the water might have experienced. *(HINT: 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.)* **(10 points each)**
   Possible fate 1:

   Possible fate 2:

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.
   a. Looking at the ages and lifetimes of the Warrego, Ares, and Tiu Valles, what do you think about the possibility that life started on Mars at the same time as Earth? **(5 points)**

   b. What must have Mars been like at that time? **(5 points)**

   c. What would have happened to this life? **(5 points)**

Name:________________________________
Date:_________________________________

8 The Volcanoes of Io

8.1 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^{o}C $= -279^{o}$F) 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

8.2 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 8.2. Io, Ganymede and Callisto are all larger than the Earth's moon, while Europa is slightly smaller. It is clear from Figure 8.2 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 8.2, 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

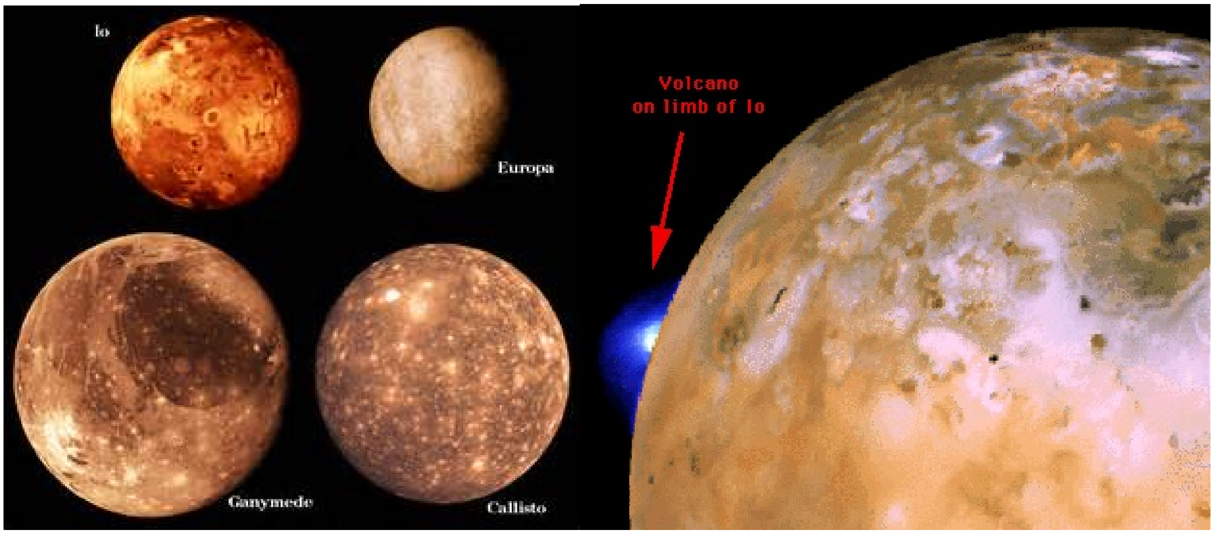


Figure 8.2: Left: The four Galilean moons of Jupiter. Right: An erupting volcano on Io seen in a Voyager image.

Earth's 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: $\mathrm{F} = \mathrm{m}a$. For gravity, Newton's second law is $\mathrm{F} = (G\mathrm{m}_1\mathrm{m}_2)/\mathrm{r}^2$ ("G" is the "gravitational constant"). Thus, even a slightly eccentric orbit, as demonstrated in Figure 8.3, means that large changes in tidal force are felt as Io goes around Jupiter (the $1/\mathrm{r}^2$ 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, $\mathrm{P}_{\mathrm{Europa}}$ = 3.551 days, and $\mathrm{P}_{\mathrm{Ganymede}}$ = 7.155 days. It we take the ratios of these orbital periods we get the following answers: $\mathrm{P}_{\mathrm{Europa}}/\mathrm{P}_{\mathrm{Io}} = 2.0$, $\mathrm{P}_{\mathrm{Ganymede}}/\mathrm{P}_{\mathrm{Io}} = 4.0$. 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 8.3. 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 interior of Io to become molten, and this liquid rises to the surface, where it erupts in vol-

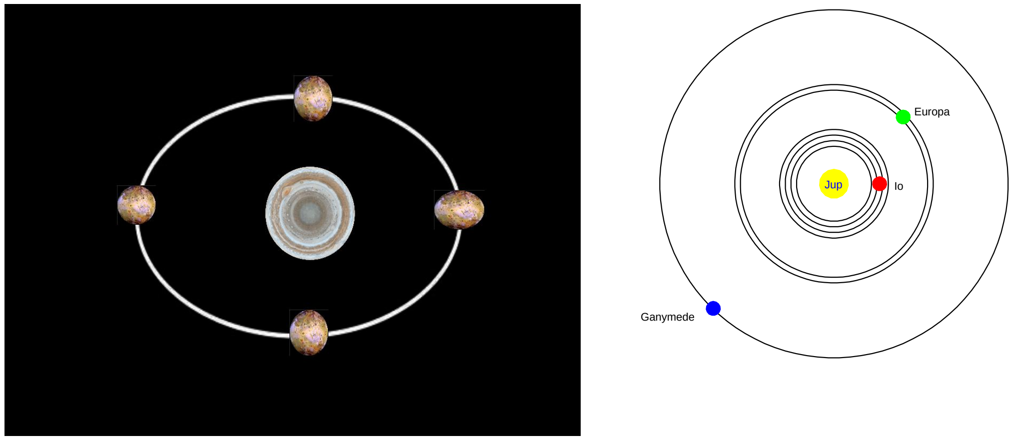


Figure 8.3: Left: Because Io's orbit around Jupiter is an ellipse, the distance is constantly changing, and so is the gravitational force exerted on Io by Jupiter (note that this figure is not to scale, and the ellipticity of the orbit and the shape of Io have been grossly exaggerated to demonstrate 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.

canoes. 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.

8.3 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. 8.4. 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 8.5. 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.

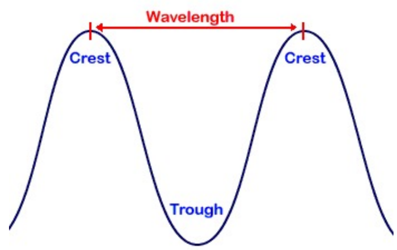


Figure 8.4: The wavelength is the distance between two crests.

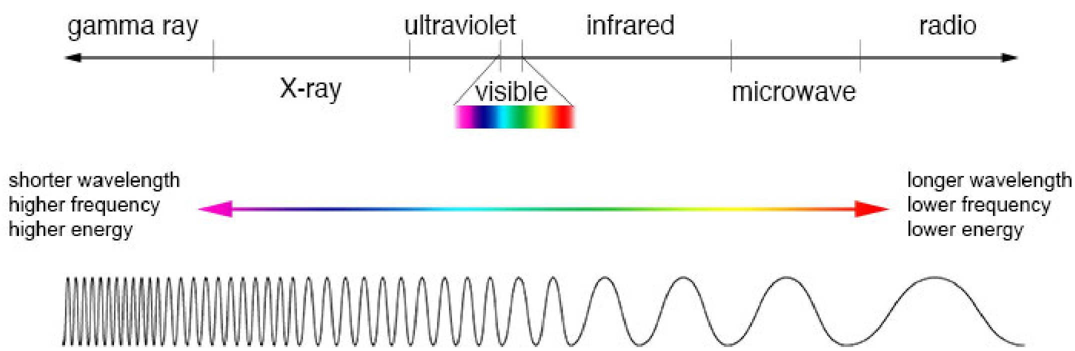


Figure 8.5: The electromagnetic spectrum.

8.4 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. 8.6. 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.

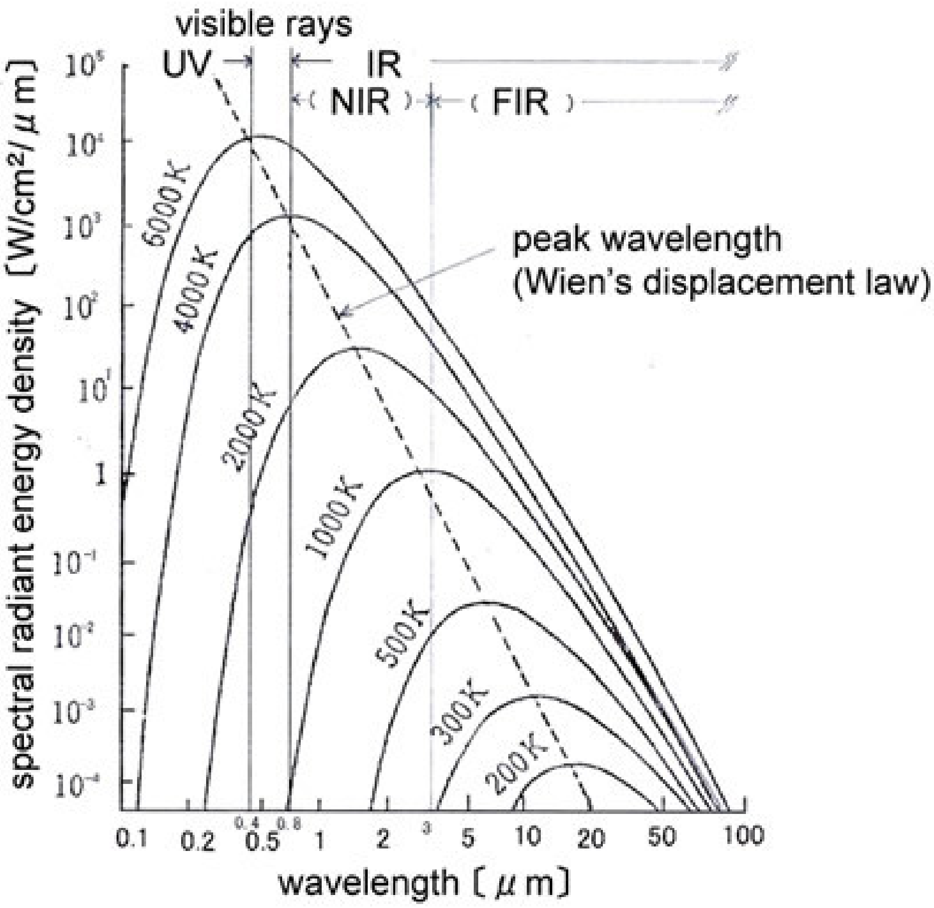


Figure 8.6: The spectra of blackbodies always have the same shape, but the wavelength where the *peak emission* occurs depends on temperature, and can be calculated using the "Wien displacement law" (since Wien is a German name, it is properly pronounced "Veen"). In this particular plot the unit of wavelength 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.

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:

$$E \propto T^4. \tag{8}$$

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 $E = sT^4$, 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 $^{o}F^4$. 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. 8.6, 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^o F" would be "hot", and "0^o F" would be "very cold." On this scale water boils at 212^o F, and freezes at 32^o F. The Fahrenheit scale is not very easy to work with, in that it has 180^o 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^o, and the boiling point was set to 100^o. This is the "Celsius" scale (denoted by "^{o} 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^o 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^o C to 0^o 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^o C, the emitted energy would be the *same* as it was at $+3^o$ C: $E = -3 \times -3 \times -3 \times -3 = 81 = 3 \times 3 \times 3 \times 3$. 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: $(10)^4 = (-10)^4 = 10{,}000$, 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, "$^{\circ}$", is not used with Kelvin). In our example, 3° C = 276 K, and 0° 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:

$$\frac{E_A}{E_B} = \frac{sT_A^4}{sT_B^4} = \left(\frac{T_A}{T_B}\right)^4 \tag{9}$$

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:

$$\frac{E_P}{E_Q} = \frac{s(43)^4}{s(33)^4} = \left(\frac{43}{33}\right)^4 = (1.3)^4 = 1.3 \times 1.3 \times 1.3 \times 1.3 = 2.86 \tag{10}$$

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: $\lambda_{\mathrm{max}} \times \mathrm{T} = 3670$]

4. If the temperature of a black body is 1000 K, at what wavelength (λ_{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 $\lambda_{\max} = 37\ \mu$m, what temperature is this object? (Remember to include the temperature unit!) (**2 points**)

8.5 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 8.1.

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 8.1. [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 8.1. (**6 points**)

Table 8.1: 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**)

8.6 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. 8.6. 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. 8.6 (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. 8.7, 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**)

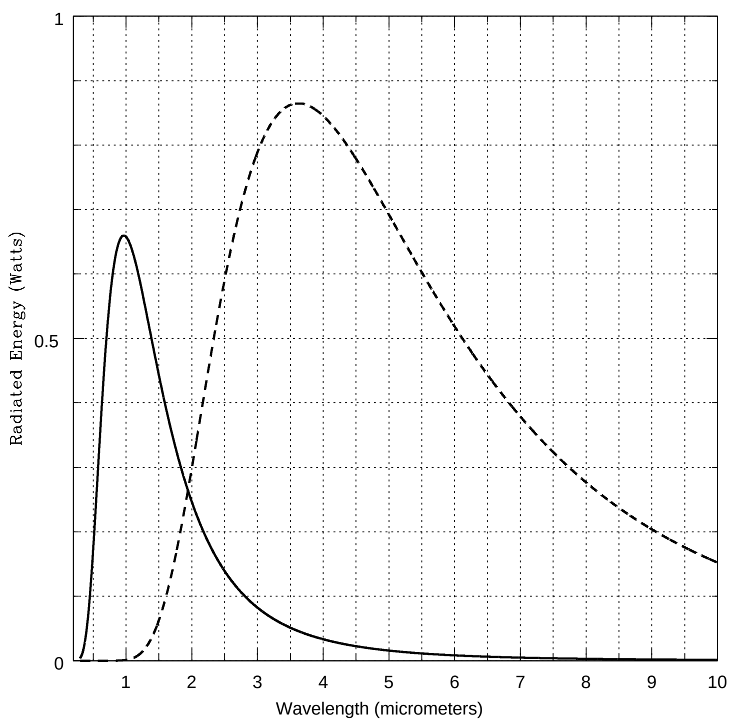


Figure 8.7: The energy vs. wavelength, the "spectra" (spectra is plural of spectrum), produced by two blackbodies with different temperatures.

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**)

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. 8.8 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 8.2: 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 = 2πR) 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 $side \times side = s^2$. 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 = $\underline{????}$ 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**)

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):

$$\frac{E_A}{E_B} = \frac{sT_A^4}{sT_B^4} = \left(\frac{T_A}{T_B}\right)^4 \tag{11}$$

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:

$$\frac{(Total\ Emitted\ Energy)_A}{(Total\ Emitted\ Energy)_B} = \frac{Area_A}{Area_B} \times \left(\frac{T_A}{T_B}\right)^4 \tag{12}$$

So,

$$\frac{(Total\ Emitted\ Energy)_{Volcano}}{(Total\ Emitted\ Energy)_{Io}} = \frac{(Area)_{Volcano}}{(Area)_{Io}} \times \left(\frac{T_{\#1}}{T_{\#4}}\right)^4 \tag{13}$$

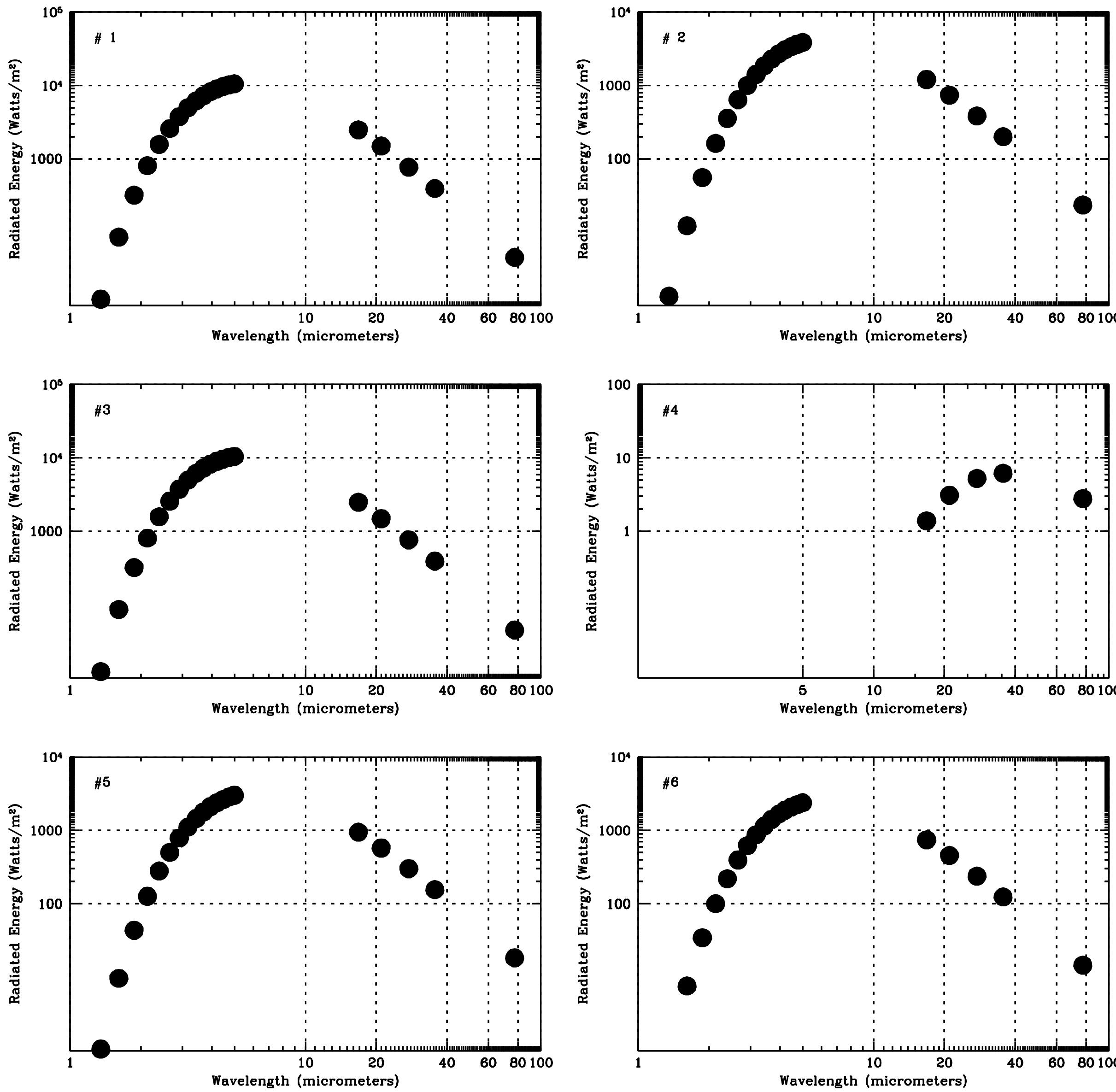


Figure 8.8: The blackbody spectra of the six boxes shown in Image #7. Be careful, these plots have *log* wavelength on the x-axis.

$$\frac{(Total\ Emitted\ Energy)_{Volcano}}{(Total\ Emitted\ Energy)_{Io}} = \tag{14}$$

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**)

8.7 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?

8.8 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: ________________
Team Number: __________

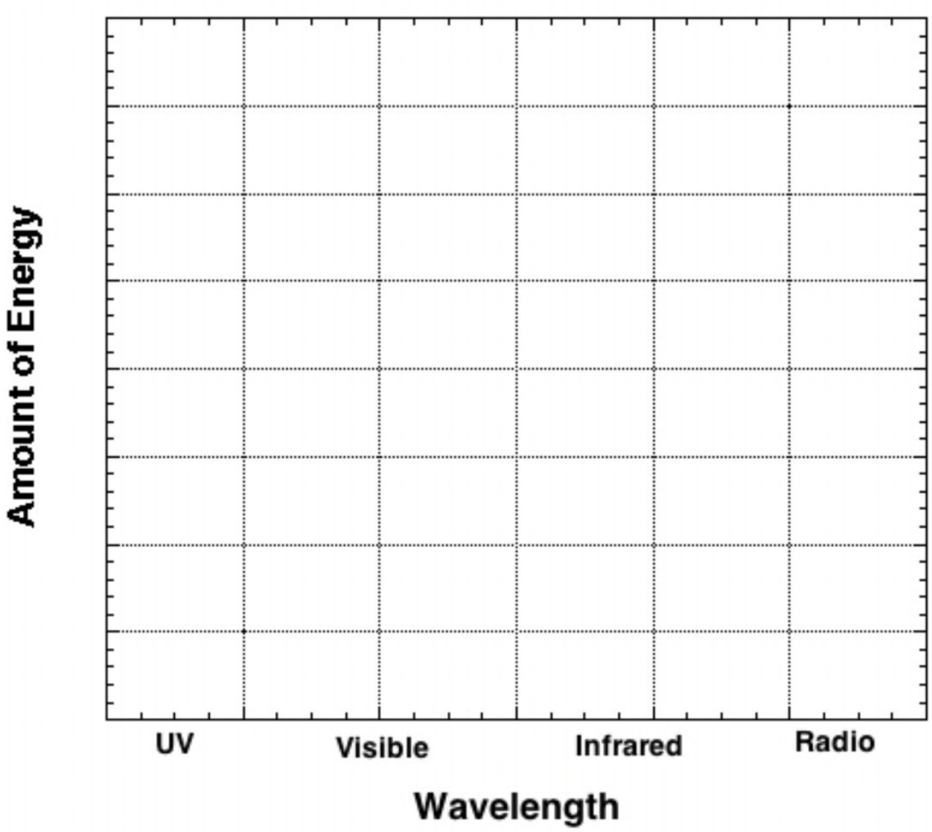
Volcanoes of Io Take-Home Exercise (35 points total)

1. In the graph below, sketch 2 curves indicating the blackbody curves (energy as a function of wavelength emitted by:

   a. A hot object (T = 6,000 K)

   b. 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. **(10 points)**



2. Why does Io have volcanoes? Answer in 1-2 sentences. **(5 points)**

3. Jupiter has several moons that are much smaller than Io and that orbit even closer to Jupiter than Io. Explain why these moons do NOT show evidence of volcanism. *(Hint: think of a man-made satellite in Earth's orbit, such as the International Space Station.)* **(5 points)**

4. Consider the orbits of Io, Europa, and Ganymede.

    a. Why is Io's orbit very eccentric? **(5 points)**

    b. What does it mean that Io, Europa, and Ganymede are in orbital resonance? **(5 points)**

    c. 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? **(5 points)**

Name:______________________________
Date:______________________________

9 Gases, Liquids and Ices in the Outer Solar System

9.1 Introduction

Water. You are familiar with water in all of its three forms: liquid, gaseous (steam), and solid (ice). Human life, and life on Earth itself, would be impossible without liquid water. Thus, NASA has used the goal of "Follow the Water" in searching for life elsewhere in our solar system. We have found that water exists in some form on just about all of the bodies in the solar system. On hot Mercury, there appears to be water ice located in the polar regions in permanently shadowed craters. The same is true for the Earth's moon. Even one of the driest bodies in our solar system, Venus, has a little bit of water vapor in its atmosphere, and probably has some water buried deep within its crust.

It is difficult to envision how any forms of life could survive on Mercury, Venus, or the Moon. The same is not true, however, as we go further out into the solar system. As you have learned in this class, the planet Mars has ample evidence that liquid water flowed on its surface in the past, as well as large deposits of ice at its poles, and frozen into the soil. The big question is whether there is liquid water *anywhere* on present-day Mars. As you also will find out this semester, several of the moons of the Jovian planets have evidence for liquid water. In fact, water ice is ubiquitous in the outer solar system–many of the solid surfaces found beyond the orbit of Mars have water ice as a major constituent.

Today we are going to investigate gases, liquids and ices. Since objects in the outer solar system are far from the Sun, they are cold, thus any liquid water on the surface will usually be frozen. To understand the conditions on Mars, or on one of the moons of the Jovian planets, we have to understand how water, and other substances, *behave at different temperatures and at different pressures.*

9.2 Water on Earth, and the Triple Point Diagram

All of you are experienced with how water behaves on the surface of Earth. If the temperature is above the freezing point, any water on the surface, or any that falls from the sky, will be a liquid. You know that this temperature is 32°F. This is the freezing point of water on the surface of the Earth. You are also aware that if you heat a pot of water on the stove for long enough, the water will boil, producing water vapor (steam). Steam is the gaseous form of water. The boiling point of water is 212°F *at sea level*.

Did you notice we added the "*at sea level*" in the previous sentence? If you are a cook, you might have noticed that many recipes (even frozen pizzas!) have different cooking times depending on altitude. Why? It is because the temperature at which water boils and becomes steam is dependent on the atmospheric pressure. For Las Cruces, our elevation is near 4,000 feet. Our air pressure is lower than at sea level, and thus the boiling point of water is lower: 204°F. It takes a little bit longer to cook spaghetti in Las Cruces, than if you lived in San Diego.

The first question you may have is "why does the atmospheric pressure drop with increasing altitude?" The answer is simple: atmospheric pressure is just the "weight" of all of the air above your head. As you climb in altitude, there is less air above you, so there is less pressure. At some altitude, there will be no atmosphere left, and thus no pressure: the vacuum of space. Most definitions of the end of the Earth's atmosphere put this altitude at 100 km.

The second question you should ask, or at least be thinking about, is "why does atmospheric pressure have anything to do with the boiling point of water?" This question is a little bit harder to answer. When you heat a substance (whether solid, liquid or gaseous), the molecules that make up that substance start vibrating. They are getting "excited" by the heat. As a liquid heats up, some of the molecules near the surface of the liquid have enough energy to jump out of the liquid, and try to escape. But the atmospheric pressure pushes back on them, and keeps them in the liquid. Eventually, however, these molecules acquire enough energy to overcome that atmospheric pressure, and the highest energy molecules can escape. Eventually, all of the molecules have enough energy to escape, and the liquid boils away.

Bell Jar Demo: We are going to demonstrate this effect in class today. To do this, a glass "bell jar" is connected to a strong pump. As we pump out the air, we lower the pressure. As the pressure drops, the water in the container will freeze—even though the temperature in the room is well above freezing! The pump, besides removing the air in the vessel, also removes the most "excited" water molecules. Thus, the water is also cooled.

Just about every substance in the Universe behaves this way. There are solid forms, liquid forms and gaseous forms of just about all substances. There is a complicated relationship between the boiling points and freezing points that depend on the local temperature and pressure. These relationships can be easily summarized in something called a triple point (or "phase") diagram. A simple version of such a plot is shown in Fig. 9.1.

9.3 Understanding the Triple Point Diagram for Water

For the first part of today's lab, we are going to be looking at the triple point diagram for water. In such a diagram, the temperature will be on one of the axes, while the pressure is on the other one. Note that sometimes temperature is on the x-axis, and sometimes it is on the y-axis. There is no rule.

Before we begin, however, we must talk about the units we are going to be using in this lab. For the temperature, these diagrams are either in Celsius or Kelvin. Remember that

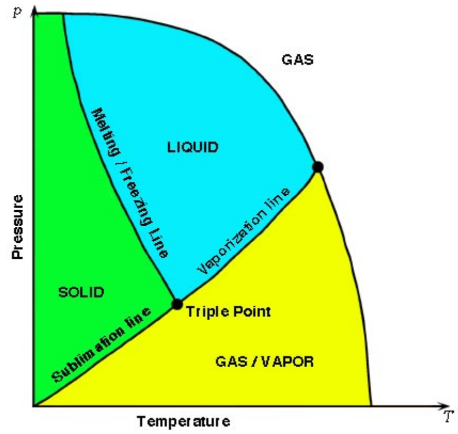


Figure 9.1: A simple triple point diagram. At certain temperatures and pressures a substance can be a solid, a liquid or a gas. **There is one place in "phase space" where all three states of matter simultaneously exist: the triple point.** In this version of the diagram, temperature is on the x-axis, and pressure on the y-axis (from http://www.kchemistry.com/Quizzes/triple_point_lg.jpg).

the Celsius temperature scale was defined with respect to the behavior of water: 0°C is the freezing point of water (= 32°F), and 100°C (= 212°F) is the boiling point. In the Kelvin system 0°C = 273 K, and 100°C = 373 K (the zero of the Kelvin scale is something called "absolute zero", and is equivalent to −273 °C = −459°F). The three scales are compared in Fig. 9.2.

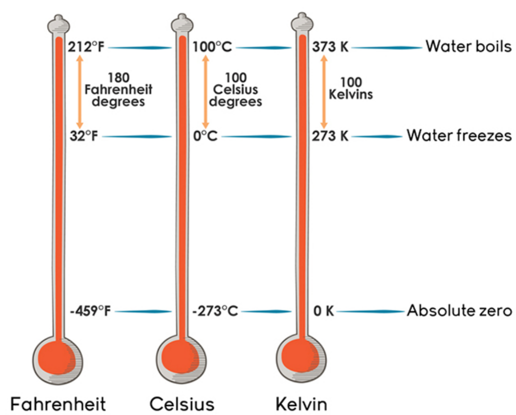


Figure 9.2: A comparison of the three temperature scales used by the public and by scientists: Fahrenheit, Celsius, and Kelvin (from https://www.learner.org/courses/chemistry/images/lrg_img/ThermometersFCK.jpg).

The other component of a triple point diagram is the pressure. There are several different units that can be used for pressure. In the US we use pounds per square inch. In countries on the metric system they may use kilograms per square centimeter. But these result in complicated numbers to memorize. The unit of pressure that we will be using is the "bar." One bar is the standard pressure at the Earth's surface, or "one unit of atmospheric pressure." If the pressure is 0.1 bar, this is equivalent to 10% of the pressure at the Earth's surface.

Now we are ready to look at a more realistic triple point diagram for water: Fig. 9.3. At one bar (the air pressure at sea level), the freezing point of water is at 0°C, and the boiling point at 100°C (or 273 K and 373 K, respectively). Note that the triple point of water is at 0°C, but at a very low pressure: 6 millibars. On Earth, this corresponds to an altitude of 60 km! Notice that the range of temperatures and pressures at which water is a liquid is smaller than found for either ice or gas. Water ice can occur over a very wide range of temperatures and pressures. At high pressures, there can be forms of water ice that exist at temperatures above 1,000°F! As this diagram delineates, there are various types of ice that are segregated by the shape of the ice crystals.

1. The (average) atmospheric surface pressure on Mars is 6 millibar (= mbar). This is very close to what special place in the phase diagram of water? What form(s) of water might we find at this pressure? (**2 points**).

Like on Earth, the temperatures at various locations on Mars depend on the season, and span the range from −140°C in winter to 20°C in the summer. Unlike the Earth, the atmospheric pressure on Mars spans a large range: from 4 mbar in winter to about 9 mbar in summer (more than a factor of two!).

2. Do we expect to find liquid water on the surface of Mars during the winter? Why? What form(s) or *phase(s)* of water can exist during the winter time on Mars? (**2 points**).

3. How about during the summer? What phases of water can exist during the summer time on Mars? (**2 points**).

It is clear that there is a very narrow window of temperatures and pressures that would allow for liquid water on the surface of Mars. Let's look at some other objects you have learned (or will learn) about in class. The Jovian planets Uranus and Neptune are also

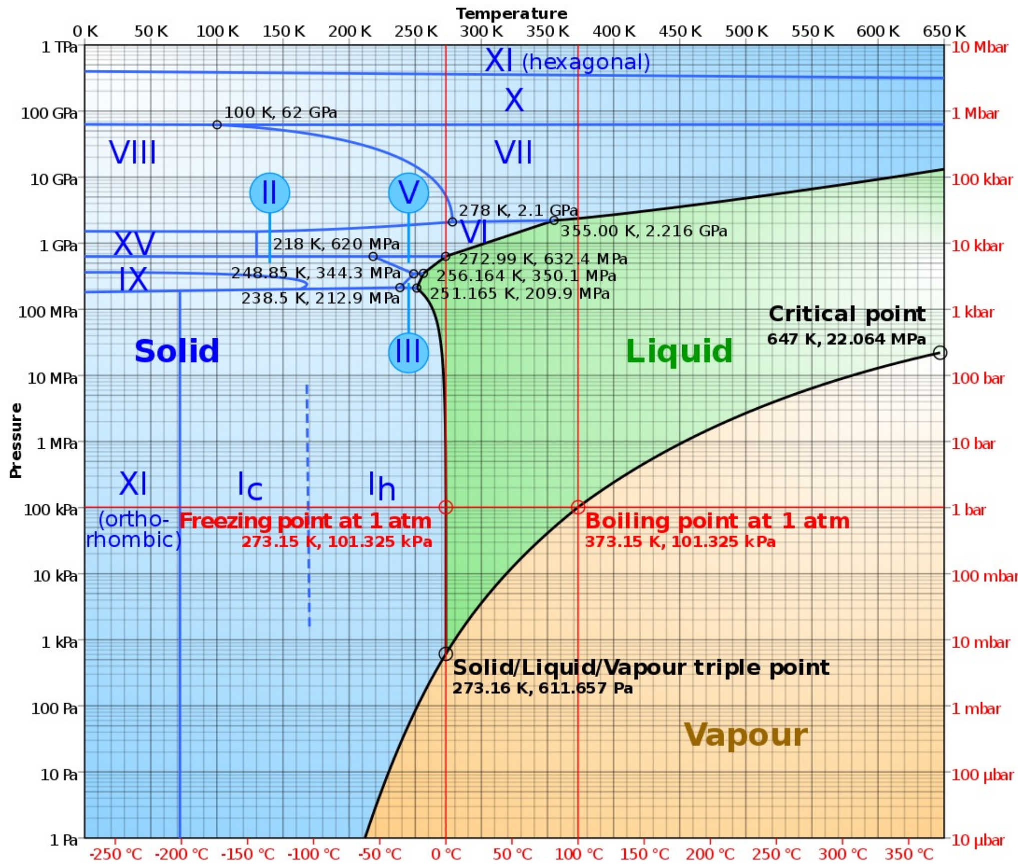


Figure 9.3: The triple point diagram for water. On the x-axis we have the temperature in Celsius, and on the top of the diagram, the temperature is in Kelvin. On the y-axis (right hand side) we have the pressure in units of bars. Note that this axis is plotted in powers of 10, or *logarithmically*. This allows us to plot the enormous range in pressures necessary to explore the triple point diagram of water. The left hand y-axis has the metric units of pressure in "Pascals," from 1 Pa, to 1 TPa (Terra Pascal = 1 trillion Pascals). 1 bar = 100,000 Pa. We will not be using Pascals in this lab! (From https://en.wikipedia.org/wiki/Triple_point.)

called "ice giants." This is not because they have icy surfaces, but because deep below the tops of the clouds there is a region of ice. The so-called "ice mantle," shown in Fig. 9.4.

4. If the temperature of the ice mantle in Uranus is 350°C (= 623 K = 660°F), and if it were composed entirely of water (not true), what must the pressure be in the ice mantle? (**2 points**)

9.4 Sublimation and Vaporization

Returning back to Fig. 9.1, there are some words in this diagram we need to become familiar with: sublimation, and vaporization. To these we add the word for the reverse of vaporization: condensation. Between the solid phase and the liquid phase, we have a line

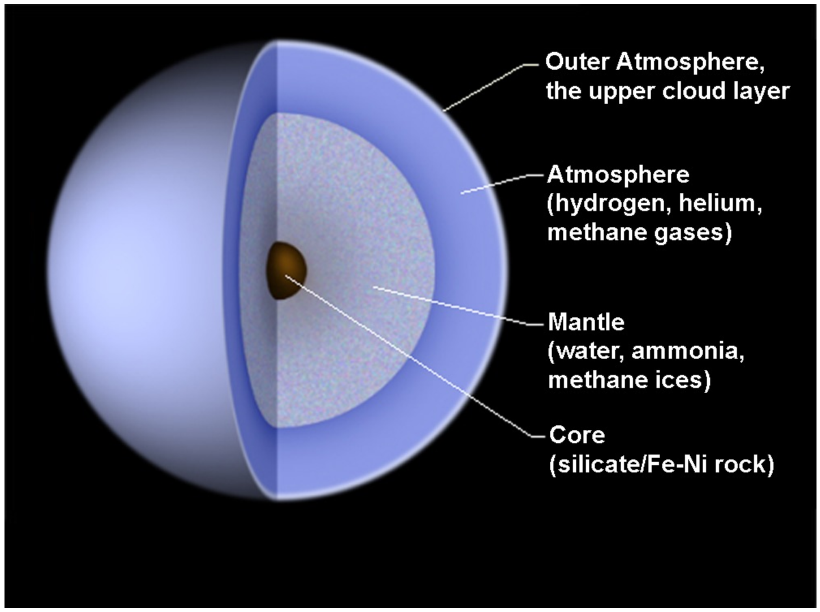


Figure 9.4: The interior structure of Uranus, showing that the "ice mantle" contains most of the mass of the planet. The ice mantle is made up of a mixture of water, ammonia, and methane ices. From https://en.wikipedia.org/wiki/Uranus.

that marks the "Melting/Freezing" line. This term needs no explanation. As you lower the temperature (move to the left in Fig. 9.1), the liquid freezes. If you raise the temperature, the solid melts and becomes a liquid.

There are two other types of transitions in the triple point diagram. The first is sublimation: this is when a gas can become a solid, or a solid can become a gas, without first becoming a liquid. If the pressure is low enough, the water molecules that form ice can instantly become vapor if they can absorb a little heat—such as if the sun shines on the frozen ice. The other type of transition is the change from liquid to gas, called vaporization. This is essentially "boiling," where the liquid turns into a gas. The reverse is also possible, called "condensation," depending on the change in temperature *or* pressure. Condensation is what happens when you take a glass containing a cold drink outside—water suddenly collects on the side of the glass. It is also why clouds form.

5. Astronomers have found that there is always water vapor (gaseous water) present in the atmosphere of Mars (we see clouds!). How is this possible if there is no liquid water on the surface? (**3 points**)

9.5 Europa, Enceladus, Titan and Pluto

Now we are going to use the knowledge we have just acquired and apply it to four bodies in the outer solar system: Europa, Enceladus, Titan and Pluto. Europa is one of the four big moons of Jupiter, while Enceladus and Titan are moons of Saturn. Pluto is the infamous "dwarf planet" discovered by Clyde Tombaugh, a former faculty member at NMSU (note that astronomers still argue about whether Pluto should be called a planet, but that discussion is for some other time and place).

Exercise #1: Understanding Europa

In the binder that you were given as part of this lab, we have some images of Europa. Of the four "Galilean satellites" of Jupiter (discovered by Galileo in 1610), Europa is the smallest and least massive. It is similar in size to the Earth's moon (a radius of 1,560 km vs. 1,738 km), but its density, 3 gm/cm^3, is lower than that of our moon, 3.3 gm/cm^3, so it is quite a bit less massive. Europa orbits Jupiter between Io and Ganymede. All three of these moons are locked in an orbital resonance, that causes tidal heating. This creates an internal heat source that supports a sub-surface ocean for Europa (and possibly Ganymede), and hundreds of volcanoes on Io.

Image #1 shows a wide view of Europa. In this wide view there is not very much surface detail. We can see what looks like a crater towards the bottom right. Otherwise there just seem to be some brownish regions, and some dark, linear streaks.

6. The average surface temperature of Europa is -160°C. If there is water on its surface, what phase will the water be in? (**1 point**)

Image #2 shows a close-up view of Europa, giving us a better view of the streaks, some other brown spots, and some white bumps, appearing to be a bit higher than the local area. Europa has the smoothest surface in the solar system, with most of the highest features having elevations of $\sim$ 10 meters. Remember, we said its radius was 1,560 km; 10 meters is 0.01 km, so its surface is essentially smooth to 1 part in 156,000. A billiard ball is smooth to 1 part in 57,150. If you could shrink Europa down to the size of a billiard ball, it would be smoother!

Why so smooth? The surface of Europa is almost pure water ice. If you have seen the surface of a frozen pond or lake, you know that such a surface can be very smooth. Astronomers believe that the pull of gravity from Jupiter, and the moons Io and Ganymede, is tugging on Europa, causing it to stretch and contract. This stretching heats the inside of Europa, melting the ice, and turning it into water. The surface of Europa is cold, so a thin (10, 20, or 100 km thick?) layer of ice forms on top the ocean.

7. Water covers much of the Earth's surface, but water ice covers the entire surface of

Europa. Why? (**4 points**)

The other thing to notice in the wide view of Europa is that there are almost no impact craters: There are only seven craters on Europa that have diameters of 20 km or more. In contrast Callisto, the fourth of the Galilean satellites, has hundreds!

8. Something is erasing the impact craters on Europa. Can you think of a reason why there are no big impact craters on the surface of Europa? [Hint: Think of the process: a high speed impactor crashes into a thin layer of ice that covers a body of water. What happens?](**4 points**)

Finally, for Europa, is Image #3: there are water vapor plumes that erupt from the surface of this moon! Presumably they come from one (or more) of the cracks. *This proves that there is a source of liquid water below Europa's icy surface.* We will see much more dynamic versions of these plumes on our next object, Enceladus.

Exercise #2: Investigating Enceladus

Enceladus is the sixth largest moon of Saturn with a radius of 500 km. It has a low density of only 1.6 gm/cm^3. Given its low density we can infer that water must make up much of the mass of Enceladus. Enceladus is the "shiniest" large object in the solar system in that it reflects about 80% of the incoming light. This, and its great distance from the Sun (1.4 billion km), means its surface is very cold: -200 °C, and any water or carbon dioxide will be frozen solid.

Image #4 is a wide view of Enceladus. The upper-right portion of Enceladus appears to be covered with craters. At the bottom are some blueish stripes, or cracks. On the left edge is a very, very smooth region devoid of any surface features.

9. Compare the surface of Enceladus to that of Europa. How are they different, and how are they similar? (**4 points**)

Image #5 is a distant picture of Enceladus taken by the Cassini spacecraft. Note the jets of material coming out of the bottom of the moon. Image #6 is a closer view of those jets, or "geysers." It is now clear that this material is shooting out of the blue stripes seen in Image #4 (note that we have to see the jets of material illuminated by the sunlight against the blackness of space, as they are faint in comparison to the moon itself).

10. We now know that most of the material in these jets is water vapor, various kinds of ice crystals, hydrogen gas, and a bit of salt (sodium chloride = table salt!). What does this tell you about what is beneath the icy surface of Enceladus? (**4 points**)

In Image #7, we take a long look at Enceladus (the tiny black dot near the bright white spot) and find that it has created its own ring around Saturn! This is the so-called "E-ring," and is made up of material ejected from the inside of Enceladus. Just like Europa, Enceladus is in a orbital resonance with a nearby moon (Dione), and the tidal heating causes some portion of the interior of Enceladus to melt, creating a sub-surface lake, or ocean, from which the geysers emanate. This ejected material then goes into orbit around Saturn, forming a ring.

Exercise #3: Exploring Titan

Titan is the largest moon of Saturn, and the second largest moon in the solar system. It has a radius of 2,575 km, making it larger in size than the planet Mercury (radius of 2,432 km). But Titan only has a density of 1.9 gm/cm^3, compared to Mercury's 5.5 gm/cm^3. Mercury is much more massive. Titan is surrounded by a very dense atmosphere, with a surface pressure of 1.45 bar. Titan has a more massive atmosphere than that of the Earth! This atmosphere is 97% nitrogen (N_2), and 2.7% methane (CH_4). Methane is a very intense "greenhouse gas," and thus the surface temperature of Titan is warmer than it would be without its atmosphere: -180^oC (= 93 K).

With an atmosphere dominated by nitrogen and methane, we now have to examine the triple point diagrams for these substances to fully understand Titan. In Fig. 9.5, we plot the (simplified) phase diagrams for water, methane and nitrogen. Note that unlike the previous diagrams, pressure is now on the x-axis, and temperature on the y-axis (and the temperature scale is in Kelvin. Remember, 0 K = -273^oC). Also note that 10^0 bar = 1 bar, 10^2 bar = 100 bar, 10^{-2} bar = 0.01 bar, etc.

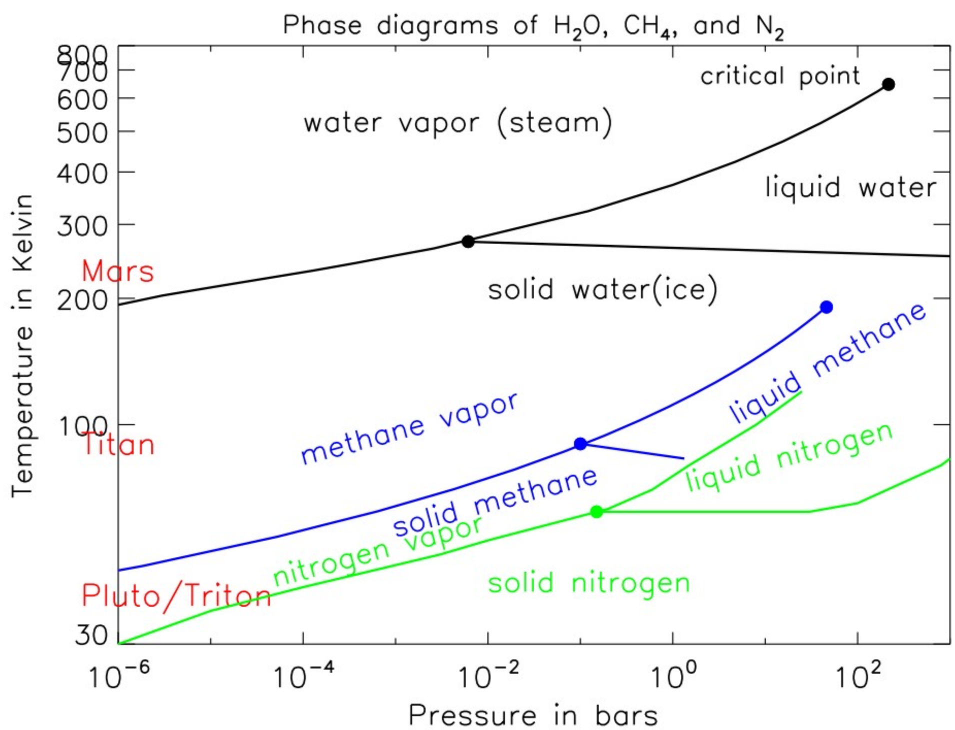


Figure 9.5: The triple point/phase diagrams for water (top, black), methane (middle, blue), and nitrogen (bottom, green). The x-axis has pressure labeled in an unusual way, but just note that 10^0 bar = 1 bar, and 10^2 bar = 100 bar, etc.

11. Given that the surface pressure is 1.4 bar, and the temperature 93K, in what phases do we expect to see water, methane, and nitrogen? (**4 points**)

12. This is a surprising result, isn't it? We now have at least one substance that should be a liquid on the surface of Titan. What do you think this might mean if we could take some images of the surface of Titan? (**2 points**)

In Image #8 we show a wide view of Titan. Boring, eh? Titan's atmosphere is very hazy and cloudy, and we cannot see anything in visible light. Fortunately, as Cassini entered the Saturnian system it dropped a little probe named Huygens into Titan's atmosphere. As Huygens floated down to the surface it took pictures, one of which is shown in Image #9.

13. What surface feature is shown in Image #9, and what do you think forms, or creates, this feature? (**4 points**)

If Titan has rivers, what else might it have? Because astronomers already knew Titan was cloudy, they equipped the Cassini probe with a radar system to map the surface of Titan (radar waves can see through clouds, a similar system was sent to Venus). Image #10 is one of these radar maps of a slice of Titan's surface: there are lakes of methane on Titan! The conditions on Titan are just right to have a "hydrological cycle" based on methane. This means that high in the atmosphere methane *condenses* from gaseous vapor into liquid droplets, these grow and fall as rain, the rain forms rivers and lakes, there is *vaporization* (evaporation) from the lakes producing gaseous methane, and the cycle is completed.

Exercise #4: Inspecting Pluto

When Pluto was discovered in 1930 by Clyde Tombaugh, astronomers thought they had finally found the most distant planet in our solar system. Pluto is indeed very far away, with an average distance of 5.9 billion kilometers (39.5 AU). But we now know that there are other objects beyond Pluto that are just as big, and thus to avoid having to add extra planets to the solar system every few years, a new classification was devised: the "dwarf planet." This did not make everyone happy (especially at NMSU), but officially, Pluto has been reclassified as a dwarf planet.

Pluto is so far away that the Sun provides little heat, and it is very cold: 44 K = -229^{o}C. Pluto has a radius of 1,188 km, smaller than the Earth's moon (1,738 km). Pluto has a density of 1.9 gm/cm^3, similar to that of Titan. Therefore it must be made of similar materials. We do not have time today to perform a deep investigation of Pluto, but the take home portion of this lab will have two questions about Pluto, so be sure to read those before you leave lab today.

Until the New Horizons spacecraft went by Pluto in 2015, we knew very little about this interesting object. Before we look at the surface of Pluto, we want you to look at what was actually one of the last pictures taken by New Horizons, Image #11. Here, Pluto is blocking the direct view of the Sun, and we see that it has an atmosphere!

14. Given that Pluto probably has water, CO_2, methane and nitrogen on its surface, use the triple point diagrams above to predict which of these substances is the *most likely one* to be in a gaseous phase at the temperature of Pluto. (**2 points**)

15. Given the substance you have chosen, what must the pressure be in this atmosphere? (**2 points**)

The surface pressure measured from New Horizons data for Pluto is 10^{-5} bar. This should now make sense to you, and demonstrates how useful triple point diagrams are. Now for the surface of Pluto. In Image #12 we present a wide view of Pluto. Note that Pluto has flat, smooth regions, highlands, shallow impact craters, and darker regions. Pluto is both quite a bit different, and at the same time somewhat similar, to the other objects we've looked at today.

In Image #13 we show a close up of some mountains that appear to have *nitrogen* glaciers flowing from them with embedded chunks of water ice that form "hill chains," and "hill clusters."

9.6 The Triple Point Diagram for Carbon Dioxide

Now we are going to change substances, from water (H_2O) to carbon dioxide (CO_2). The triple point diagram for carbon dioxide is shown in Fig. 9.6. It is quite a bit simpler than that for water. Note where the triple point is located in this diagram: 5.2 bar, −56°C.

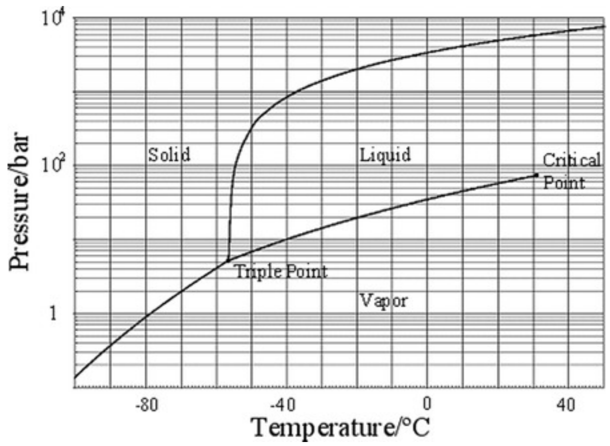


Figure 9.6: The triple point diagram for carbon dioxide. Note the units for pressure on the y-axis: $10^2 = 100$ bar. The mid-way point between 1 and 100 bar is of course 10 bar (the tickmarks in a log plot are not evenly spaced, but still run from 1 to 10, or 10 to 100, etc.).

16. Can liquid or solid carbon dioxide ever exist on the Earth's surface? What if you were told that the coldest temperature ever recorded on Earth (in Antarctica, of course), was −94.7°C? (**2 points**).

17. Predict how carbon dioxide will behave on Mars as we pass from winter into summer. How might this influence that change in atmospheric pressure we noted earlier? (**4 points**)

Experiment #1: Solid Carbon Dioxide. Your TA is going to give you a small chunk of frozen carbon dioxide (dry ice) inside a ziploc bag. Zip up the baggie for a few minutes.

18. Describe what is happening. What process is occurring here? Why is frozen carbon dioxide called "dry ice?" (**4 points**).

Now, unzip the baggie, but leave the dry ice in it, and move it to the side.

Experiment #2: Liquid Carbon Dioxide. We are now going to see if we can make liquid carbon dioxide at room temperature. Look back at the triple point diagram for carbon dioxide. How can we make liquid CO_2 at temperatures well above the triple point?

19. What do we need to increase in order to get liquid carbon dioxide to be stable at warmer temperatures? (**1 point**)

Your TA is going to give everyone safety goggles, a small amount of finely crushed dry ice in a paper towel, a plastic pipet, like used in chemistry and biology labs, a small funnel (a piece of wire to help convince the dry ice to go through the funnel), and a pair of pliers. We have cut off the tip of pipet so you can fit the funnel into it. Use the paper towel to pour the dry ice into the funnel so that **THE DRY ICE FILLS THE PIPET BULB BY ABOUT ONE THIRD!** Now, take the pliers and bend over the tip of the pipet, and clamp it–we need to create a good, tight seal–we do not want the CO_2 gas to escape, we need to increase the pressure! One member of the group needs to start timing: After about 90 seconds or so, you should begin to see liquid CO_2 form. As soon as all of the dry ice turns to liquid, release the pressure: **Warning: there is going to be a small pop! IF YOU WAIT TOO LONG THERE WILL BE A BIG POP—THE PIPET WILL EXPLODE!**

20. Explain what happened in this demo. What allowed us to form the liquid CO_2? What happened when you released the pressure? Into what phase did the liquid CO_2 return? Why? (**4 points**).

9.7 The Importance of Density in Shaping the Surfaces of Objects in the Outer Solar System

Earlier this semester you might have had a lab on density. As a reminder, density is simply the mass of an object divided by its volume: Density = Mass/Volume. It has units of gm/cm^3, or kg/m^3. The densities of various substances are listed in Table 9.1. Note that we have two densities listed here, one for the solid phase and one for the liquid phase.

Table 9.1: The Densities of Various Substances

Substance	Density as a Solid (g/cm^3)	Density as a Liquid (g/cm^3)
Water	0.92	1.0
Carbon Dioxide	1.6	1.1
Nitrogen	1.03	0.80
Iron	7.9	6.9
Silver	10.5	9.3
Gold	19.3	17.3

21. Compared to the other substances listed in Table 9.1, water is unusual. Why do we say that? What does this actually mean? [Hint: what happens when you put the solid phase of a substance on top of its liquid phase?] (**4 points**)

Experiment #3: Let's confirm your answer to question #11. Using the beaker with water in it that your TA gave you, drop an ice cube into the water.

22. What happens? (**2 points**)

Now we are going to drop the piece of dry ice into the beaker (this is going to be a bit more exciting!). Before doing so, look at Table 9.1, what do you think is going to happen? Carefully drop the chunk of dry ice from the Ziploc bag into the beaker.

23. What happened? (**2 points**)

Name:________________________________
Date:_________________________________

9.8 Take Home Exercise (35 points total)

Answer the following questions in the space provided:

1. What is a triple point diagram? What are the two quantities on the axes of the plot? What does this diagram tell you, and how do you use it? (**10 points**)

2. In this week's lab, we encountered three objects that were very smooth, or had very smooth regions on their surfaces (Europa, Enceladus, and Pluto). The solar system is a violent place, with meteors crashing into the planets and moons all of the time (more so long ago). How can Enceladus or Pluto have such smooth regions on their surfaces? [Hint: Words you might use in your explanation are "activity," "resurfacing," "convection," or "recycling." Do some research! Make sure to cite your sources.]

   (a) Europa (**5 points**)

   (b) Enceladus (**5 points**)

(c) Pluto (**5 points**)

3. In the Introduction we mentioned that if we are going to find life elsewhere in our solar system, we need to locate liquid water. Given what you know now, where would you go to search for life in our solar system? How would you go about doing this? (**10 points**)

9.9 Possible Quiz Questions

1. What is a triple point diagram?
2. What does 1 bar, a unit of pressure, actually mean?
3. List the three phases, or states, of ordinary substances.
4. What is a Kelvin?

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

In several of the triple point diagrams in this week's lab there was a point labeled the "critical point." What is the critical point? See if you can identify two more elements/substances that behave like water (i.e., their solid forms are less dense than their liquid forms).

Name:____________________________________
Date:____________________________________

10 Building a Comet

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

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

10.1 Asteroids and Comets

There are two main types of objects in the solar system that represent left over material from its formation: asteroids and comets. In fact, both objects are quite similar, their differences arise from the fact that comets are formed from material located in the most distant parts of our solar system, where it is very cold, and thus they have large quantities of frozen water and other frozen liquids and gases. Asteroids formed closer-in than comets, and are denser, being made-up of the same types of rocks and minerals as the terrestrial planets (Mercury, Venus, Earth, and Mars). Asteroids are generally just large rocks, as shown in Fig. 10.1 shown below.

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

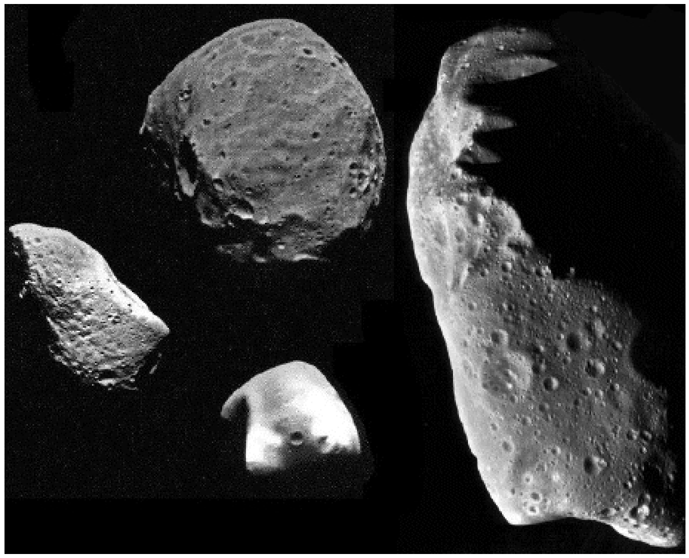


Figure 10.1: Four large asteroids. Note that these asteroids have craters from the impacts of even smaller asteroids!

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 10.2). Some asteroids, however, are in orbits that take them inside that of the Earth, and could

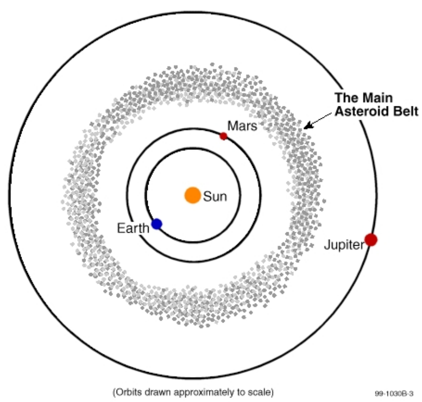


Figure 10.2: The Asteroid Belt.

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.

10.2 Comets

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

10.3 Composition and Components of a Comet

Comets are composed of ices (water ice and other kinds of ices), gases (carbon dioxide, carbon monoxide, hydrogen, hydroxyl, oxygen, and so on), and dust particles (carbon and silicon). The dust particles are smaller than the particles in cigarette smoke. In general, the model for a comet's composition is that of a "dirty snowball." 10.3

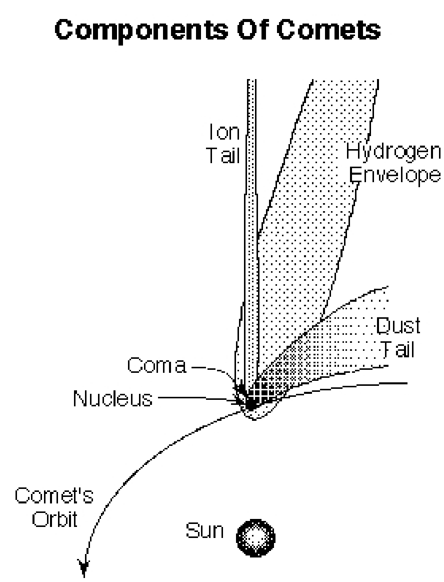


Figure 10.3: The main components of a comet.

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

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

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

These various components of a comet are shown in the diagram, above (Fig. 10.3).

10.4 Types of Comets

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

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

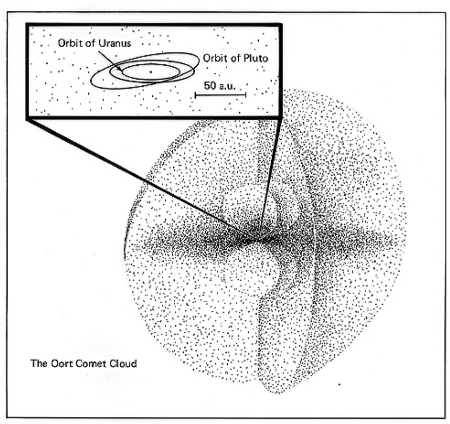


Figure 10.4: The Oort cloud.

10.5 The Impacts of Asteroids and Comets

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

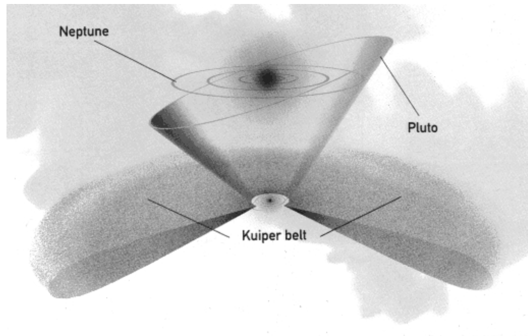


Figure 10.5: The Kuiper belt.

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

10.6 Exercise #1: Creating Impact Craters

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

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

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

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

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

5. The person with the ball bearing now holds the ball bearing so that it is located exactly one half meter (50 cm) above the surface of the flour.
6. Drop the ball bearing into the center of the flour-filled tub.
7. Use the magnet to carefully extract the ball bearing from the flour so as to cause the least disturbance.
8. Carefully measure the diameter of the crater caused by this impact, and place it in the data table, below.
9. Repeat the experiment for heights of 1 meter and 2 meters using the smaller ball bearing (note that someone with good balance might have to *carefully* stand on a chair to get to a height of two meters!).
10. Now repeat the entire experiment using the larger ball bearing. Record all of the data in the data table.

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

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

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

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

10.6.1 Impact crater questions

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

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

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

10.7 Crater Illumination

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

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

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

points)

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

10.8 Exercise #2: Building a Comet

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

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

10.8.1 Comets and Light

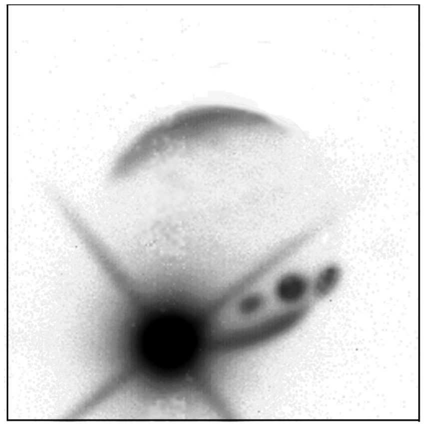
1. Observe the comet as it is sitting on a desk. Make some notes about its physical characteristics, for example: shape, color, smell (**5 points**):

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

10.8.2 Comet Strength

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

Exercise: After everyone in your group has carefully examined your comet (make sure to note its appearance, shape, smell, weight), it is time to say goodbye. Take a sample rock and your comet, go outside, and drop them both on the sidewalk. What happened to each 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 10.6: The Impact of "Fragment K" of Comet Shoemaker-Levy/9 with Jupiter. Note the dark spots where earlier impacts occurred.

10.8.3 Comet Questions

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

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

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

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

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

10.9 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?

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

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

Name: ________________
Team Number: __________

Building a Comet Take-Home Exercise (35 points total)

1. How does the mass of an impacting asteroid or comet affect the size of an impact crater? **(3 points)**

2. How does the speed of an impacting asteroid or comet affect the size of an impact crater? **(3 points)**

3. a) Why are comets important to planetary astronomers? **(4 points)**

   b) What can comets tell us about the solar system? **(4 points)**

4. What are the four components of comets? (<u>NOT</u> what the comet is made of, but the 4 different 'parts' that make up a comet.) **(2 points each)**

   a.

   b.

   c.

   d.

5. Which components of a comet are affected by the Sun, and how are they affected? **(5 points)**

6. List two ways are comets are different from asteroids. **(4 points each)**

   a.

   b.

Name:_________________________________

Date:_________________________________

11 Discovering Exoplanets

11.1 Introduction

One of the most exciting discoveries in Astronomy over the last twenty years was the conclusive detection of planets orbiting other stars. At last count, we are closing-in on having discovered *two thousand* planets orbiting other stars. Planets orbiting other stars are called "exoplanets." These exoplanets range in size from similar to the Earth, to larger than Jupiter. With much hard work, we now know that small exoplanets are much more common than big exoplanets, and some astronomers believe that Earth-sized planets orbit nearly every normal star. The current goal of astronomers is to find exoplanets that are most similar to Earth (same mass, radius, orbiting their host star at 1 AU, etc.). With improvements in technology, we will one day be able to determine whether such exoplanets support life. In the distant future, maybe we will be able to send a space probe to those exoplanets to investigate the life found there.

Astronomers have been studying the sky with advanced instruments for more than 100 years, but it was only in the early 1990's that the first real exoplanets were found. Why did it take so long? The answer is that compared to their host stars, exoplanets are tiny, and hard to see. We will quantify how hard it is to see them shortly. First though, how might we discover such objects? There are three main techniques: direct imaging, transits (mini-eclipses), and "radial velocity" measurements. As its name suggests, direct imaging is simply taking a picture of a star and looking for its planets. The big problem is that the star is very bright (it generates its own energy), while an exoplanet shines by reflected light from the star. This is by far the hardest method to find exoplanets. To be effective, we will need to launch special telescopes into space where our image-disturbing atmosphere does not exist, allowing us to see much, much more clearly.

The transit method is much easier in that what we monitor is the light output from a star, and if an exoplanet crosses in front of the star, the light briefly dims. As we will learn, this technique also tells us the *diameter* of the exoplanet. The radial velocity method uses the Doppler effect to detect the orbital motion of the planet. The radial velocity technique allows us to determine the *mass* of the exoplanet. If we can combine the transit and radial velocity techniques, we can get the size and mass of a planet, and thus measure its *density*, and therefore constrain its composition. We will investigate all three methods in this lab, and then learn how we can characterize the properties of these objects.

11.2 Why are Exoplanets so hard to see?

In our first experiment, we are simply going to demonstrate how hard it is to directly see an exoplanet. First, however, a diagram to remind you how small the Earth and Jupiter are compared to the Sun (Figure 11.1).

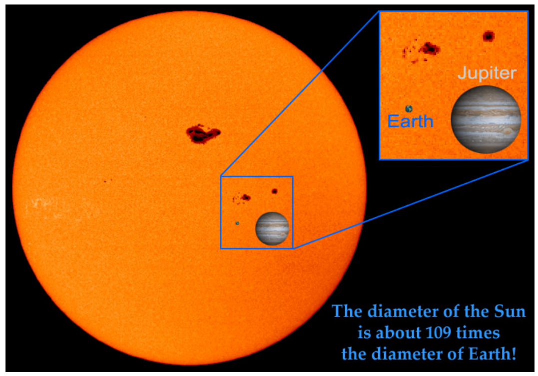


Figure 11.1: Comparison of the size of the Earth and Jupiter to the Sun.

Let's look at some numbers. The radius of the Sun is 695,550 km, the radius of Jupiter is 69,911 km, and the radius of the Earth is 6,371 km. Note that these objects are all spheres, and thus when we look at them from space, they all appear to be circles ("disks"). What is the area of a circle? $A_{\mathrm{circle}} = \pi R^2$.

Exercise #1: Calculate the areas of the circular disks of the Sun, Jupiter, and Earth (if you want make the calculation simpler, just set R_{Sun} = 700,000 km, R_{Jupiter} = 70,000 km, and R_{Earth} = 6000 km). **(3 points)**.

(Area of Earth) = ______________________ km^2

(Area of Jupiter) = ______________________ km^2

(Area of Sun) = ______________________ km^2

If we are going to take a picture of a exoplanet around a star, we have two problems: how much light will the exoplanet reflect compared to its star, and how close-in is it? Let's tackle the first question.

Exercise #2: We are going to keep everything very simple, and just estimate how much sunlight the Earth or Jupiter would reflect compared to that emitted by the Sun. We will assume that these planets reflect 100% of the light that hits them, and we are going to ignore the fact that the amount of sunlight at the orbits of each of these planets is less than at the surface of the Sun (remember, the amount of light passing through a sphere surrounding a light source drops off as $1/R^2$). In this unrealistic scenario, the maximum amount of light that a planet can reflect is simply the ratio of its area to that of the star it orbits. Calculate the following: **(2 points)**.

(Area of Earth)/(Area of Sun) = ______________________

(Area of Jupiter)/(Area of Sun) = ______________________

These already small numbers are actually way too big. As we noted, Earth can only reflect the amount of light it intercepts at the distance it is from the Sun. In fact, the Earth only intercepts 1.67×10^{-9} of the Sun's light output, and the amount of visible light it reflects (its "albedo") is 40%. So, seen from distant space, the Earth is only *one billionth* as bright as the Sun! Jupiter is obviously much bigger than the Earth, but remember, Jupiter is at 5.2 AU, so it actually receives $1/27^{\text{th}}$ the amount of sunlight as does the Earth. Thus, to an observer outside our solar system, Jupiter is only 4.4 times more luminous than the Earth.

Directly detecting exoplanets is going to be hard, besides being very faint, they are located very close to their host stars. We need a way to "turn off" the star. One way to do this is to block its light out with a small, opaque metal disk. As shown in Figure 11.2, we now have the capability to do this, but only for finding big planets located far from their host stars (in fact, to date, only Jupiter-sized planets located at large distances from their host stars have been directly imaged). There is a more complex technique called "nulling interferometry" where you use the star's own light to cancel itself out, but not its planets, that lets astronomers search for planets closer to the host star. While it can be done from the ground, it is better from space. You can more read about this method by searching for the canceled NASA mission "Terrestrial Planet Finder" on the web (it was killed due to budget cuts).

11.3 Exoplanet Transits

The exoplanet transit method of discovery is simple to envision, and the easiest to carry-out. As shown in Figure 11.3, a transit occurs when an exoplanet crosses the disk of its host star as seen by observers on Earth. Since the planet does not emit any light (we are looking at the "nighttime side"), it is completely dark. Thus, the amount of light from the star will dim as the planet blocks out ("eclipses") a small portion of the star's light-emitting disk. The plot of the brightness of a star versus time is called a "light curve". The light curve of the transit is shown below the cartoon of the star and exoplanet in Figure 11.3.

Exercise #3: Simulating an Exoplanet transit

As part of the materials set out for you to use during today's lab is a device to simulate an exoplanet transit. Take a look at the wooden device. It has a light meter attached to the back, and three rods that dangle down in front of the light meter. We will use the desk lamp as our light source ("star"), and move the rods across the light meter. Note that the dowel rod on top has five notches. The two furthest from the center represent where we will be at the start and end of our simulation. At these positions, no light is blocked (similar to

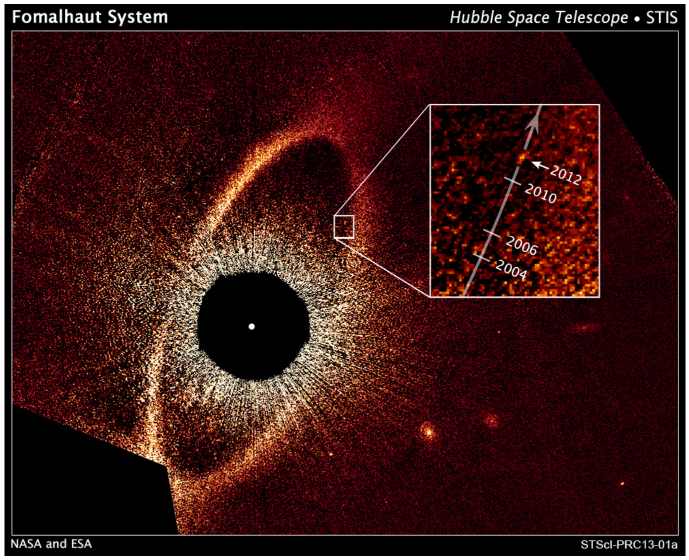


Figure 11.2: A planet orbiting the star Fomalhaut (inside the box, with the arrow labeled "2012"). This image was obtained with the Hubble Space Telescope, and the star's light has been blocked-out using a small metal disk. Fomalhaut is also surrounded by a dusty disk of material—the broad band of light that makes a complete circle around the star. This band of dusty material is about the same size as the Kuiper belt in our solar system. The planet, "Fomalhaut B", is estimated to take 1,700 years to orbit once around the star. Thus, using Kepler's third law ($P^2 \propto a^3$), it is roughly about 140 AU from Fomalhaut (remember that Pluto orbits at 39.5 AU from the Sun).

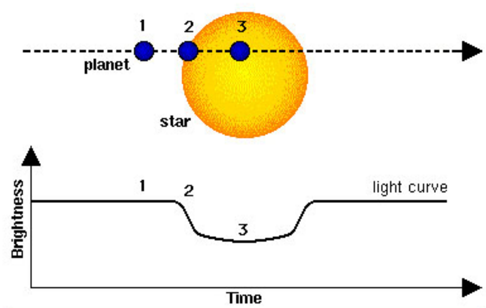


Figure 11.3: The diagram of an exoplanet transit. The planet, small, dark circle/ disk, crosses in front of the star as seen from Earth. In the process, it blocks out some light. The light curve shown on the bottom, a plot of brightness versus time, shows that the star brightness is steady until the exoplanet starts to cover up some of the visible surface of the star. As it does so, the star dims. It eventually returns back to its normal brightness only to await the next transit.

position #1 in Figure 11.3). Note also that we have two planets, one big, one small, and a bare rod without a planet. What do you think the latter is used for? Yes, our planets need to be attached to *something* to allow us to perform this experiment. Thus, this planet-less rod allows us to measure how much light just the bare rod blocks out. We will have to take this into account when we plot our light curves.

The light meter itself is rather simple, it has power, mode, and hold buttons. We only will use the power and mode buttons. Hit the power button (note that to extend battery life, the device automatically shuts off after 45 seconds). At the bottom of the device display window there will either be a "LUX" or "FC" displayed. We want the unit to be in LUX, so click the mode button until LUX is displayed.

Setting things up: Move all of the metal rods to the left end of the dowel rod so that nothing is blocking the lamp light from illuminating the white circle. Turn on the light meter. Note that the number bounces around–this is due to electronic noise. Every electronic device has this type of noise, and it takes much hard work (and expense) to minimize this noise (one way is to chill the device to low temperatures). Here we have to live with it, but this is just like what an astronomer would have to deal with in a real observation. You are going to have to make a mental average of the values at each measurement point. For example, in five seconds, if the numbers are 78, 81, 79, 82, and 78, we would just estimate the count rate as "80". Note: the light meter is very sensitive, so you must keep yourself and your hands well away from the front of the device when making a measurement (the meter will detect light reflected off of *you*, making it hard to figure out what is going on!).

With the room lights turned off, set the desk lamp about two feet in front of the transit device. Power on the light and the light meter. With no rods in front of the glass disk, adjust the *height and direction* of the desk lamp to maximize the number of counts. Make sure the light bulb in the lamp is at roughly the same height as the round, glass disk in front of the light meter. One way to do this is move the big planet in front (putting the rod in the center-most notch) and make sure its shadow hits the center of the glass disk. Move all of the rods out of the way, and then move the transit device closer to the lamp until it gives a reading above 200 counts.

Now we are simply going to move each of the three rods (Bare Rod, Small Planet, Large Planet) into the five notches on the top dowel rod, and write down the average value of the light meter measurement at each position into Table 11.1. We do this one rod at a time. Once done, move that rod to the far right side of the dowel rod to start the process for the next rod. The rods may swing around a bit, just let them stop moving, back away from the front of the device, and take your measurement. It sometimes takes a few seconds for the light meter to settle to the correct value, so give it a few seconds, and then make a estimate of the average light value at this position. Note: if you accidently bump the lamp or transit device you have to start over! Small changes in the separation or lamp height will result in bad data.

Now we have to account for the dimming effect of the rod. First, add the bare rod measurements at positions #1 and #5 together and divide by 2 to create the average unobscured value. Now, in the column labeled "δ", fill in the differences between the

Table 11.1: Exoplanet Transit Data

Position	**Bare Rod**	δ	**Small P.**	**S.P.+δ**	**Large P.**	**L.P.+δ**
#1		0.0				
#2						
#3						
#4						
#5		0.0				

average unobscured value you just calculated, and your bare rod measurements at positions 2 through 4 (δ = Ave. − #2, etc.). Then in columns 5 (S.P. + δ) and 7 (L.P. + δ), add the value in column 3 to the measurements in columns 4 and 6, respectively for all five measurements [obviously, you add the value of δ at position #2 to the value of Small P. at position #2 to get the value of (S.P. + δ) at position #2]. **(14 points)**

Making Light Curves

Now we want to plot the data in Table 11.1 to make a light curve for our two planets. Plot your data on the graph paper in the next two windows. We have filled-in the X axis with notation for the five positions you measured. You will have to put values on the Y axis that allow the entire light curve to be plotted. For example if the unobscured value was near 285 (positions #1 or #5), the top Y axis grid line might be set to 300. If the value at position #3 was 223, the bottom of the Y axis could have a value of 200. It depends on your light meter, and how bright the light source was. You will have to decide how to label the Y axis! Plot the data for both planets in Figures 11.4 and 11.5. **(8 points)**.

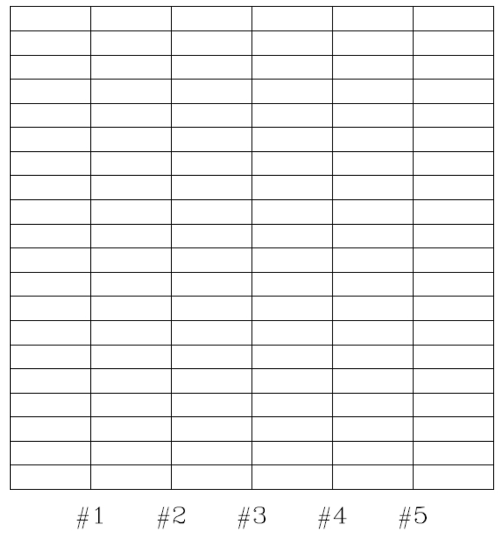


Figure 11.4: The light curve of the transit of the small planet.

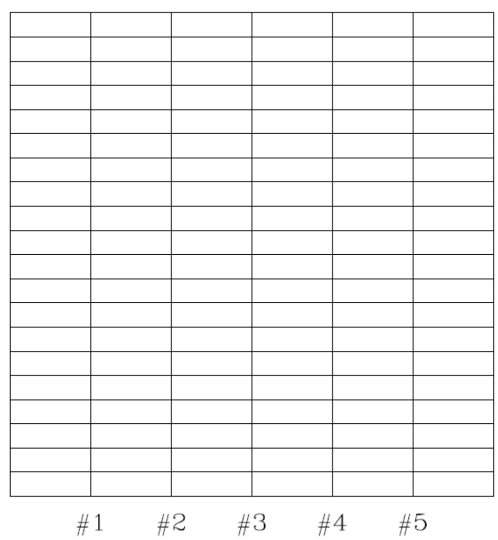


Figure 11.5: The light curve of the transit of the large planet.

11.3.1 Real exoplanet transits

Now that we have seen how one might observe a real exoplanet transit, and construct its light curve. We now want to examine how hard this really is. You probably have already found the dimming signal due to the small planet was quite small. Let's calculate how much the light dimmed in our simulations so we can compare them to real exoplanet transits. First we need to find the difference between the unobscured value, and the value at position #3 for both planets: **(2 points)**

Total dimming small planet = (Position #1) − (Position #3) = ________ counts

Total dimming large planet = (Position #1) − (Position #3) = ________ counts

Now let's put this in the fractional amount of dimming ("ΔF/F"):

Fractional dimming small planet = (Total dimming small planet)/(Position #1) = _____

Fractional dimming large planet = (Total dimming large planet)/(Position #1) = ______

How does this compare to the real world? You actually already calculated the percent dimming for the Earth and Jupiter in Exercise #2. In that exercise we calculated the ratio of the areas of the planets relative to the Sun—this ratio is in fact how much the light from the Sun would dim (in fractional terms) when the Earth or Jupiter transited it as seen from a very distant point in space (or as some alien would measure watching those crazy exoplanets transit the star we call the Sun!).

Questions:

1) Compare the percent dimming of our simulated exoplanets to the values for the Earth and Jupiter found in Exercise #2. Was our simulation very realistic? **(2 points)**

2) Let's imagine an alien pointed their telescope at our Sun to watch a transit of the Earth. If his light meter was measuring 25,000 counts from the Sun before the Earth transited (i.e., Point #1), what would it read at mid-transit (i.e., Point #3)? Show your math. [Hint: remember the dimming is very small, so the mid-transit number will be very close to the unobscured value.] **(2 points)**

As you have now seen, detecting planets around other stars is very hard. The amount of dimming during a transit is only about 1% for a Jupiter-sized exoplanet that orbits another star. To make such high precision measurements, especially to see Earth-sized planets, requires us to get above the Earth's atmosphere and use special detectors that have very low noise. Note that we also have to observe for a very long time—the Earth only has one transit per year! Jupiter would have one every 12 years! These events only last a few hours, so we also have to observe the star continuously so we do not miss the transit. This requires a dedicated instrument, and this need was the genesis of the Kepler mission launched by NASA several years ago. Kepler detected over 1,000 transiting exoplanets during its four year mission. Unfortunately, Kepler is no longer fully functional, and it will not be able to continue searching for Earth-like planets.

Before we leave the subject of transits behind, we want to talk a little more about how we can use light curves to get actual information on the exoplanet. In Figure 11.6 is plotted an exoplanet transit and light curve, with all of the math (scary, eh?) that needs to be taken into account to decipher exactly what is going on (actually the math is not real scary, as it is derived from Kepler's laws). In the preceding we have assumed that the planet crosses the center of the star—but this almost never happens. The orbit is tilted a little bit, so the transit path is shortened. There are ways to figure all of this out, as demonstrated by the many math equations in this figure. But we want to focus your attention on the most important result that a transit tells you: the radius of the exoplanet. In the top corner of Figure 11.6 there is a simple equation: $\Delta F/F = (R_p/R_*)^2$. As we have calculated above, the depth of the eclipse, $\Delta F/F$, allows you to determine the radius of an exoplanet. As all of the math in this figure shows you, if you can estimate the stellar parameters (R_*, M_*), you can also determine other characteristics of the exoplanet orbit (semi-major axis, orbital inclination). It is fairly simple to estimate R_* and M_*. In fact, if we measure the period of the orbiting planet, we can measure the mass of the host star using Kepler's laws (the $P^2 = 4\pi^2/GM_*$ equation). Thus observing transits provides much insight into the nature of an exoplanet, its orbit, and the host star.

11.4 Exoplanet Detection by Radial Velocity Variations

The final method we are going to investigate today, the technique of radial velocity variations, is the most difficult to understand as we have to talk about "center of mass", the Doppler effect, and spectroscopy. You have probably heard about all three of these during the lectures over this past semester, but we are sure you need to have a review of these topics.

You are certainly aware of the concept center of mass, even if you never knew what it was called. Take the pencil or pen that you have with you today and try to balance it across the tip of your finger. The point on the pencil/pen where it balances on your finger tip is its center of mass. A teeter totter is another good way to envision the center of mass. If a small kid and a big kid are playing on the teeter totter, the balance is not good, and it is hard to have fun. You need to either adjust the balance point of the teeter totter, or have two kids with the same weight use it.

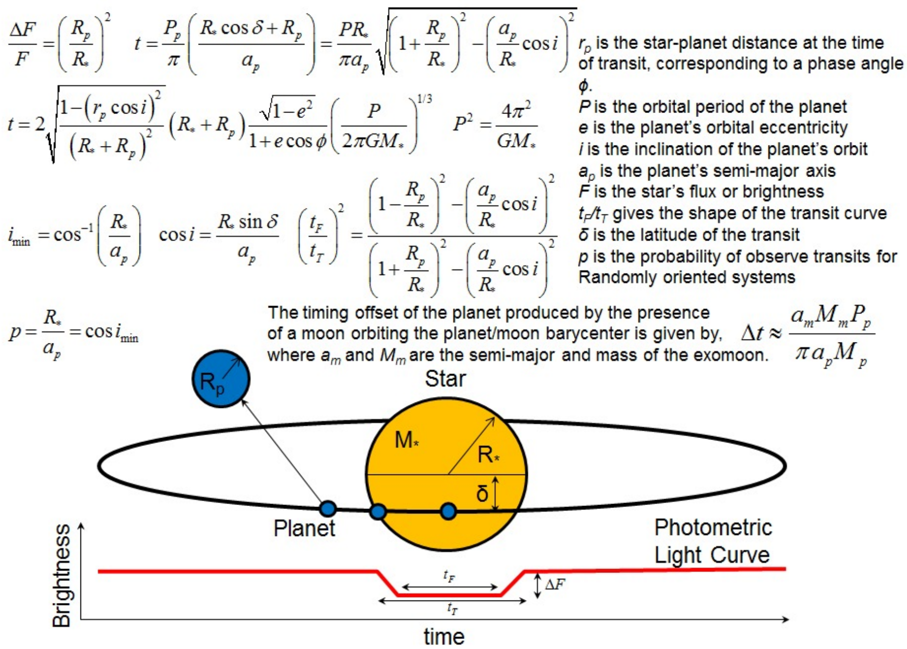


Figure 11.6: An exoplanet transit light curve (bottom) can provide a useful amount of information. As we have shown, the most important attribute is the radius of the exoplanet. But if you know the mass and radius of the exoplanet host star, you can determine other details about the exoplanet's orbit. As the figure suggests, by observing multiple transits of an exoplanet, you can actually determine whether it has a moon! This is because the exoplanet and its moon orbit around the center of mass of the system ("barycenter"), and thus the planet appears to wobble back and forth relative to the host star. We will discuss center of mass, and the orbits of stars and exoplanets around the center of mass, in the next subsection.

A diagram for defining the center of mass for two objects with different masses is shown in Figure 11.7. If the two objects had the same mass, the center of mass would be halfway between them. If one object has a much bigger mass, than the center of mass will be located closer to it. You have a device today that clearly demonstrates this type of system.

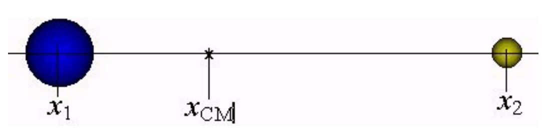


Figure 11.7: Center of mass, "x_{CM}", for two objects that have unequal masses. The center of mass can be thought as being the point where the system would balance on a "fulcrum" if connected by a rod.

Exercise #4: Defining the Center of Mass for a Two Body System

As part of the materials for today's lab, you were given a center of mass demonstrator. It consists of a large black mass connected to a small white mass by a long rod. There is also a wooden handle with a small pin at one end.

Remove the wooden handle from the long rod. Using the meter stick, estimate the length of the entire device, from the **center** of the black sphere (we will call it "M_1"), to the **center** of the white sphere ("M_2"). What is this number in cm? **(1 point)**:

Ok, now find the halfway point from the center of one ball to the next. You need to divide the length you just measured by two, and measure in from one of the balls and note its location (if necessary, use a piece of tape). Is there a hole there? If you try to balance the device on the tip of your finger at this center point/hole, what happens? **(2 points)**

Now put the device on the tip of your finger and find the balance point of the device. There is also a hole there. Use the meter stick to estimate (and write down) the distance between the center of the black ball to this point (we will call this "X_1"), and the distance between the center of the white ball and this point (we will call this "X_2"). This exercise is best done by two people. **(2 points)**

X_1 = ________________________ cm

X_2 = ________________________ cm

This spot on the rod is "the center of mass". The center of mass point is important, as it allows us to determine the "mass ratio", and if we know the mass of one of the objects, we can figure out the mass of the other object. The equation for center of mass is this:

$$M_1X_1 = M_2X_2$$

and the mass ratio is:

$$M_1/M_2 = X_2/X_1$$

Determine the mass ratio for the center of mass device. **(2 points)**

$M_1/M_2 =$

If M_1 = 250 grams, what is the mass of M_2? **(2 points)**

M_2 = ________________________ grams

Now that we have explored the concept of center of mass, let's see how it applies to objects that orbit each other. Inserting the pin on the wooden handle into the center point of the rod (not the center of mass hole!), hold the wooden handle and try to spin the device (watch your head!). Now, move the wooden handle to the center of mass hole. Spin the device. Explain what happened at both locations: **(2 points)**

Any two objects in orbit around each other actually orbit the center of mass of the system. This is diagrammed in Figure 11.8[1]. Thus, the Earth and Sun orbit each other around their center of mass, and Jupiter and the Sun orbit each other around their center of mass, etc. In fact, the motion of the Sun is a complex combination of the orbits of all of the planets in our solar system. For now, we are going to ignore the other planets, and figure out where the center of mass is for the Sun−Earth system.

The Sun has a mass of $M_{Sun} = 2.0 \times 10^{30}$ kg, while the Earth has a mass of $M_{Earth} = 6.0 \times 10^{24}$ kg. We will save you some math and just tell you that the approximate mass ratio is:

$M_{Sun}/M_{Earth} = 330{,}000$

To determine where the center of mass is for the Earth-Sun system, we have to do a little bit of algebra. Remember that the mean distance between the Earth and the Sun is 1 AU. Thus, using our notation from above:

$$1 \text{ AU} = X_1 + X_2$$

Therefore,

[1]An animation of this can be found at http://astronomy.nmsu.edu/tharriso/ast105/Orbit3.gif

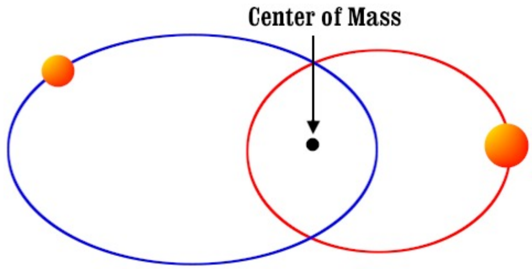


Figure 11.8: If two stars are orbiting around each other, or a planet is orbiting a star, they both *actually* orbit the center of mass. If the two objects have the same mass, the center of mass is exactly halfway between the two objects. Otherwise, the orbits have different sizes.

$$X_1 = 1\ \mathrm{AU} - X_2 \qquad \text{(Equation \#1)}$$

Does that make sense to you? X_1 and X_2 are the distance from the Sun to the center of mass, and the Earth to the center of mass, respectively. As the center of mass demonstration device shows you, the center of mass is located somewhere on the line that connects the two objects. Thus, $X_1 + X_2$ = distance between the two masses. For the Earth and Sun, $X_1 + X_2 = 1$ AU. Now, going back to our center of mass equation:

$$M_1X_1 = M_2X_2 \qquad \text{(Equation \#2)}$$

We can substitute the result for X_1 in equation #1 into Equation #2:

$$M_1(1\ \mathrm{AU} - X_2) = M_2X_2 \qquad \text{(Equation \#3)}$$

Dividing both sides of Equation #3 by M_1 gives:

$$1\ \mathrm{AU} - X_2 = (M_2/M_1)X_2 \qquad \text{(Equation \#4)}$$

But $(M_2/M_1) = 1/330{,}000$ for the Earth-Sun system, and now we can solve to find X_2:

$$1\ \mathrm{AU} = (M_2/M_1)X_2 + X_2 = (1/330{,}000 + 1)X_2$$

Thus,

$$X_2 = 1.0/(1 + 1/330{,}000) = 0.999997 \text{ AU}$$

Essentially, the Earth is 1 AU from the center of mass, how far away is the Sun from the Earth-Sun center of mass? Go back to equation #1:

$$X_1 = 1 - 0.999997 = 0.000003 \text{ AU}$$

The Sun is very close to the center of mass of the Earth-Sun system.

Exercise #5: Determining the Size and Velocity of the Sun's "Reflex Motion"

We are going to calculate the size of the Sun's orbit around the center of mass for the Sun-Earth system, and then determine how fast the Sun is actually moving. The motion of the Sun (or any star) due to an orbiting planet is called the "reflex motion." Like the name suggests, it is the response of the star to the gravitational pull of the planet. Since AU per year is not a normal unit with which to measure velocity, we need to convert the numbers we have just calculated to something more useful.

1 AU = 149,597,871 km. How far from the center of mass is the Sun in km? **(1 point)**:

X_1 (km) = X_1 (AU) × 149,597,871 (km/AU) = ________________ km

Hopefully, you noticed how the units of length canceled in the last equation.

So, we now have the distance of the Sun from the center of mass. Note that this number puts the center of mass of the Earth-Sun system well inside the Sun (actually very close to its core). We now want to figure out what the length of the orbit is that the Sun executes over one year (remember, the Earth takes one year to orbit the Sun, so the "orbital period" of the Sun around the Earth-Sun center of mass will be one year). Referring back to the center of mass device, if you put the handle in the center of mass hole and spin the system, what path do the masses trace? That's right, a circle. Do you remember how to calculate the circumference of a circle? $C = 2\pi R$, where R is the radius of the circle and $\pi = 3.14$.

What is the circumference of the orbit circle (in km) that is traced-out by the Sun? **(2 points)**:

This is how far the Sun travels each year, thus we can turn this into a velocity (km/hr =

kph) by dividing the distance traveled (in km) by the number of hours in a year. Show your math **(2 points)**:

$$V_{\text{Sun}}\ (\text{km/hr}) = \text{C}\ (\text{km}) \div (\#\ \text{hours in year}) = ???$$

1) Comment on the size of the reflex velocity (V_{Sun}) of the Sun. Note that the Earth travels much, much further during the year, so its velocity is much, much higher: 107,000 km/hr! **(3 points)**:

Because all of the math above involved simple, "linear" equations, we can quickly estimate the reflex velocity of the Sun if we replaced the Earth by something more massive. For example, if we put an object with 10 Earth masses in an orbit with R = 1 AU, the reflex velocity of the Sun would be 10 times that which you just calculated for the Earth.

2) Jupiter has a mass that is 318 times that of the Earth. If Jupiter orbited the Sun at 1 AU, what would the reflex velocity of the Sun be? **(2 points)**:

Since Jupiter is at 5.2 AU, and its orbital period is 11.9 yr, the reflex motion of Jupiter is actually: $V_{\text{Jupiter}} = 318 \times V_{\text{Earth}} \times 5.2 \div 11.9 \approx 45$ km/hr.

Exercise #6: Understanding the Sizes of the Reflex Motions

For the final exercise of today's lab, we want to demonstrate how big these reflex motions are by comparing them to the velocities that you can generate. To do so, we are going to be using radar guns just like those used by the police to catch speeders. These devices are very expensive, so please be extremely careful with them. The radar guns are a bit technical to set-up, so your TA will put them in the correct mode for measuring velocities in km/hr.

Your lab group should head out of the classroom, and into the hallway (or outside) to get a long enough path to execute this part of the lab. The idea is to have one of the lab members move down the hallway, and act as the "speeding car". Note that if there are other people moving around in the hallway, the radar gun might get a confusing signal and not read correctly. So, make sure only one person is moving when doing this.

1) One lab member hold the radar gun, have another lab member walk towards the radar gun. Hold down the trigger a few seconds and then let go. Do this several times to get a good reading. What is the average velocity of the walking speed of this lab member? **(2 points)**:

2) Now, we are going to measure the running speed. **BE CAREFUL!**. Have everyone participate, and see who can run the fastest. What are the velocities for the various lab members? **(2 points)**:

3) Compare your walking and running velocities to the Sun's reflex velocity caused by the Earth that you calculated above. How massive a planet (in Earth masses) would it take to get your walking reflex motion to be executed by the Sun? How about your running reflex motion? **(5 points)**.

11.5 Radial Velocity and the Doppler Effect

Earlier we called this final exoplanet discovery technique "the radial velocity" method. What do we mean by this term? The radial velocity is a measurement of how fast something is coming towards you, or going away from you. If an object is moving across your line of sight (like the cars on the road as you wait to cross a street at the pedestrian crossing), it has no radial velocity (formally, they would have a "tangential velocity" only). If we were an alien watching the Sun, the Sun would sometimes have a radial velocity coming towards us (normally defined to be a negative number), and a radial velocity going away from us (normally defined as a positive number), due to the reflex motions imparted on it by the planets in our solar system. This gives rise to something called a "radial velocity curve."

So how do we detect the radial velocity of a star? We use something called the Doppler effect. The Doppler effect is the change in frequency of a sound or light *wave* due to motion of the source. Think of an ambulance. When the ambulance is coming towards you, the siren has a high pitch. As it passes by you, the pitch drops (for audio examples, go here: http://www.soundsnap.com/search/audio/doppler/score?page=1"). This is shown in Figure 11.9. The radar guns you just used emit microwaves that are Doppler shifted by moving objects. Stars are too far away to use radar. Fortunately, the same process happens with all types of electromagnetic radiation. Astronomers use visible light to search for Exoplanets. In a source coming towards us the light waves get compressed to higher frequency. When it is receding the light waves are stretched to lower frequency. Compressing the frequency of light adds energy, so it "blueshifts" the light. Lowering the frequency removes energy, so it "redshifts" the light. For an object orbiting the center of mass, sometimes the light is blueshifted (at point #4 in Figure 11.10), sometimes it is redshifted (at point #2 in Figure 11.10).

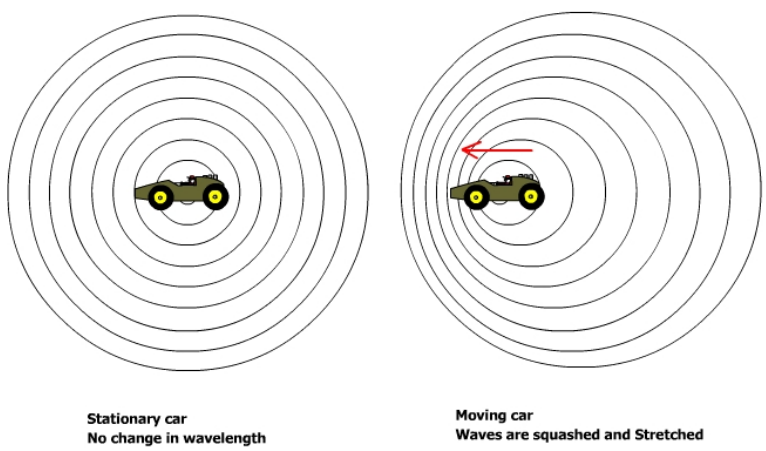


Figure 11.9: For a stationary vehicle emitting sound, there is no Doppler effect. As the vehicle begins to move, however, the sound is compressed in the direction it is moving, and stretched-out in the opposite direction.

This is how astronomers discover exoplanets, they monitor the spectrum of a star and look for a changing radial velocity like that shown in Figure 11.10. What they see is that the

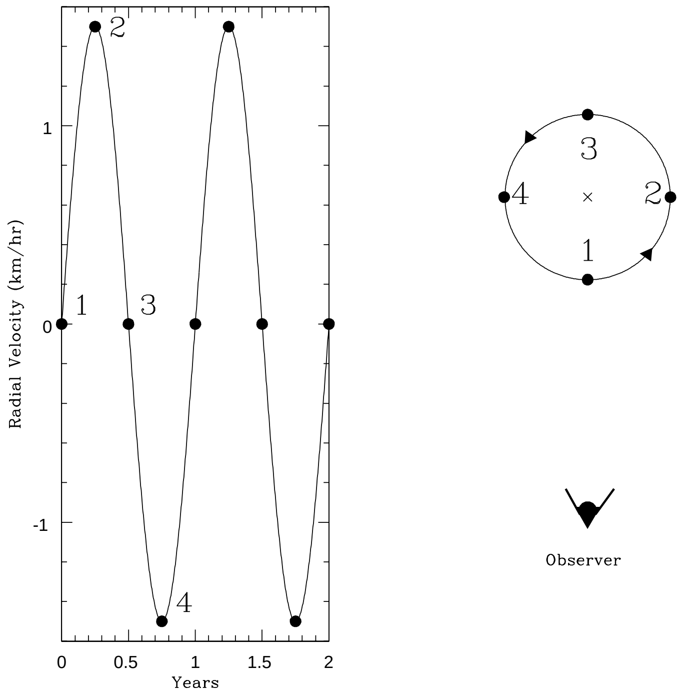


Figure 11.10: A radial velocity curve (left) for a planet with a one year orbit like Earth, but that imparts a reflex velocity of 1.5 km/hr on its host star. When the motion is directly away from us, #2, we have the maximum amount of positive radial velocity. When the motion of the object is directly towards us, #4, we have the maximum negative radial velocity. At points #1 and #3, the object is not coming towards us, or going away from us, thus its radial velocity is 0 km/hr. The orbit of the object around the center of mass ("X") is shown in the right hand panel, where the observer is at the bottom of the diagram. The numbered points represent the same places in the orbit in both panels.

absorption lines in the spectrum of the exoplanet host star shift back and forth, red to blue to red to blue. Measuring the shift gives them the velocity. Measuring the time it takes to go from maximum blueshift to maximum redshift and back to maximum blueshift, is the exoplanet's orbital period. Remember, the exoplanet is too faint to detect directly, it is only the reflex velocity of the host star that can be observed. And, now you should understand how we measure the mass of the exoplanet. The amount of reflex velocity is directly related to the mass of the exoplanet and the size of its orbit. We can use the orbital period and Kepler's laws to figure out the size of the exoplanet's orbit. We then measure the radial velocity curve, and if we can estimate the host star's mass, we can directly measure the mass of the exoplanet using the techniques you have learned today.

Here is how it is done. To determine the mass of an exoplanet, we first must figure out the semi-major axis of its orbit (for the Earth, the semi-major axis = R = 1 AU). We return to Kepler's laws:

$$R^3 = \frac{GM_{star}}{4\pi^2}P^2 \quad (Equation\ \#5)$$

In this equation, "G" is the gravitational constant. P is the orbital period. In physics equations like these, the *system* of units used must be the same for each parameter. Such as centimeter-gram-second, or meter-kilogram-second. We call these the "'cgs" and "mks" systems, respectively. You cannot mix and match. Thus, there have to be two flavors of G for this equation: $G_{cgs} = 6.67 \times 10^{-8}$, and $G_{mks} = 6.67 \times 10^{-11}$. The equation above is just Kepler's third law $P^2 \propto a^3$ you learned about at the beginning of the semester. What Isaac Newton did was figure out what is needed to change the "$\propto$" into the "=" sign. If we know "R" and the exoplanet host star mass (M_{star}) we can figure out the exoplanet's mass. So using equation #5 above, we find R. Since we know the orbital period (P), we can estimate the exoplanet's orbital velocity:

$$V_{pl} = \frac{2\pi R}{P} \quad (Equation\ \#6)$$

The mass of the planet is simply:

$$M_{pl} = \frac{M_{star}V_{star}}{V_{pl}}$$

In this equation V_{star} is the host star reflex velocity like those we calculated above for the Earth-Sun, and Jupiter-Sun systems. The biggest unknown when making such mass measurements is estimating the host star mass. There are ways to do this, but they are beyond the scope of today's lab. We will use these equations in the take-home part of this lab, so make sure you understand what is going on here before leaving today.

Name:____________________________________
Date:____________________________________

11.5.1 Possible Quiz Questions

1) What is an Exoplanet?
2) Name one of the techniques used to find Exoplanets
3) Why are Exoplanets so hard to discover?

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

Using the web, search for an article on an "Earth-like exoplanet" and write a one page discussion of this object, and what makes it "Earth-like". Note that there are quite a few such objects, just pick the one you find most interesting (and one that has sufficient discussion to allow you to write a short paper).

Name: Date:
Team Number:

Discovering Exoplanets Take Home (35 points total)

1. About how many exoplanets have been found to date? What method has detected the most exoplanets? **(4 pts)**

2. Describe two methods of detecting exoplanets (we talked about 3 in lab: Direct Imaging, Transits, and Radial Velocity). Describe how your chosen methods work, discuss we can learn about an exoplanet from it, and challenges associated with your selected method. Answer these questions in the table below. **(2 pts per answer)**

	Method 1	Method 2
What is the name of the method?		
How does this method work?		
What can you learn about an exoplanet if you observe it with this method?		
What are some challenges associated with detecting exoplanets with this method?		

3. Choose one exoplanetary system to research. Briefly describe the system (how many planets, are they earth-like or Jupiter-like, what kind of star do they orbit around), and mention how the planets were detected. Answer these question in the table below. **(3pts per answer)**
   a. Here are a few of our favorite systems, if you need ideas (but you are not limited to these!):
      i. TRAPPIST-1, which is a nearby solar system of 7 planets that could be habitable!

ii. Proxima Centauri, the closest star to the Sun, which was recently discovered to have a planet
iii. Kepler 16-B, which includes a exoplanet orbiting around a two-star binary system (like Tatooine from Star Wars)

Name of your exoplanetary system:	
How many Planets are there:	
What type of planet(s) do they have:	
What type of star are they orbiting:	
How were the planets detected:	

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. While 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 "Comet Lab").

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.

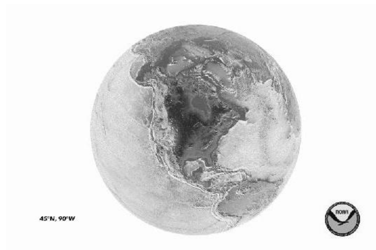


Figure 12.1: A topographic map showing one hemisphere of Earth centered on North America. In this 3D representation the continents are correctly rendered.

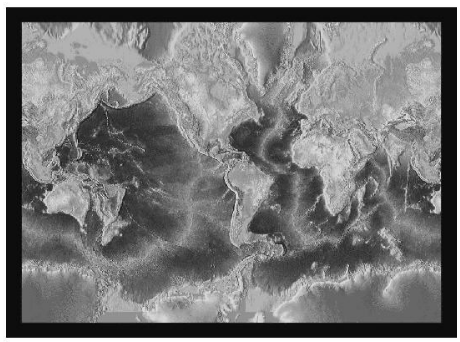


Figure 12.2: A topographic map showing the entire surface of the Earth. In this 2D representation, the continents are incorrectly rendered. Note that Antarctica (the land mass that spans the bottom border of this map) is 50% smaller than North America, but here appears massive. You might also be able 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. Note that Mercury has recently been visited by the Messenger spacecraft. Much new data has recently become available, but we do not yet have the same type of plots for Mercury as we do for the other planets.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

12.4 Detailed Comparison of the Surfaces of the Terrestrial Planets

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

In the Moon lab, there is a discussion on how impact craters form (in case you have not done that lab, read that discussion). For large impacts, the center of the crater may "rebound" and produce a central mountain (or several small peaks). Sometimes an impact is large enough to crack the surface of the planet, and lava flows into the crater filling it up, and making the floor of the crater smooth. On the Earth, water can also collect in a crater, while on Mars it might collect large quantities of dust.

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

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

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

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

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

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

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

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 dune fields are located in arid regions.

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

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

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

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

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

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

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

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

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

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

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

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.

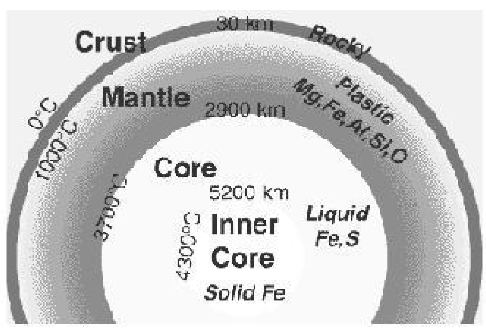


Figure 12.3: A cut away diagram of the structure of the Earth showing the hot core, the mantle, and the crust. The core of the Earth is very hot, and is composed of both liquid and solid iron. The mantle is a zone where the rocks are partially melted ("plastic-like"). The crust is the cold, outer skin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

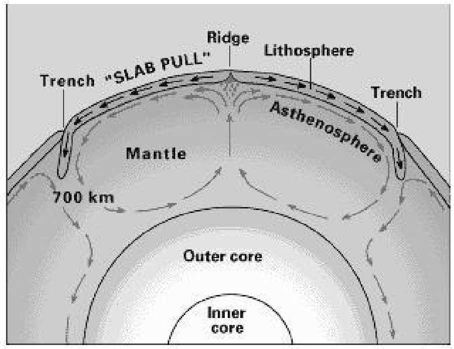


Figure 12.4: The escape of the heat from the Earth's core sets-up a boiling motion in the mantle. Where material rises to the surface it pushes apart the plates and volcanoes, and mountain chains are common. Where the material is cooling, it flows downwards (subsides) back into the mantle pulling down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

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

24. Now, examine the topographic maps for Mars and Venus (ignoring the grey areas that are due to a lack of spacecraft data). Do you see any evidence for large scale tectonic activity on either Mars or Venus? (**3 points**)

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

25. Here are some images of Martian volcanoes (Photos #37 to #41). What one type of volcano does Mars have? How did you arrive at this answer? (**2 points**)

26. In the next set (Photos #42 to #44) are some false-color images of Venusian volcanoes. Among these are both overhead shots, and 3D images. Because Venus was mapped using radar, we can reconstruct the data to create images as if we were located on, or near, the surface of Venus. *Note, however, that the vertical elevation detail has been exaggerated by a factor of ten!* It might be hard to tell, but Venus is also dominated by one main type of Volcano, what is it? (**5 points**)

12.7 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?

12.8 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: _________________
Team Number: __________

Geology of Terrestrial Planets Take-Home (35 points total)

As we have seen, many of the geological features common to the Earth can be found on the other terrestrial planets. Each planet 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 has 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.

1. Describe the surfaces of each of the terrestrial planets, and the most important geological forces that have shaped their surfaces. **(6 points each)**
    a. Mercury

    b. Venus

    c. Earth

    d. Mars

2. Consider the four terrestrial planets.
    a. Which one seems to be the least interesting? **(2 Points)**

    b. Can you think of one or more reasons why this planet is so inactive? **(4 points)**

3. If you were in charge of searching for life on Mars, where would you want to begin your search? **(5 points)**

Name:____________________________________
Date:_____________________________________

13 Apendix A: Algebra Review

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

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

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

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

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

13.1 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.

14 Observatory Worksheets

Campus Observatory Observation Sheet

Your Name: ____________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ______________

Type of Object: ________________ Object Name: __________

Object Description: ______________________________________

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Fact about this object (and the source of information):

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Campus Observatory Observation Sheet

Your Name: ____________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ______________

Type of Object: ________________ Object Name: __________

Object Description: ____

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Fact about this object (and the source of information):

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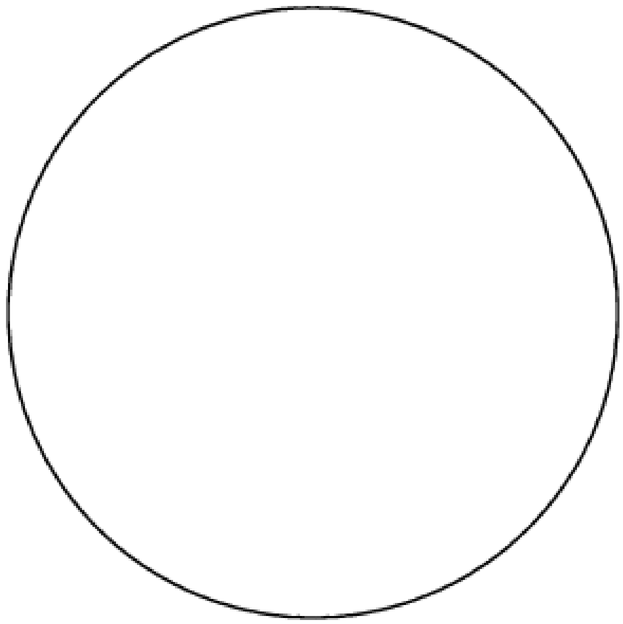
Campus Observatory Observation Sheet



Your Name: ____________________ T.A.: ____________________

Date & Time: __________________ Telescope: ______________

Type of Object: ________________ Object Name: __________

Object Description: ______________________________________

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Fact about this object (and the source of information):

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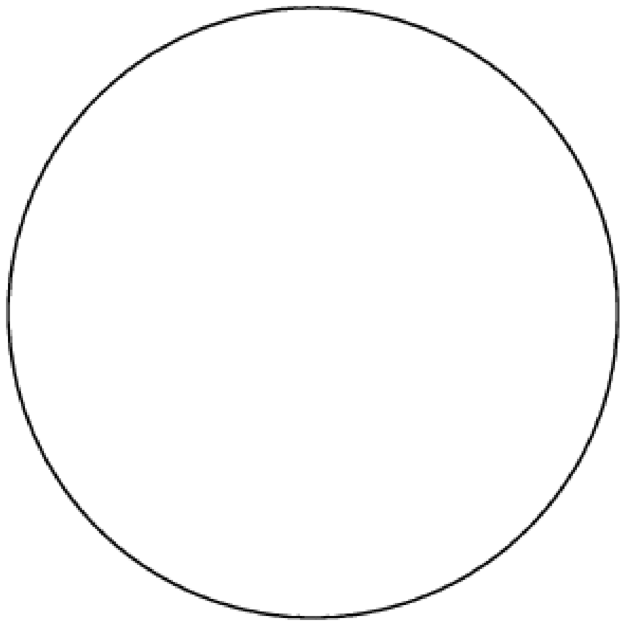
Campus Observatory Observation Sheet



Your Name: ____________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ______________

Type of Object: ________________ Object Name: ___________

Object Description: ____________________________________

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Fact about this object (and the source of information):

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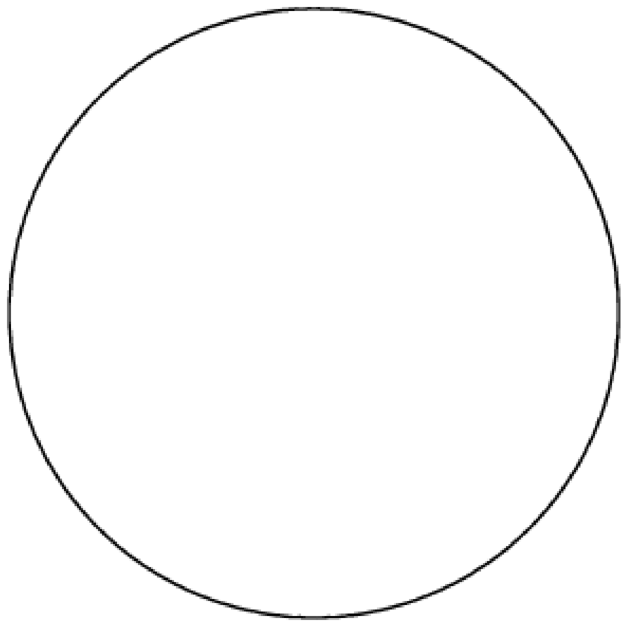
Campus Observatory Observation Sheet



Your Name: ____________________ T.A.: ____________________

Date & Time: __________________ Telescope: ______________

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Object Description: ______________________________________

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Fact about this object (and the source of information):

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Campus Observatory Observation Sheet

Your Name: ____________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ______________

Type of Object: ________________ Object Name: __________

Object Description: ______________________________________

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Fact about this object (and the source of information):

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Campus Observatory Observation Sheet

Your Name: ____________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ______________

Type of Object: ________________ Object Name: __________

Object Description: ______________________________________

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Fact about this object (and the source of information):

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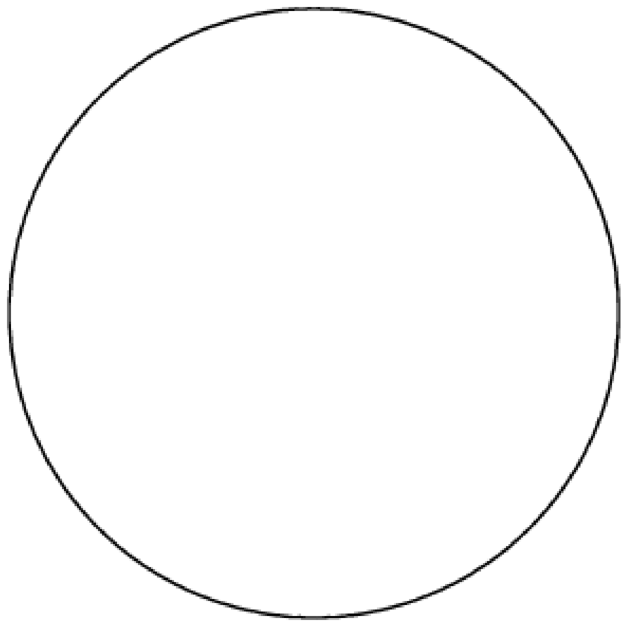
Campus Observatory Observation Sheet



Your Name: ____________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ________________

Type of Object: ________________ Object Name: ____________

Object Description: ______________________________________

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Fact about this object (and the source of information):

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