ASTR 1120G Lab Manual
Spring 2025
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Contents

Name:__________________________________
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1 Tools for Success in ASTR 1120G

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 A Note About Ratios

You will encounter ratios in many of your classes, cooking, recipes, money transactions, etc.! A ratio simply indicates how many times one number contains the other number. For example, if I had a bowl of fruit with 8 apples and 6 bananas, the ratio of apples to bananas would be eight to six (or we could say 8:6. Which is equal to 4:3). We know this bowl of fruit has 14 total fruit in it. So we know that there is 8 apples out of the total of 14 fruit, or a ratio of 8:14 (which is equal to a ratio of 4:7. Which we are able to get by noting that both "8" and "14" have something in common! They can be divided by 2!).

Additionally, if I take the ratio 8:14 and I divide 8 by 14 I would get 0.57 (or 57%). From knowing the ratio of apples to total number of fruit in the bowl, I know there are 57% apples. Similarly, we said that the ratio of 8:14 was similar to 4:7. If we did the same thing by dividing 4 by 7, we would also get 0.57 (or 57%)! Which makes sense since we said they were equal!!

In fact, a ratio may be considered as an ordered pair of numbers, or a fraction! The first number in a ratio would be the numerator of a fraction. And the second number in the ratio would be the denominator.

Ratios may be quantities of any kind! They can be counts of people or objects! These ratios can be lengths, weights, time, etc.

Practice with ratios:

Remember, a ratio compares two different quantities. Those two quantities can be anything. In your astronomy labs they will most likely be comparing two distances, lengths, or time. The order of a ratio matters!

1. If you drive for 60 miles in 2 hours, how fast were you driving? Show how you figured this out! (**1 points**)

   This is a common use of ratios (and proportions). This is comparing the number of miles (60) to the number of hours it took to drive (2). So the ratio is 60:2 (which we would verbal express as "60 miles in 2 hours").

2. Now let's say you rode your bike at a rate of 10 miles per hour for 4 hours. How many miles did you travel? Show your work with how you solved it. (**2 points**)

   We know our ratio is 10:1 (10 miles per 1 hour). So that tells us that in 4 hours, we will have traveled a total of 40 miles.

3. Looking ahead to the scale model lab, we will place all the planets on the Football field with Pluto at the 100 yard line. One of the instructions asks you to figure out how many yards there are per AU based on the fact that Pluto is at the 100 yard line (an AU is an Astronomical Unit which is the average distance between the sun and Earth). We know that Pluto is 40 AU away in space. So if we were to "scale" down the distance to yards on a football field, we know that there would be a ratio of 100 yards to AU. Similar to the miles per hour example above, how many yards per AU is there in a "Scale Model" of the solar system? (**2 points**)

1.3 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 1.3.

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)

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.

1.4 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.

1.5 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?

1.5.1 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?

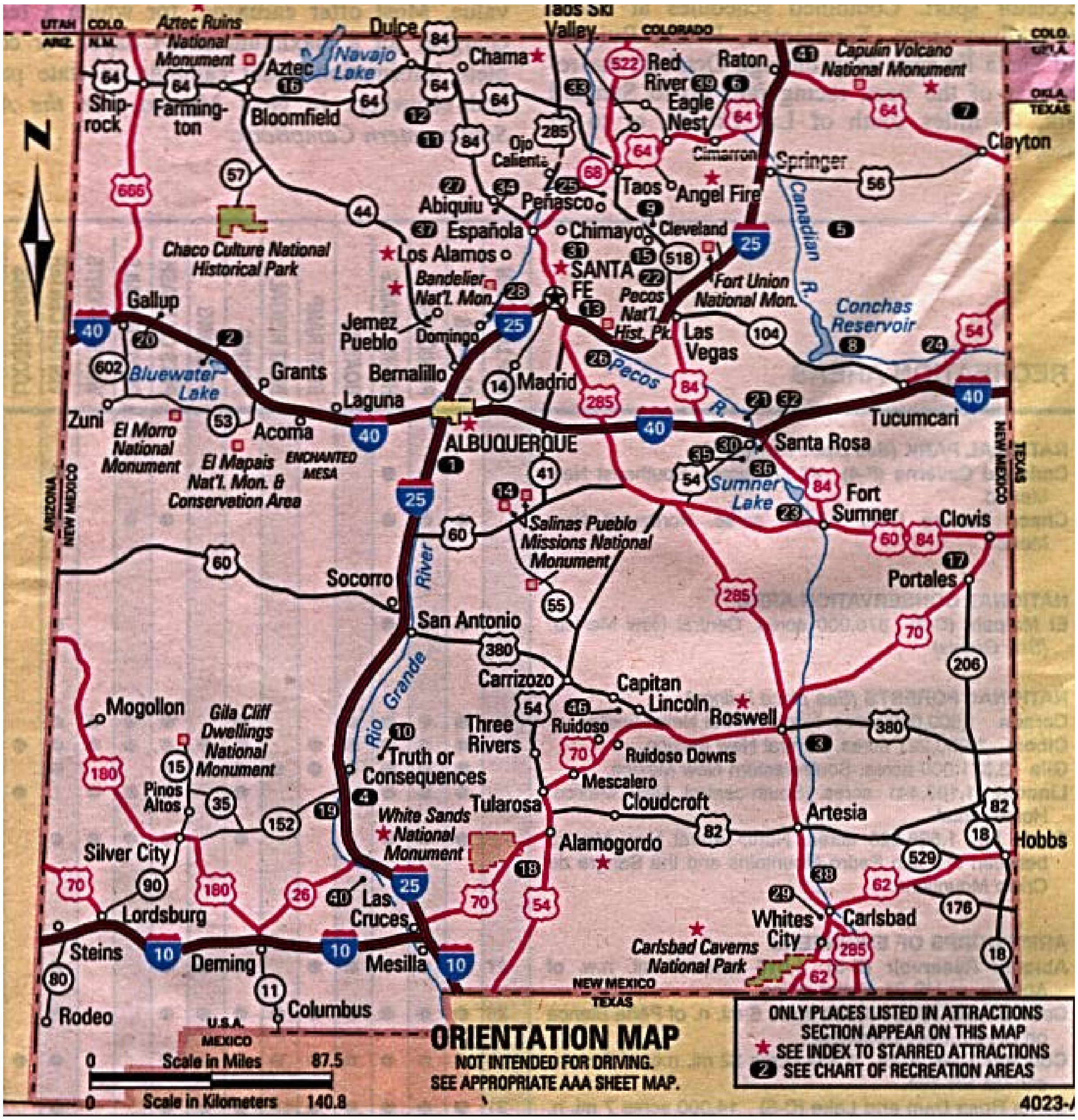


Figure 1.1: Map of New Mexico.

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?

1.6 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 × 2 = 4. The square root of 9 is 3 (9 = 3 × 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 × 3 × 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

1.7 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 = 6.563×10^3. 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 = 1.216×10^3
- 8,735,000 = 8735000.0 = 8.735000×10^6
- 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 ensure that its value is quickly and easily communicated to someone else. For example, if you tell someone the answer for some measurement is 0.0033 meter, the person receiving that information has to count over the zeros to figure out what that means. It is better to say that the measurement was 3.3×10^{-3} meter. But telling someone the answer is 215 kg, is much easier than saying 2.15×10^2 kg. It is common practice that numbers bigger than 10,000 or smaller than 0.01 are best written in scientific notation.

1.8 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.

1.8.1 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}

1.8.2 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. $20 \div (12 - 2) \times 3^2 - 2 =$

1.9 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)

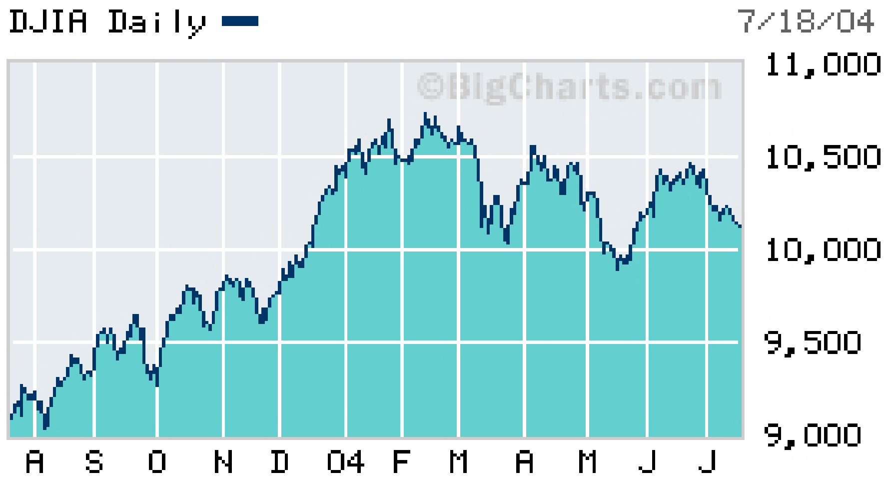


Figure 1.2: The change in the Dow Jones stock index over one year (from April 2003 to July 2004).

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

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.

1.9.1 The Mechanics of Plotting

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

First of all, the plot axes **must be labeled.** This will be emphasized throughout the

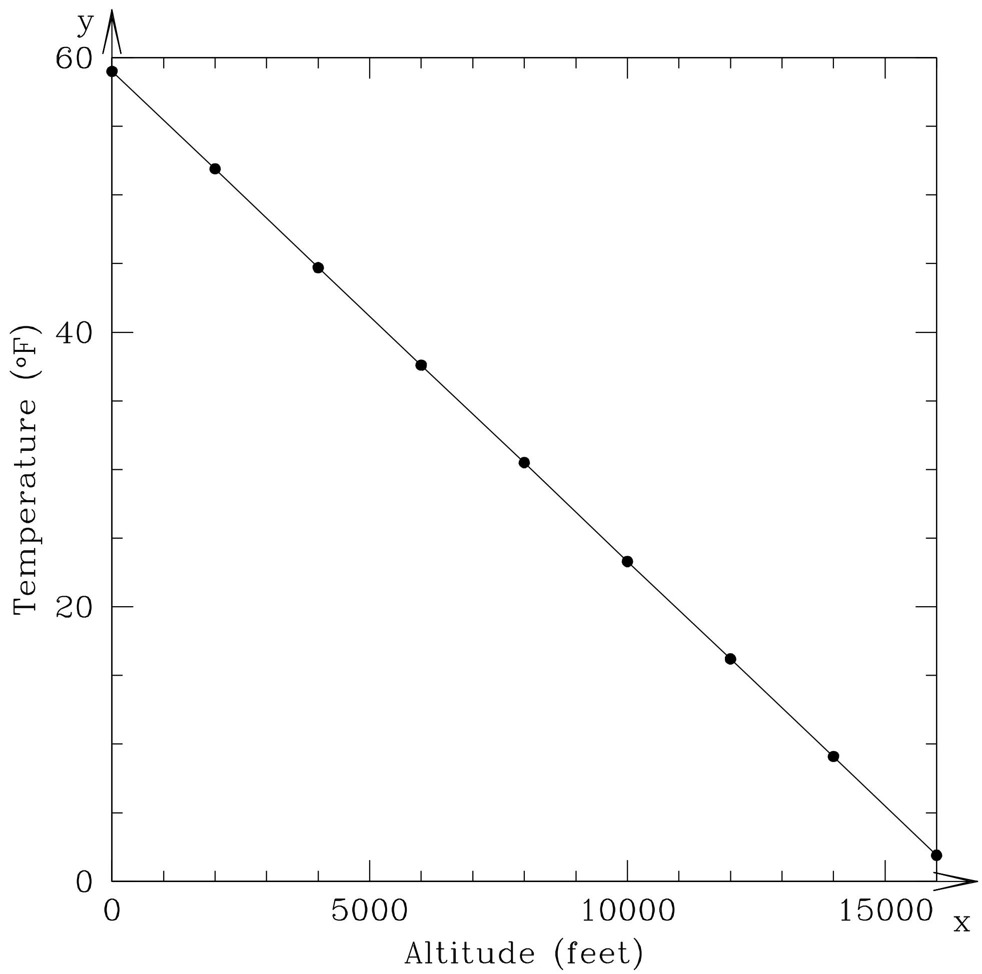


Figure 1.3: The change in temperature as you climb in altitude with the data from Table 1.2. At sea level (0 ft altitude) the surface temperature is 59°F. As you go higher in altitude, the temperature goes down.

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.

1.9.2 Plotting and Interpreting a Graph

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

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

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**)

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

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

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.

1.10 Does it Make Sense?

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

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°?

1.11 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 Kepler's Laws

2.1 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. 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! The Egyptian astronomer Ptolemy (85 − 165 AD) finally came up with a model for the motion of the planets that accounted for some of challenges. Ptolemy developed a complicated system to explain the motion of the planets, including "epicycles" and "equants", that in the end worked reasonably well, and 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.

2.2 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. 2.1. Here $F_{gravity}$ is the gravitational attractive force between two objects whose masses are M_1 and M_2. The distance between the two objects is "R". The gravitational constant G is just a small number that scales the size of the force. **The most important thing about gravity is that the force depends only on the masses of the two objects and the distance between them.** This law is called an Inverse Square Law because the distance between the objects is *squared*, and is in the denominator of the fraction. There are several laws like this in physics and astronomy.

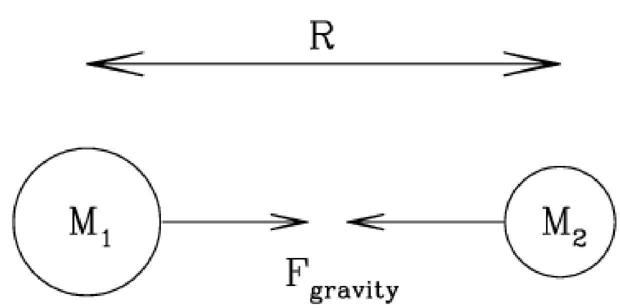


Figure 2.1: The force of gravity depends on the masses of the two objects (M_1, M_2), and the distance between them (R).

2.3 Kepler's Laws

Before you begin the lab, let's state 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: $\mathbf{P^2 \propto a^3}$**

In this lab, we will investigate these laws to develop your understanding of them.

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. 2.2.

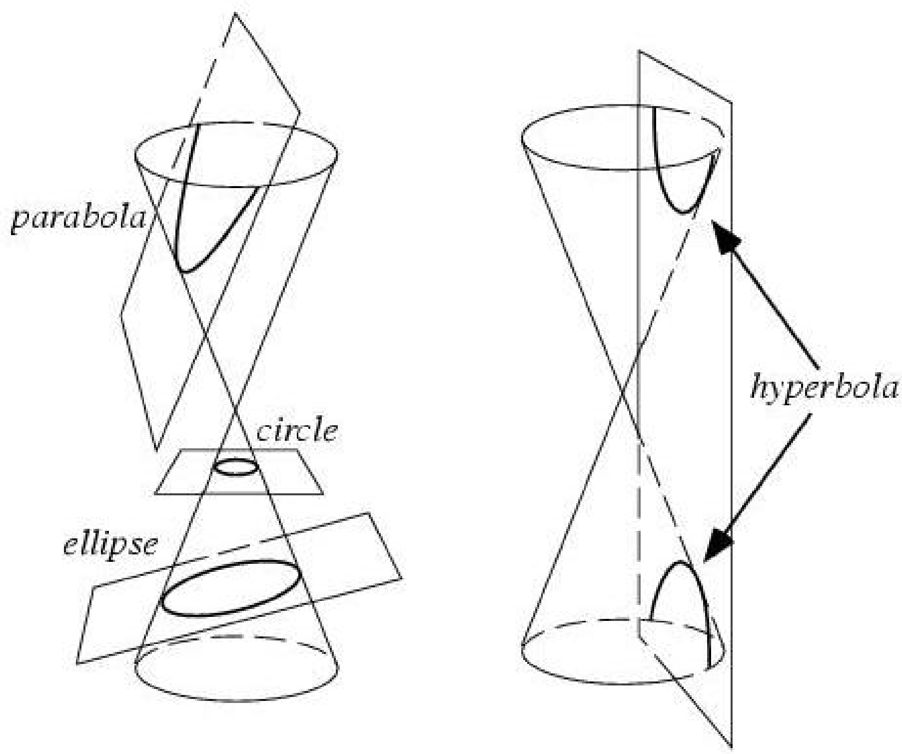


Figure 2.2: Four types of curves can be generated by slicing a cone with a plane: a circle, an ellipse, a parabola, and a hyperbola. Strangely, these four curves are also the allowed shapes of the orbits of planets, asteroids, comets and satellites!

Before we describe an ellipse, let's examine a circle, as it is a simple form of an ellipse. As you are aware, the circumference of a circle is simply $2\pi R$. The radius, R, is the distance between the center of the circle and any point on the circle itself. In mathematical terms, the

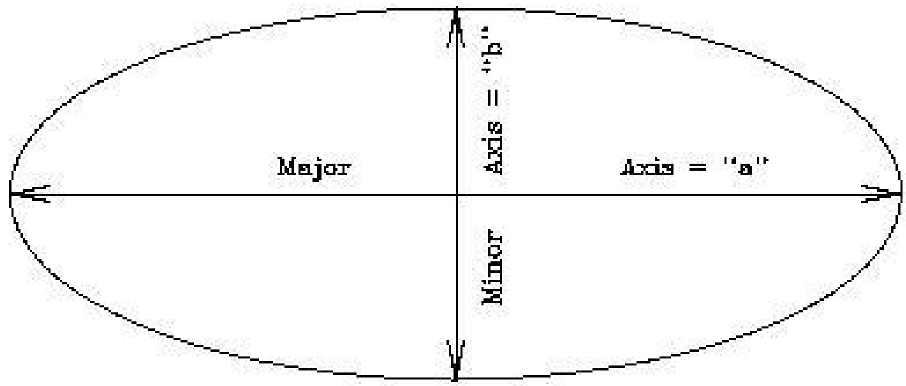


Figure 2.3: An ellipse with the major and minor axes identified.

center of the circle is called the "focus". An ellipse, as shown in Fig. 2.3, 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. 2.4 is an ellipse with the two foci identified, "F_1" and "F_2".

Exercise #1: On the ellipse in Fig. 2.4 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. (**3 points**)

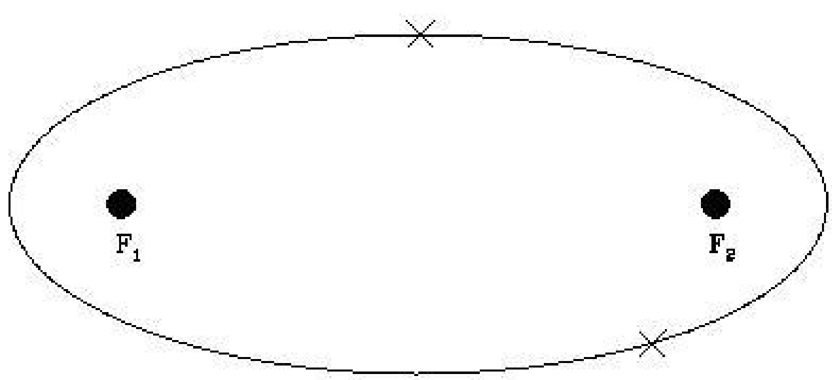


Figure 2.4: An ellipse with the two foci identified.

Exercise #2: In the ellipse shown in Fig. 2.5, 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. (**3 points**)

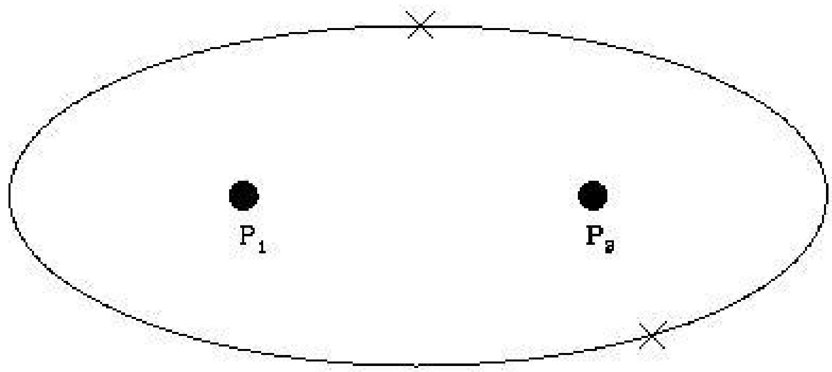


Figure 2.5: An ellipse with two non-foci points identified.

We will now use various online simulators to explore Kepler's Laws of planetary motion

2.4 Simulator

We will be using the NAAP simulators which are located here:

https://astro.unl.edu/naap/pos/animations/kepler.html

2.5 Kepler's 1st Law

If you have not already done so, launch the NAAP Planetary Orbit Simulator.

- Open the Kepler's 1st Law tab if it is not already (it's open by default).
- Enable all 5 check boxes.
- The white dot is the simulated planet. One can click on it and drag it around.
- Change the size of the orbit with the semimajor axis slider. Note how the background grid indicates change in scale while the displayed orbit size remains the same.
- Change the eccentricity and note how it affects the shape of the orbit.

Tip: You can change the value of a slider by clicking on the slider bar or by entering a number in the value box.

Be aware that the ranges of several parameters are limited by practical issues that occur when creating a simulator rather than any true physical limitations. The simulator limits the semi-major axis to 50 AU since that covers most of the objects in which we are interested in our solar system and have limited eccentricity to 0.7 since the ellipses would be hard to fit on the screen for larger values. Note also that the semi-major axis is aligned horizontally for all elliptical orbits created in this simulator, where they are randomly aligned in our solar system.

- Animate the simulated planet. You may need to increase the animation rate for very large orbits or decrease it for small ones.
- The planetary presets set the simulated planet's parameters to those like our solar system's planets. Explore these options.

We will now be using this simulator to answer some questions on Kepler's 1st law.

1. For what eccentricity is the secondary focus (which is usually empty) located at the sun? What is the shape of this orbit? **(2 points)**

2. Create an orbit with a = 20 AU and e = 0. Drag the planet first to the far left of the ellipse and then to the far right. What are the values of r1 and r2 at these locations? **(2 points)**

	r1 (AU)	r2 (AU)
Far Left		
Far Right		

3. Create an orbit with a = 20 AU and e = 0.5. Drag the planet first to the far left of the ellipse and then to the far right. What are the values of r1 and r2 at these locations? **(2 points)**

	r1 (AU)	r2 (AU)
Far Left		
Far Right		

4. What is the value of the sum of r1 and r2 and how does it relate to the ellipse properties? Is this true for all ellipses? **(3 points)**

5. It is easy to create an ellipse using a loop of string and two thumbtacks. The string is first stretched over the thumbtacks which act as foci. The string is then pulled tight using the pencil which can then trace out the ellipse. Assume that you wish to draw an ellipse with a semi-major axis of $a = 20$ cm and an eccentricity of $e = 0.5$. How long would your string need to be? (Hint: think about the case where $e = 0$, i.e., a circle). Given that the eccentricity of an ellipse is c/a, where c is the distance of each focus from the center of the ellipse, how far apart would the thumbtacks (at the focii) need to be? **(4 points)**

2.6 Kepler's 2nd Law

- Use the 'clear optional features' button to remove the 1st Law features.
- Open the Kepler's 2nd Law tab.
- Press the 'start sweeping' button. Adjust the semimajor axis and animation rate so that the planet moves at a reasonable speed.
- Adjust the size of the sweep using the 'adjust size' slider.
- Click and drag the sweep segment around. Note how the shape of the sweep segment changes, but the area does not.
- Add more sweeps. Erase all sweeps with the 'erase sweeps' button.
- The 'sweep continuously' check box will cause sweeps to be created continuously when sweeping. Test this option.

1. Erase all sweeps and create an ellipse with a = 1 AU and e = 0. Set the fractional sweep size to one-twelfth of the period. Drag the sweep segment around. Does its size or shape change? **(2 points)**

2. Leave the semi-major axis at a = 1 AU and change the eccentricity to e = 0.5. Drag the sweep segment around and note that its size and shape change. Where is the sweep segment the widest? Where is it the narrowest? Where is the planet when it is sweeping out each of these segments? What names do astronomers use for these positions? **(4 points)**

3. What eccentricity in the simulator gives the greatest variation of sweep segment shape? **2 points)**

4. Halley's comet has a semimajor axis of about 18.5 AU, a period of 76 years, and an eccentricity of about 0.97 (so Halley's orbit cannot be shown in this simulator.) The orbit of Halley's Comet, the Earth's Orbit, and the Sun are shown in the diagram below (not exactly to scale). Based upon what you know about Kepler's 2nd Law, explain why we can only see the comet for about 6 months every orbit (76 years)? **(4 points)**

2.7 Kepler's 3rd Law

Kepler's third law is:

Here is an example of how use this equation 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:

$$P(Jupiter)^2 = a(Jupiter)^3 = 5^3 = 5 \times 5 \times 5 = 125 \tag{2}$$

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, which you can easily do with a calculator.

$$\sqrt{P^2} = P = \sqrt{125} = 11.2 \;\; years \tag{3}$$

The orbital period of Jupiter is approximately 11.2 years.

Similarly, if you are given the period of an orbit, you can find the semimajor axis: just take the square of the period, and then you have to take the cube root of that number:

$$a^3 = P^2 \tag{4}$$

$$a = \sqrt[3]{P^2} \tag{5}$$

You should also be able to do cube roots on your calculator.

Let's investigate Kepler's third law using the simulator.

- Use the 'clear optional features' button to remove the 2nd Law features.

- Open the Kepler's 3rd Law tab.

1. Use the simulator to complete the table below. **(7 points)**

Object	P(years)	a (AU)	e	P^2	a^3
Earth		1.00			
Mars		1.52			
Ceres		2.77	0.08		
Chiron	50.7		0.38		

2. As the size of a planet's orbit increases, what happens to its period? **(2 points)**

3. Start with the Earth's orbit and change the eccentricity to 0.6. Does changing the eccentricity change the period of the planet? **(2 point)**

4. Kepler's third law is $P^2 = a^3$ where P is measured in years, and a is measured in astronomical units. Using this relation, what would the period of an object be if it was an in orbit with a semi-major axis of 4 AU? Show your work. **(3 points)**

5. What would the orbital semimajor axis be for an object that had an orbital period of 10 years? **(3 points)**

If one used units other than years for the period and AU for the semimajor axis, there would be some other numbers in the equation for Kepler's third law, but the basic relation between the square of the period (P^2) and the semimajor axies (a^3) would still be the same. For example, say we measured the semimajor axis in kilometers (km) instead of in AU. We can do a unit conversion (remember those from earlier labs?). Since 1 AU $= 1.496 \times 10^8$ km, we have:

$$P_{years}^2 = a_{AU}^3 = \left(a_{km} \frac{1AU}{1.496 \times 10^8 km}\right)^3 = 2.99 \times 10^{-25} a_{km}^3 \tag{6}$$

You would get some different number if you used some different units for either the period or the semimajor axis, but you would always see a P^2 on the left side and an a^3 on the right. For this reason, scientist often represent the fundamentally important part of the relation as a *proportionality* rather than as an *equality*, in other words, they would say that P^2 is *proportional to* a^3, which is a statement that is true independent of the units used. This is often written as:

$$P^2 \propto a^3 \tag{7}$$

If you take the square root of both sides, this becomes:

$$P \propto a^{3/2} = a^{1.5} \tag{8}$$

Using proportionalities often makes calculations easier, because you can use ratios of quantities from different objects. For example, if someone says that the semimajor axis of some object is twice that of Jupiter, you can tell them what the period of that object is relative to the period of Jupiter:

$$\left(\frac{P(object)}{P(Jupiter)}\right) = \left(\frac{a(object)}{a(Jupiter)}\right)^{1.5} = 2^{1.5} = 2.82 \text{ times the period of Jupiter} \tag{9}$$

without ever needing to know what the semimajor axis or the period of Jupiter is at all!

1. The *proportionality* part of Kepler's third law holds for all orbiting objects, although the equality does not. Imagine we discovered another system of planets around another star, and found that a planet located at 1 AU from the star took 2 years to go around (this would happen if the star was less massive than our Sun). How long would it take a planet that was located at 4 AU from that star to orbit the star? Use equation 9 and explain your reasoning. **(5 points)**

2.8 Take Home Exercise (35 points total):

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

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

2.9 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.

Name:______________________________
Date:_______________________________

3 Scale Model of the Solar System

3.1 Introduction

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

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

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

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

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

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

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

3.2 The Distances of the Planets From the Sun

Fill in the first and second columns of Table 6.1. In other words, list, in order of increasing distance from the Sun, the planets in our solar system and their average distances from the Sun in Astronomical Units (usually referred to as the "semi-major axis" of the planet's orbit). You can find these numbers in back of your textbook. **(21 points)**

Table 3.1: Planets' average distances from Sun.

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

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

3.3 Sizes of Planets

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

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

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

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

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

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

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

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

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

Observations:

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

Table 3.2: Planets' diameters in a football field scale model.

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

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

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

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

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

3.4 Questions About the Football Field Model

When all of the "planets" are in place, note the relative spacing between the planets, and the size of the planets relative to these distances. Answer the following questions using the information you have gained from this lab and your own intuition:

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

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

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

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

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

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

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

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

3.5 Take Home Exercise (35 points total)

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

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

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

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

1. List the planets in our solar system and their average distances from the Sun in units of Astronomical Units (AU). Then, using a scale of 40 AU = 455 miles (1 AU = 11.375 miles), determine the scaled planet-Sun distances and the city near the location of this planet's scaled average distance from the Sun. Insert these values into Table 6.4, and draw on your map of New Mexico (on the next page) the locations of the solar system objects. **(20 points)**

2. Determine the scaled size (diameter) of objects in the Solar System for a scale in which 40 AU = 455 miles, or 1 AU = 11.375 miles). Insert these values into Table 6.5. **(15 points)**

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

Table 3.4: Planets' average distances from Sun.

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

Table 3.5: Planets' diameters in a New Mexico scale model.

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


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

3.6 Possible Quiz Questions

1. What is the approximate diameter of the Earth?
2. What is the definition of an Astronomical Unit?
3. What value is a "scale model"?

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

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

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

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

Name: ______________________________

Date: ______________________________

4 The Power of Light: Understanding Spectroscopy

4.1 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

4.2 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 4.1 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.

4.3 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*.]

4.3.1 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

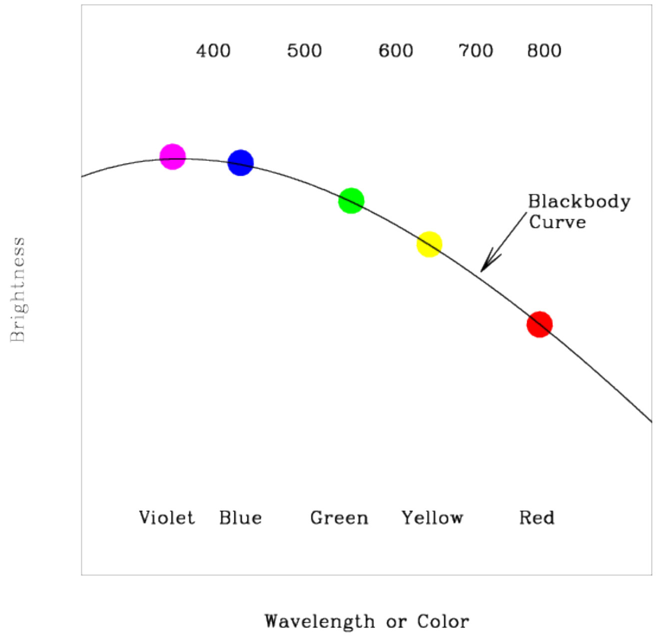


Figure 4.1: Astronomers measure the amount of light at a number of different wavelengths (or colors) to determine the temperature of a blackbody source. Every blackbody has the same shape, but the peak moves to the violet/blue for hot sources, and to the red for cool sources. Thus we can determine the 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 4.2, 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

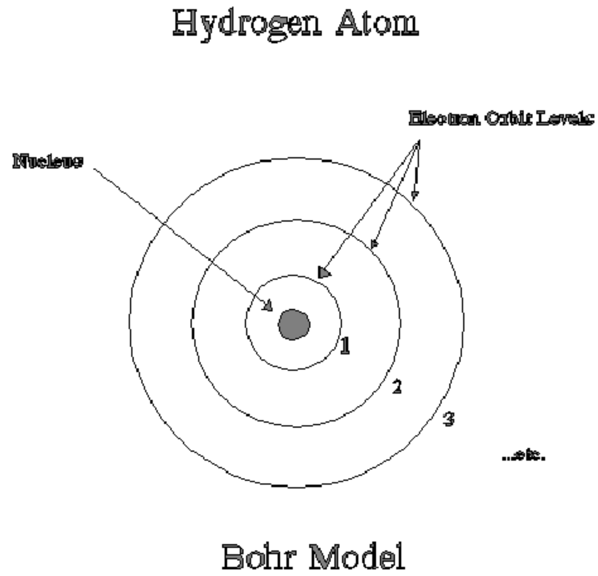


Figure 4.2: In the Bohr model, the negatively charged electrons can only orbit the positively charged nucleus in specific, "quantized", orbits.

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?

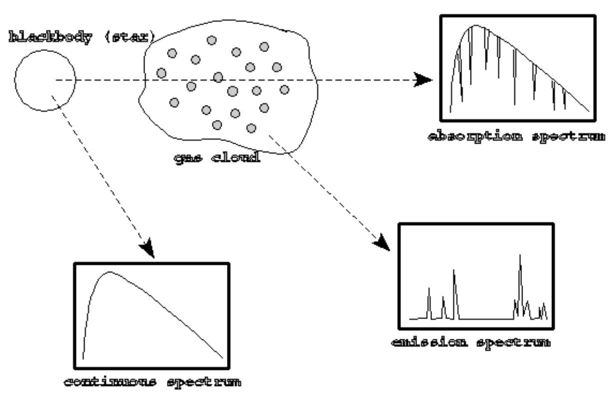
After much study, the physicists found out that the atom had taken-in energy from the collision or from the surrounding environment and that as it jumps downward in levels, it re-emits the energy as light. The light is a particular color because the electron really is allowed only to be in certain discrete 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.

4.3.2 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.

4.4 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.

4.5 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 4.3 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.

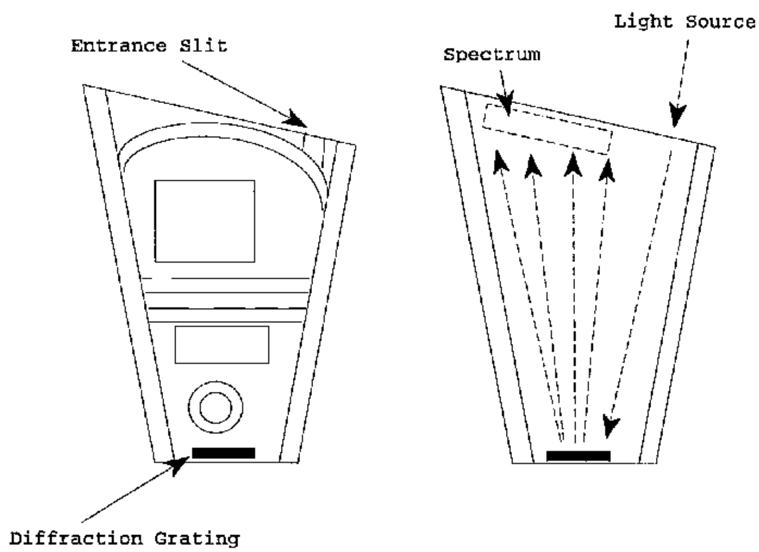


Figure 4.3:

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 brightest?(**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**)

4.6 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:

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

where λ_{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)**

4.7 Spectral Lines Experiment

4.7.1 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.

4.7.2 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)**

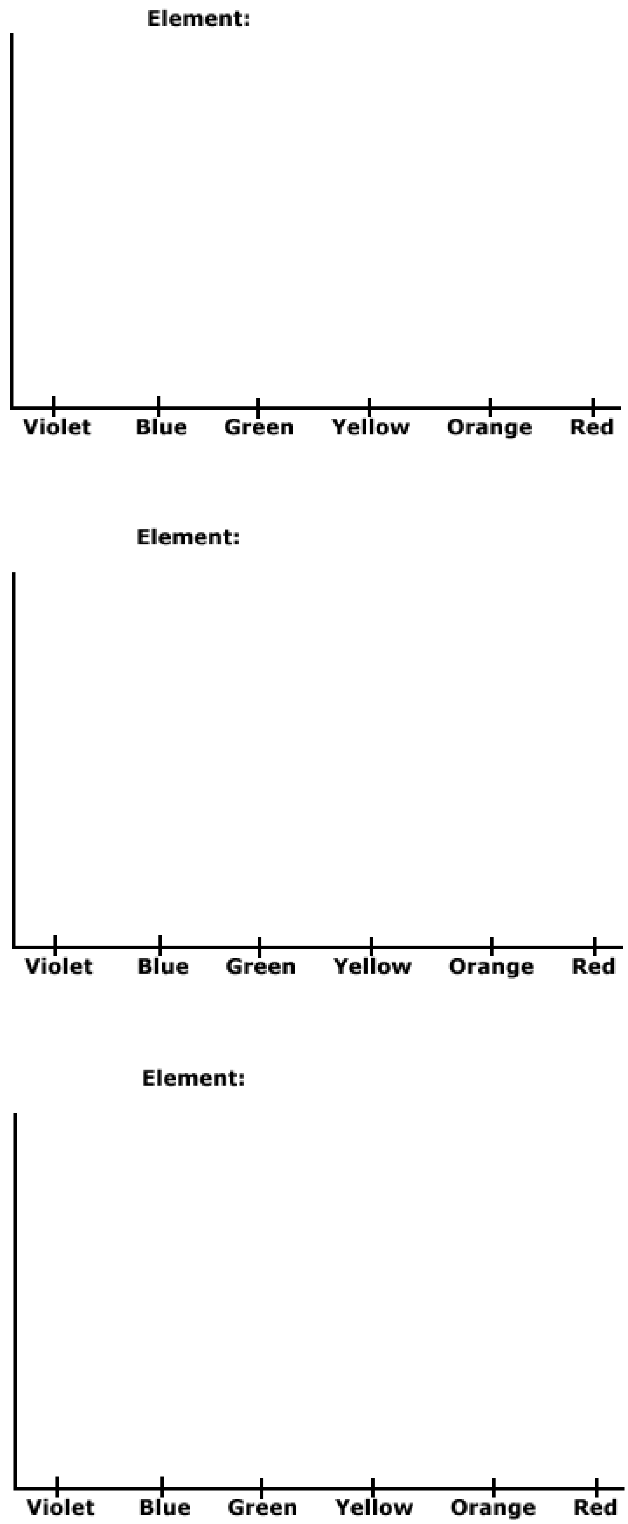


Figure 4.4: Draw your Hydrogen, Mercury and Neon spectra here.

4.7.3 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 4.1: 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 4.2: 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)**

4.8 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. 4.5, 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. 4.5, 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)**

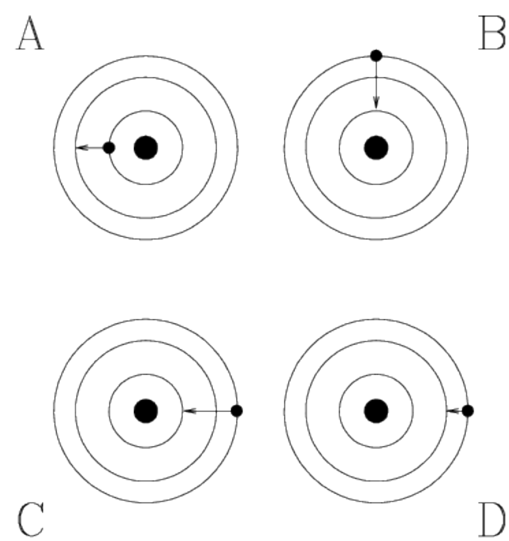


Figure 4.5: Electron transitions in an atom (the electrons are the small dots, the nucleus the large black dots, and the circles are possible orbits.

4.9 Summary (35 points)

Summarize the important ideas covered in this lab. Some questions to answer are:

- What information you can learn about a celestial object just by measuring the peak of its blackbody spectrum?
- What does a blackbody spectrum look like?
- How does the peak wavelength change as the temperature of a blackbody changes?
- How can you *quantitatively* measure the color of an object?
- Do the color of items you see around you on Earth (e.g. a red and blue shirt) tell you something about the temperature of the object? Why or why not?
- What information can you learn about an astronomical object from its spectrum?
- Explain how you would get this information from a spectrum.

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

4.10 Possible Quiz Questions

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

4.11 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.

f Name:______________________________

Date:______________________________

5 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

5.1 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. 5.1 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 700,000 asteroids that have been discovered (as of 2015), ranging in size from Ceres, all the way down to large rocks that are just a few hundred meters across. It has been estimated that there are at least 1 million asteroids in the solar system with diameters of 1 km or more. Most asteroids are harmless, and spend all of their

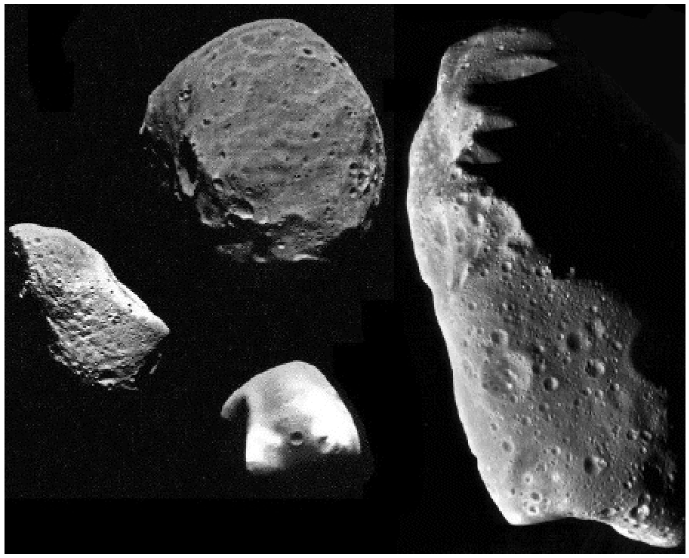


Figure 5.1: Four large asteroids. Note that these asteroids have craters from the impacts of even smaller asteroids!

time in orbits between those of Mars and Jupiter (the so-called "asteroid belt", see Figure 5.2). Some asteroids, however, are in orbits that take them inside that of the Earth, and

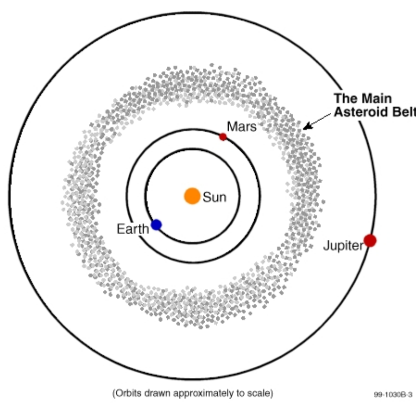


Figure 5.2: The Asteroid Belt.

could potentially collide with the Earth, causing a great catastrophe for human life. It is now believed that the impact of a large asteroid might have been the cause for the extinction of the dinosaurs when its collision threw up a large cloud of dust that caused the Earth's climate to dramatically cool. Several searches are underway to ensure 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.

5.2 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.

5.3 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." 5.3

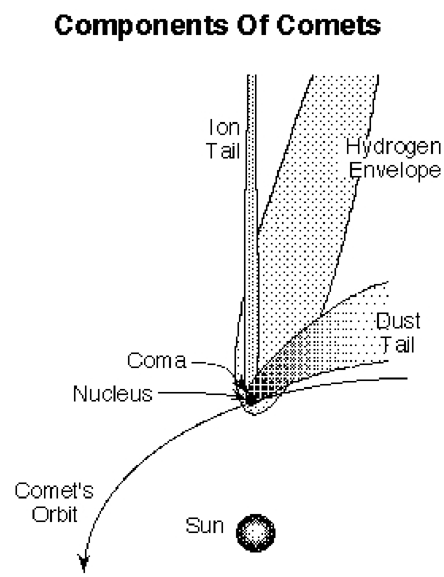


Figure 5.3: The main components of a comet.

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. 5.3).

5.4 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.

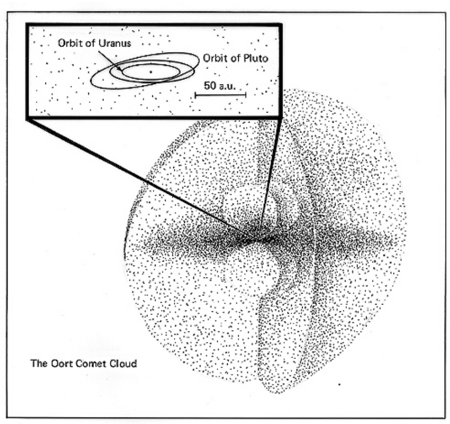


Figure 5.4: The Oort cloud.

5.5 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

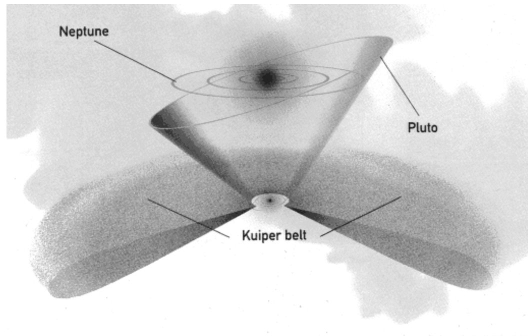


Figure 5.5: The Kuiper belt.

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

5.6 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 $v = (2a\mathrm{y})^{1/2}$. In this equation, "y" is the height above the Earth's surface (in the case of this lab, it is 0.5, 1, and 2 meters). The constant "a" is the acceleration of gravity, and equals 9.80 m/s^2. The exponent of 1/2 means that you take the square root of the quantity inside the parentheses. For example, if $y = 3$ meters, then $v = (2 \times 9.8 \times 3)^{1/2}$, or $v = (58.8)^{1/2} = 7.7$ m/s.

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

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

5.7 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**)

5.8 Exercise #2: Building a Comet

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

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

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

5.8.1 Comets and Light

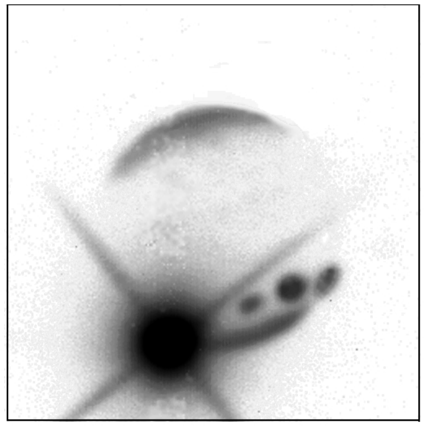
1. Observe the comet as it is sitting on a desk. Make some notes about its physical characteristics, for example: shape, color, smell (**5 points**):

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**):

5.8.2 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



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

object? (**2 points**)

5.8.3 Comet Questions

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

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

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

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

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

Name:____________________________________

Date:____________________________________

5.9 Take Home Exercise (35 points total)

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

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

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

5.10 Possible Quiz Questions

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

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

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

Name:________________________________
Date:_________________________________

6 Paleoclimate

6.1 Introduction

While the gravitational force on the Earth is dominated by the force of gravity between the Earth and the Sun, other bodies in the Solar System affect the orbit of the earth in small ways, leading to some variations in orbital parameters over time. Given that the orbital parameters of planets can have an effect on climate, **changes in the orbital parameters can lead to climate changes over long periods of time**.

In this lab, we will investigate several effects on the Earth's orbital parameters over time, and see how, together, they are expected to lead to variations in Earth's climate.

We will also learn about how scientists can measure the past climate of the Earth uses samples of ice that have accumulated over hundreds of thousands of years. We will see whether the predictions of climate change from the changes in orbital parameters are matched by the climate record.

Finally, we will consider recent changes in climate and compare them to historical changes.

Before we begin, let's review the timeline of the Earth's history, which is shown graphically in Figure 6.1 The Earth was formed, along with the Sun, about 4.5 *billion* years ago. The simplest forms of life arose about 2-4 billion years ago. Abundant life on Earth started about 0.5 billion years ago (500 million years). Dinosaurs disappeared about 65 million years ago. The first homo sapiens appeared about 200 thousand years ago (=0.2 million years = 0.0002 billion years!).

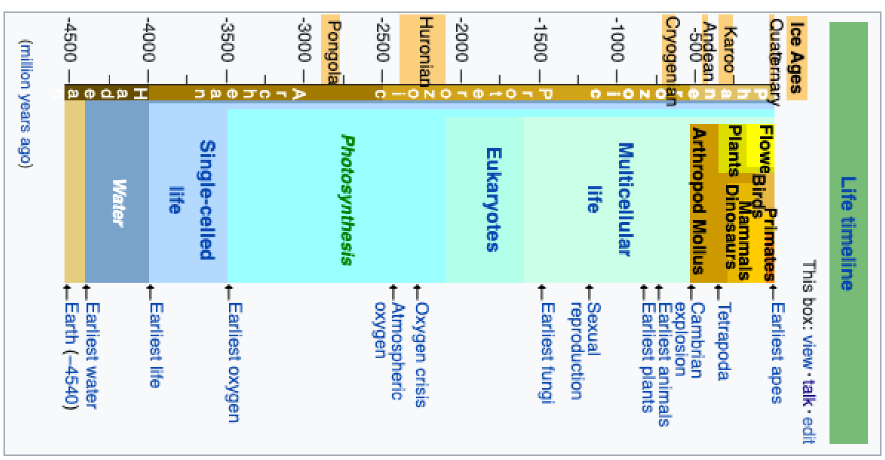


Figure 6.1: A life timeline of planet Earth starting with the Ice Age.

6.2 Milankovich Cycles

Changes in the orbital parameters of Earth are often known as *Milankovich cycles*. Read about these at the following two sites:

- https://earthobservatory.nasa.gov/features/MilankovitchUse this link to find out who Milutin Milankovitch was.
- https://climate.nasa.gov/news/2948/milankovitch-orbital-cycles-and-their-role-in-earths-climate/Use this link to read about orbital cycles and their role in Earth's climate
- **Question 1** Define the following terms in your own words: **(3 Points)**
  - eccentricity
  - obliquity (or tilt)
  - precession

Let's investigate how variations in these parameters are expected to lead to climate changes on Earth.

Go to http://cimss.ssec.wisc.edu/wxfest/Milankovitch/earthorbit.htmlthe Earth Orbit cimss link provided by your TA.

Notes on using this simulator:

- The red and gray buttons at the bottom can be turned on and off. Red is on; gray is off. In some cases, multiple buttons can be selected at the same time, such as tilt, precession and eccentricity.
- The yellow triangle on the graph on the side can be adjusted to move around in time.

Click on Orbit and Faster Orbit, as well as Top View and Oblique View to see how the system works. Also drag the yellow arrow on the chart up and down.

Click on the button Top View. You should now be able to view the orbit of the earth from above. Note where in the orbit the Earth is closest to the Sun (perihelion) and where it is farthest (aphelion),

- **Question 2** At what time of the year is the Earth the farthest from the Sun? What season is that in the northern hemisphere? What can you infer about the importance **(2 points)** of distance from the Sun on climate at the current time?

Click on the button Oblique View. You should now be able to view the tilt of the earth on its axis as it rotates around the sun.

- **Question 3** Describe the direction of the tilt of the N pole of the Earth's rotation axis at aphelion. (*Hint: Using the Season Lock button may be useful.) **(2 points)**

- **Question 4** Describe the direction of the tilt at perihelion. **(2 points)**

Select the Eccentricity button and go to Top View. Drag the yellow arrow up and down and make note of any changes you see.

- **Question 5** How do you think eccentricity could impact climate? **(2 points)**

- **Question 6** The predicted effects on temperature show a regular spacing in time. What is the approximate amount of time for each cycle (the time between successive peaks in the purple line)? **(2 points)**

Unselect the Eccentricity button and click on Precession. Drag the yellow arrow up and down while you are in the "Top View." Do the same for Oblique View. Make a note of any changes you see while moving the yellow arrow while in Oblique View and Top View. (Note, you might want to start off moving the yellow arrow slowly, paying attention to the Earth).

- **Question 7** From this investigation, describe what you think Precession means. How do you think precession could impact climate? **(2 points)**

- **Question 8** The predicted effects on temperature show a regular spacing in time. What is the approximate amount of time for each cycle (the time between successive peaks in the purple line)? **(2 points)**

Unselect the Precession button and click on Tilt. Drag the yellow arrow up and down while in Top view and Oblique View, make note of any changes you see.

- **Question 9** What is the approximate amount of time for each tilt cycle (the time between successive peaks in the purple line)?

  (2 points)

Collectively, the natural variations in these three parameters are called the Milankovitch Cycles. To see the combined effect of all three cycles, click on Eccentricity, Precession and Tilt at the same time. Note the Cycle indicated by the purple line that you see in the right-hand graph. It is a combination of all three effects, and predicts the change in temperature coming from the combined effect of the different orbital parameter variations.

- **Question 10** In your own words, explain how the tilt of the earth and its orbit determine the amount of solar radiation we receive. **(2 points)**

6.3 Ice cores and past climate record

The Vostok ice core was the result of a collaborative ice-drilling project between Russia and the U.S. in 1998. The core was drilled at the Russian station named Vostok in East Antarctica and produced the deepest ice core ever recovered. It reached a depth of 3,623 meters and the trapped air in the ice reveals changes in atmospheric composition of trace gases, which can be used to study temperatures in the past as well as the amount of certain gases in the Earth's atmosphere in the past. The deeper the ice core goes, the further back in time we are able to examine. In total, there was about 420,000 years worth of data that was able to be provided from the Vostok ice cores.

To learn more about ice cores:
https://www.youtube.com/watch?v=8BgD9xul16gWatch the Ice Core Video Link sent by your TA

- **Question 11** What does each layer of an ice core represent? (Select one of the following.) **(2 points)**

  1. a different atmospheric gas
  2. a different year of weather and snow
  3. a different glacier

Age is calculated in two different ways within an ice core. The ice age is calculated from an analysis of annual layers in the top part of the core, and using an ice flow model for the bottom part (the details of which are beyond the scope of this unit). The gas age data accounts for the fact that gas is only trapped in the ice at a depth well below the surface where the pores close up. The following is a plot of both types of ages as a function of depth below the surface.

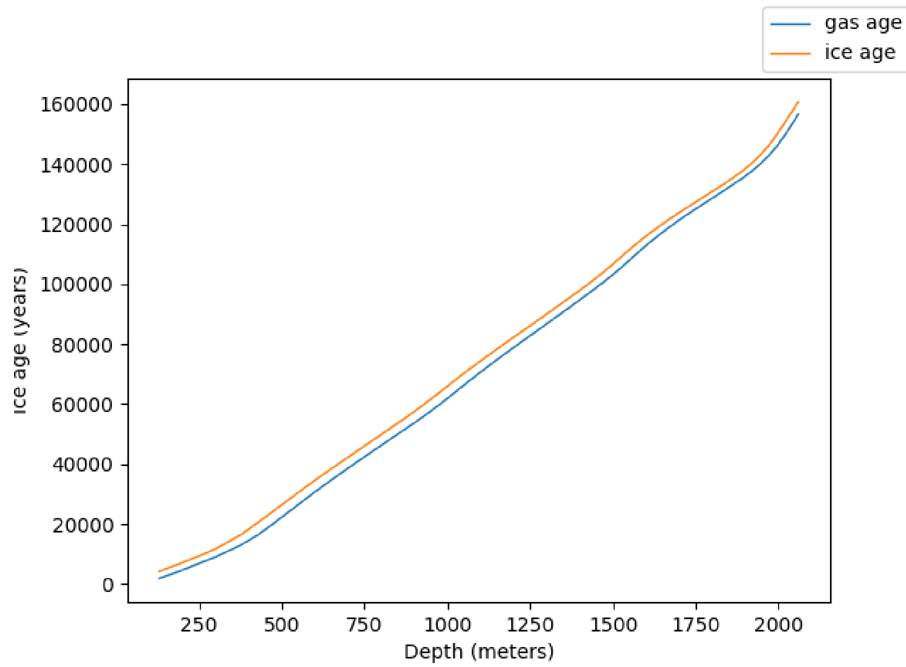


Figure 6.2: Note, the line on top is the ?ice age? line while the line on bottom is the ?gas age? line.

- **Question 12** What is the gas age at a depth of 500 meters? **(2 points)**

- **Question 13** At what depth in the ice core is the ice age closest to 100,000 years? **(2 points)**

- **Question 14** Based on what you read, why is there is difference between the gas age and the ice age? **(2 points)**

The maximum amount of moisture that air can hold drops with decreasing temperatures. When humid air cools, the water molecules will condensate to form precipitation. Heavier isotopes (atoms with an extra neutron) have a slightly higher tendency to condensate, so humid air gradually loses relatively more and more of the heavier water molecules. Every time precipitation forms, the air mass becomes more depleted in heavy isotopes. During cold conditions (e.g., during winter or in a cold climatic period), the air masses arriving in over ice sheets have cooled more and have formed more precipitation, which means that the remaining vapor is more depleted in heavy isotopes. Measuring the abundance of different isotopes can be used as a proxy for temperature.

The following is a plot of the derived temperature vs age:

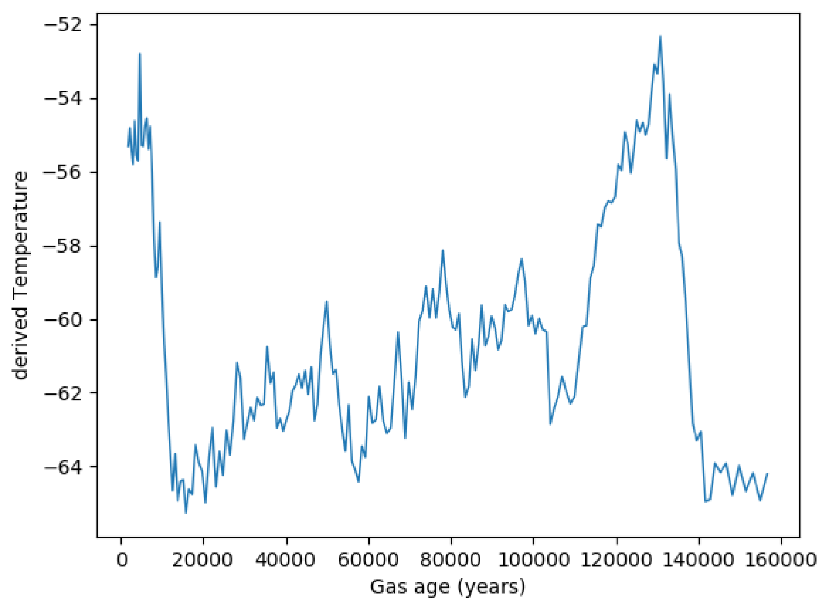


Figure 6.3: Plot of the derived temperature vs age.

- **Question 15** Approximately how long ago did the maximum temperature occur? **(2 points)**

- **Question 16** Approximately how long ago did the minimum temperature occur? **(2 points)**

6.4 Relation of paleoclimate to orbital parameter variations

Milankovitch found that there are seasonal and latitudinal variations in the amount of solar radiation the earth receives. We have seen that it is possible to measure the past climate of the Earth over the past several hundred thousand years. Let's see whether the observed climate changes match up with the predicted ones from orbital parameter variations.

Go back to http://cimss.ssec.wisc.edu/wxfest/Milankovitch/earthorbit.htmlthe cimss link for Earth's Orbit

Turn off (grey) all of the orbital parameters (eccentricity, tilt, precession). Turn on (red) the Vostok Ice Core button to plot a green line that represents Earth's recent temperature fluctuations. Note that the data here go back about 400,000 years, while the data we used in the last section only go back about 160,000 years. Can you match up the last graph with the data shown by the green line?

- **Question 17** Are present day temperatures the warmest we have ever experienced in the last 400,000 years? **(2 points)**

Click on the Eccentricity box on the bottom of the screen. This will produce a purple line on the Vostok ice core graph.

- **Questions 18** Does the shape of the Earth's orbit by itself correlate well with the observed temperature record? **(2 points)**

Unclick the Eccentricity box on the bottom of the screen. Click on the Precession box on the bottom of the screen to produce another purple line on the Vostok ice core graph.

- **Question 19** Does the precession of the Earth's rotation axis by itself correlate well with the observed temperature record? **(2 points)**

Unclick the Precession box on the bottom of the screen. Click on the Tilt box on the bottom of the screen. This will produce a purple line on the Vostok ice core graph.

- **Question 20** Does the tilt of the Earth's rotation axis by itself correlate well with the observed temperature record? **(2 points)**

Experiment with combining multiple effects of tilt, eccentricity, and precession.

- **Question 21** Which combination of eccentricity, tilt, and precession mostly closely matches the temperatures over the last 400,000 years as inferred from the ice cores? **(2 points)**

The Milankovitch Theory that cyclical variations in three elements of Earth-sun geometry combine to produce variations in the amount of solar energy that reaches Earth explains past climates. The Vostok ice core data corroborates this theory.

6.5 Recent climate changes

Recent studies show that the earth is warming up, for example, as demonstrated by the worldwide climates stripe shown in Figure 6.4 that we have seen before.

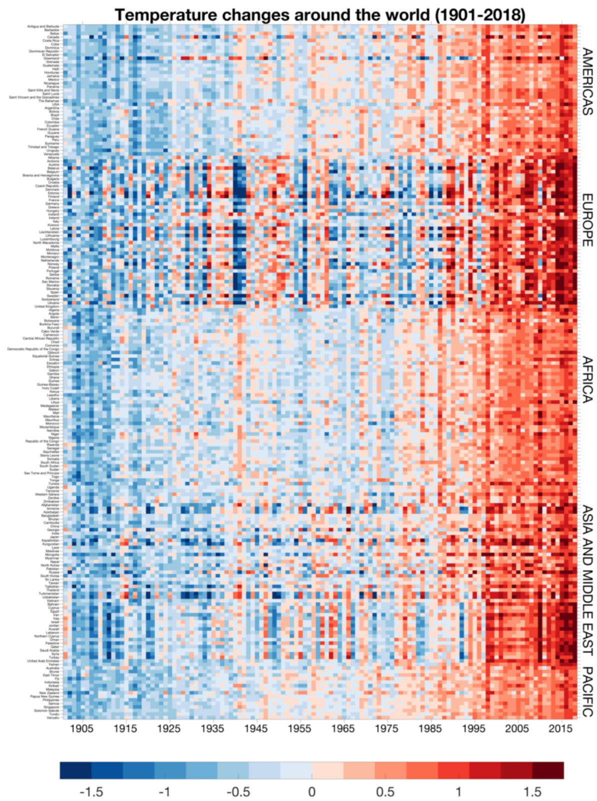


Figure 6.4: Climate stripes for all countries, showing warming around the globe over the past century, which is a rapid change that we have not seen before.

We will demonstrate that this warming is unlike any warming seen in the climate record.

To do this, we will use the link - https://applets.kcvs.ca/HistoricClimateTrends/HistoricalTemperatures.htmlFor Historical Temperatures provided by your TA

Historic Climate Trends Learning Tool to measure the rate of current warming and compare it to the rate of past warming episodes. After you open the tool, you should see various options at the bottom of the graph: Temperature, CO2, N2O, Methane, Trendlines, and lines. If the word / box is highlighted in blue, that means its is turned on. If Temperature is not turned on already, click on Temperature to view past temperatures. If you don't see anything, make sure that trendlines and lines are turned on. You can zoom in on a region of data by clicking on the graph and dragging across the range you want to see. To reset to the full time range, use the Reset item at the top.

- **Question 22** Find a region where you think the temperature has risen the fastest. What range of times did you choose to measure the slope over? **(2 points)**

Zoom in on this region. To measure the rate of temperature change, we will use the Calculate Slope feature (at the top of the window) to calculate the average rate of change of temperature. To calculate the change in temperature across the region we are looking at, click on Calculate Slope and then click on Temperature from the drop-down menu. Once you've done this, start hovering over the graph, and you will see a dot. When you click a location on the curve, that dot will be locked into place. It will then ask you to select another point on the graph and calculate the slope between the two points. Do this by choosing the lowest point before a temperature rise, and then the highest point. The tool will then report the average rate of temperature change in degrees per year.

- **Question 23** What value did you get for average rate of temperature change (the slope) during your chosen interval? **(2 points)**

Now let's measure the recent rate of temperature rise. To do so, either reset and zoom in on the far right of the plot, or use the show item at the top of the screen and select the last 5000 years. You should see a relatively constant temperature with a rise in the last 100-200 years.

Measure the rate of this temperature rise using the Calculate Slope tool as before.

- **Question 24** What range of times did you choose to measure the slope over? **(2 points)**

- **Question 25** What value did you get for average rate of temperature change? **(2 points)**

- **Question 26** Compare the rate of temperature change in the last 100-200 years with that of the fastest rate of change in the last 800,000 years: which is bigger? **(3 points)**

- **Question 27** Considering the rate of change of temperature you see in the Milankovich cycle simulator, what are the connections (if any) between the Milankovitch Cycles . **(3 points)**

6.6 Long term climate change

Ice cores provide records of temperature over the last several hundred thousand years. This is only a tiny fraction of the Earth's history: the Earth is about 4.5 billion years old, and 500,000 years is 0.0005 billion years!

Tracking temperatures over longer periods of time is less precise, but scientists have provides some estimates.

Figure 6.5 shows estimates of temperature change over the last 500 *million* years. Note that the scale on the horizontal axis is not linear in time! The data we have been looking at appears in the rightmost two panels, but the more recent times are stretched out compared to older times. The same is true as one goes farther back in time on the plot, as you can see from the axis labels.

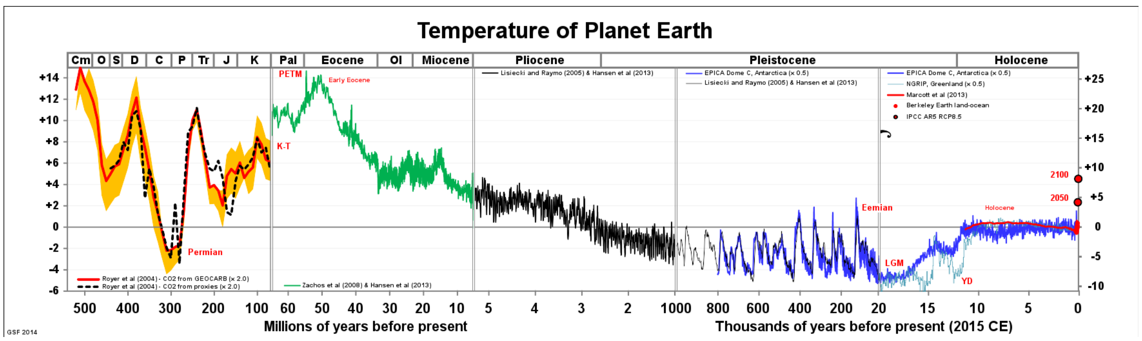


Figure 6.5: Long term temperature changes on Earth

- **Question 28** Has the Earth been significantly hotter than it is now at any point in the past? When? **(3 points)**

- **Question 29** If the Earth was warmer in the past, does that mean that we shouldn?t be concerned about a rapid rise in temperature now over the recent 100-200 years? Why or why not? **(5 points)**

Name(s):______________________________
Date:____________________________________

7 The Origin of the Seasons

7.1 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

7.2 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 7.1 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 7.1, 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 7.1: **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 7.1 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.

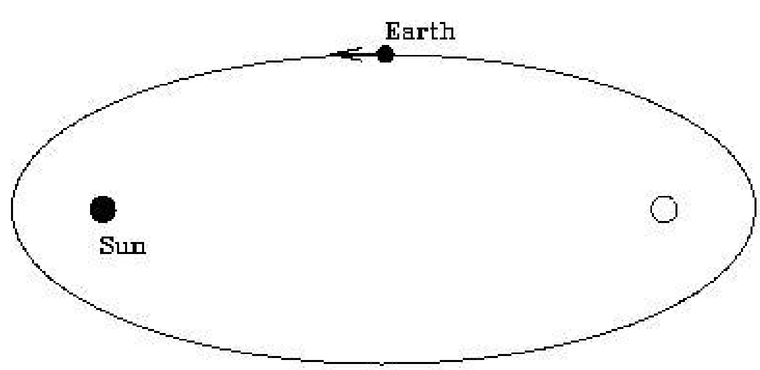


Figure 7.1: An ellipse with the two "foci" identified. The Sun sits at one focus, while the other focus is empty. The Earth follows an elliptical orbit around the Sun, but not nearly as exaggerated as that shown here!

Exercise #1. In Figure 7.1, 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 23rd, 1992, and one was taken on the 21st of July 1992 (as the "date stamps" on the images show). Using a ruler, *carefully* measure the diameter of the Sun in each image:

Sun diameter in January image = ____________ mm.

Sun diameter in July image = ____________ mm.

3) Take the ratio of bigger diameter / smaller diameter, this = ____________. (**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 7.1. 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 7.1, 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^o, the Summer Sun is up all day (24 hrs of daylight, the so called "land of the midnight Sun") for at least one day each year, while in the Winter there are times when the Sun never rises! 66.5^o is a special latitude, and is given the name "Arctic Circle". Note that Fairbanks is very close to the Arctic Circle, and the Sun is up for just a few hours during the Winter, but is up for nearly 22 hours during the Summer! The same is true for the southern hemisphere: all latitudes south of -66.5^o experience days with 24 hours of daylight in the Summer, and 24 hours of darkness in the Winter. -66.5^o is called the "Antarctic Circle". But note that the seasons in the Southern Hemisphere are exactly opposite to those in the North. During Northern Winter, the North Pole experiences 24 hours of darkness, but the South Pole has 24 hours of daylight.

7.3 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 7.2: 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 7.3, 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 7.3: 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 7.1, 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 7.2: 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 7.3: 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 7.4: Position #1: Length of Night and Day

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

18) The caption for Table 7.3 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 7.4 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 7.6 for +45° latitude with those for Minneapolis in Table 7.1. Since Minneapolis is at a latitude of +45°, what season does this orientation of the globe correspond to? (**2 points**)

Table 7.5: Position #2: Solstice Data Table

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

Table 7.6: 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 7.1, 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 7.7: 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 7.8: 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 7.1, 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 7.1 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 7.4). *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 7.4.

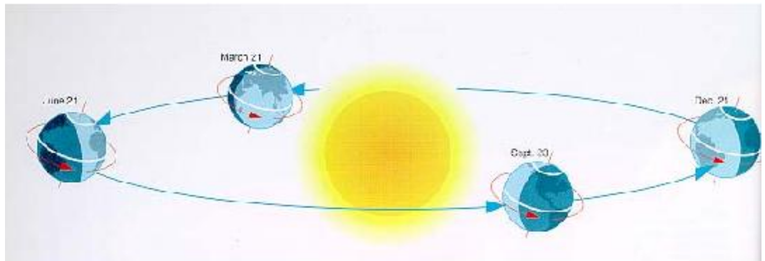


Figure 7.4: The Earth's spin axis always points to one spot in the sky, *and* it is tilted by 23.5° to its orbit. Thus, as the Earth orbits the Sun, the illumination changes with latitude: sometimes the North Pole is bathed in 24 hours of daylight, and sometimes in 24 hours of night. The exact opposite 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.

7.4 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. 7.5.

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).

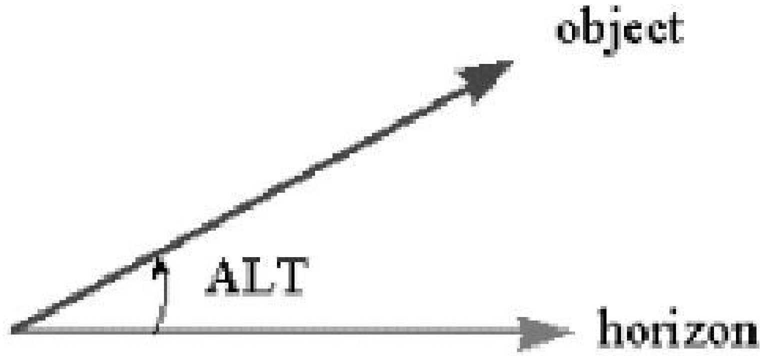


Figure 7.5: Altitude ("Alt") is simply the angle between the horizon, and an object in the sky. The smallest this angle can be is 0°, and the maximum altitude angle is 90°. Altitude is interchangeably known as elevation.

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. 7.6. The minor axis is the smallest diameter, while the major axis is the longest diameter of an ellipse.

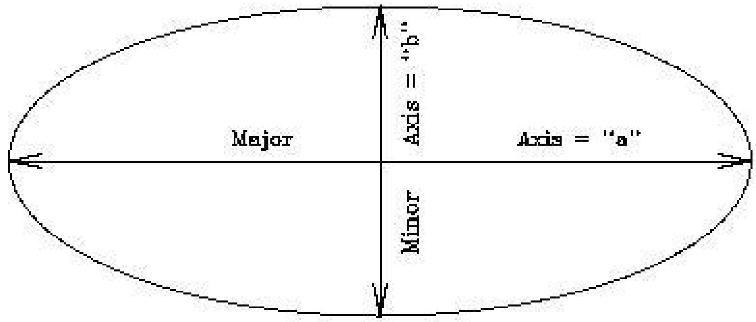


Figure 7.6: An ellipse with the major and minor axes defined.

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. 7.3. 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. 7.7. 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

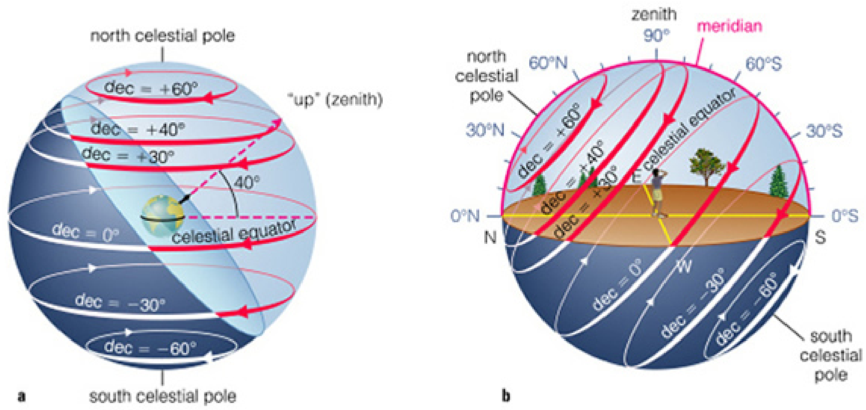


Figure 7.7: The Celestial Equator is the circle in the sky that is straight overhead ("the zenith") of the Earth's equator. In addition, there is a "North Celestial" pole that is the projection of the Earth's North Pole into space (that almost points to Polaris). But the Earth's spin axis is tilted by 23.5° to its orbit, and the Sun appears to move above and below the Celestial Equator over the course of a year.

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

Name:______________________________
Date:______________________________

7.5 Take Home Exercise (35 total points)

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

1. Why does the Earth have seasons?
2. What is the origin of the term "Equinox"?
3. What is the origin of the term "Solstice"?
4. Most people in the United States think the seasons are caused by the changing distance between the Earth and the Sun. Why do you think this is?
5. What type of seasons would the Earth have if its spin axis was *exactly* perpendicular to its orbital plane? Make a diagram like Fig. 7.4.
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.

7.6 Possible Quiz Questions

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

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

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

Name:________________________________
Date:_________________________________

8 Density

8.1 Introduction

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

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

8.2 Mass versus Weight

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

8.3 Volume

Now that we have discussed mass, we need to talk about the other quantity in our equation for density, and that is volume. Volume is pretty easy to calculate for objects with regular shapes. For example, you probably know how to calculate the volume of a cube: V = $s \times s \times s = s^3$, where s is the length of a side of the cube. Let us generalize this to any rectangular solid. In Figure 8.1 we show a drawing for a box that has sides labeled with "length," "width," and "height." What is its volume? Its volume is V = length × width × height. If we told you that the length = 10 cm, the height = 5 cm, and the depth = 5 cm, what is the box's volume? V = 10 cm × 5 cm × 5 cm = 250 cubic cm = 250 cm^3. Do you now see why volume is measured in cm^3? This is where that comes from—everyday objects are "three dimensional" in that they *have* volume (cm^3, m^3, km^3, $inches^3$, $miles^3$).

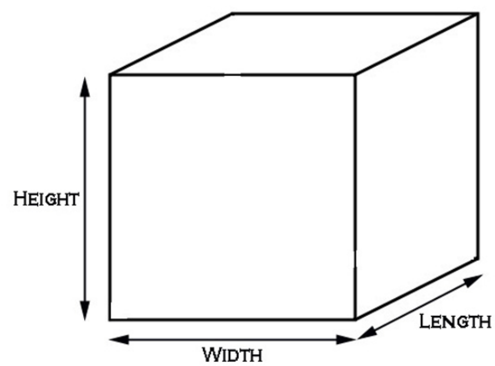


Figure 8.1: A rectangular solid has sides of length, width, and height.

Now that we understand how volume is calculated, how do we do it for objects that have more complicated shapes, like a coke bottle, a car engine, or a human being? You may have heard the story of Archimedes. Archimedes was asked by the King of Syracuse (in ancient Greece) to find out if the dentist making a gold crown for one of his teeth had embezzled some of the gold the king had given him to make this crown (by adding lead, or another cheaper metal to the crown while keeping some of the gold for himself). Archimedes pondered the problem for a while and hit on the solution while taking a bath. Archimedes became so excited he ran out into the street naked shouting "Eureka!" What Archimedes realized was that you can use water to figure out a solid object's volume. For example, you could fill a teacup to the brim with water and drop an object in the teacup. The amount of water that overflows and collects in the saucer has the same volume as that object. All you need to know to figure out the object's volume is the conversion from the amount of liquid water to its volume in cm^3. An example of the process is shown in Fig. 8.2.

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

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

Exercise #1: Measuring Masses, Volumes and Densities

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

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

Task #1: Fill in column #2 ("Mass") of Table 8.1 by measuring the masses of your ten objects. **(10 points)**

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

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

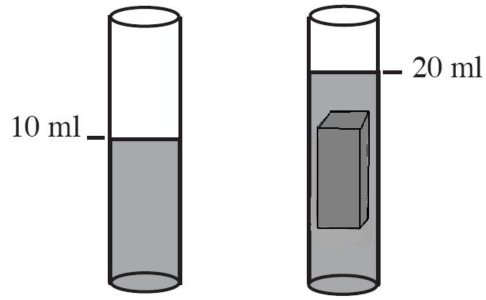


Figure 8.2: The rectangular object displaces 10 ml of water. Therefore, it has a volume of 10 ml = 10 cm^3.

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

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

Task #3: Fill in the Density column in Table 8.1. **(5 points)**

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

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

Table 8.1: The Masses, Volumes, and Densities of the Different Objects.

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

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

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

Task #4: Fill in Table 8.2. Copy the mass measurements from Table 8.1 for the five metal "cubes". Calculate the volumes of these "cubes" using the caliper. **(5 points)**

Table 8.2: The Masses, Volumes, and Densities of the Metal Cubes.

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

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

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

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

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

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

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

Now let's compare the densities of these rocks to two familiar objects: the Earth and the Moon. We have listed the mean densities of the Earth and Moon in Table 8.3, along with the density of the Earth's crust. As you can see, the mean density of the Earth's crust is similar to the value you determined for Gabbro and/or Obsidian–it better be, as these rocks *are from the Earth's crust*!

Table 8.3: Densities of the Earth and Moon

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

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

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

It is clear from Table 8.3, that the mean density of the whole Earth is much higher than the density of its crust. There must be denser material below the crust, deep inside the Earth.

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

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

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

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

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

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

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

Volume(Gabbro) = Mass(Pumice)/Density(Gabbro) = ________________ cm^3

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

r = Volume(Gabbro)/Volume(Pumice) = ________________ %

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

1 - r = ________________ %

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

Name:____________________________________

Date:_____________________________________

8.4 Take Home Exercise (35 points total)

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

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

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

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

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

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

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

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

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

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

8.5 Possible Quiz Questions

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

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

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

Name:___________________________________
Date:____________________________________

9 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.

9.1 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 9.1: A dendritic drainage pattern in Yemen (left), and an anastomosing drainage in Alaska (right).

9.1.1 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 9.1. (**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!

9.1.2 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**)

9.2 The Global Perspective

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

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

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

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

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

Name:________________________________
Date:_________________________________

9.3 Take Home Exercise (35 points total)

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

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

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

9.4 Possible Quiz Questions

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

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

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

Name:____________________________________

Date:____________________________________

10 Measuring Distances Using Parallax

10.1 Introduction

How do astronomers know how far away a star or galaxy is? Determining the distances to the objects they study is one of the the most difficult tasks facing astronomers. Since astronomers cannot simply take out a ruler and measure the distance to any object, they have to use other methods. Inside the solar system, astronomers can simply bounce a radar signal off of a planet, asteroid or comet to directly measure the distance to that object (since radar is an electromagnetic wave, it travels at the speed of light, so you know how fast the signal travels–you just have to count how long it takes to return and you can measure the object's distance). But, as you will find out in your lecture sessions, some stars are hundreds, thousands or even tens of thousands of "light years" away. A light year is how far light travels in a single year (about 9.5 trillion kilometers). To bounce a radar signal off of a star that is 100 light years away would require you to wait 200 years to get a signal back (remember the signal has to go out, bounce off the target, and come back). Obviously, radar is not a feasible method for determining how far away stars are.

In fact, there is one, and only one direct method to measure the distance to a star: "parallax". Parallax is the angle that something appears to move when the observer looking at that object changes their position. By observing the size of this angle and knowing how far the observer has moved, one can determine the distance to the object. Today you will experiment with parallax, and appreciate the small angles that astronomers must measure to determine the distances to stars.

To introduce you to parallax, perform the following simple experiment:

Hold your thumb out in front of you at arm's length and look at it with your left eye closed. Now look at it with your right eye closed. As you look at your thumb, alternate which eye you close several times. You should see your thumb move relative to things in the background. Your thumb is not moving but your point of view is moving, so your thumb *appears* to move.

- *Goals:* to discuss the theory and practice of using parallax to find the distances to nearby stars, and use it to measure the distance to objects in the classroom
- *Materials:* classroom "ruler", worksheets, ruler, protractor, calculator, small object

10.2 Parallax in the classroom

The "classroom parallax ruler" will be installed/projected on one side of the classroom. For the first part of this lab you will be measuring motions against this ruler.

Now work in groups: stand at the back of the room and have the TA place the parallax device on one of the tape marks along the line that goes straight to the front wall. You should be able to see the plastic stirrer against the background ruler. The observer should blink his/her eyes and measure the number of lines on the background ruler against which the object appears to move. **Note that you can estimate the motion measurement to a fraction of tick mark, e.g., your measurement might be 2 1/2 tick marks).** Do this for the three different marked distances. Switch places and do it again. Each person should estimate the motion for each of the three distances.

1. How many tick marks did the object move at the closest distance? **(2 points)**:

2. How many tick marks did the object move at the middle distance? **(2 points)**:

3. How many tick marks did the object move at the farthest distance? **(2 points)**:

4. 'Parallax' is the term used for the apparent motion of the object against the background ruler. It is caused by looking at an object from two different vantage points. In this case, the two vantage points are the locations of your two eyes. Qualitatively, what do you see? As the object gets farther away, is the apparent motion smaller or larger? **(1 point)**:

5. What if the vantage points are further apart? For example, imagine you had a huge head and your eyes were a foot apart rather than several inches apart. What would you predict for the apparent motion? **(1 point)**:

   Try the experiment again, this time using the object at one of the distances used above, but now measuring the apparent motion by using just one eye, but moving your whole head a few feet from side to side to get more widely separated vantage points.

6. How many tick marks does the object move as seen from the more widely separated vantage points? **(1 point)**:

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

10.3 Measuring distances using parallax

We have seen that the apparent motion depends on both the distance to an object and also on the separation of the two vantage points. We can then turn this around: if we can measure the apparent motion and also the separation of the two vantage points, we should be able to infer the distance to an object. This is very handy: it provides a way of measuring a distance without actually having to go to an object. Since we can't travel to them, this provides the only direct measurement of the distances to stars.

We will now see how parallax can be used to **determine the distances to the objects you looked at** just based on your measurements of their apparent motions and a measurement of the separation of your two vantage points (your two eyes).

10.3.1 Angular motion of an object

How can we measure the apparent motion of an object? As with our background ruler, we can measure the motion as it appears against a background object. But what are the appropriate units to use for such a measurement? Although we can measure how far apart the lines are on our background ruler, the apparent motion is not really properly measured in a unit of length; if we had put our parallax ruler further away, the apparent motion would have been the same, but the number of tick marks it moved would have been larger.

The apparent motion is really an *angular* motion. As such, it can be measured in *degrees*, with 360 degrees in a circle.

Figure out the angular separation of the tick marks on the ruler as seen from the opposite side of the classroom. Do this by putting one eye at the origin of one of the tripod-mounted protractors and measuring the angle from one end of the background ruler to the other end of the ruler. You might lay a pencil from your eye at the origin of the protractor toward each end and use this to measure the the total angle. Divide this angle by the total number of tick marks to figure out the angle for each tick mark.

1. Number of degrees for the entire background ruler (between the 0 and 20 marks):

2. Number of tick marks between 0 and 20 on the ruler:

3. Number of degrees in each tick mark:

   Convert your measurements of apparent motion in tick marks from Section 10.2 to angular measurements by multiplying the number of tick marks by the number of degrees per tick mark:

4. How many degrees did the object appear to move at the closest distance? **(2 points)**:

5. How many degrees did the object appear to move at the middle distance? **(2 points)**:

6. How many degrees did the object appear to move at the farthest distance? **(2 points)**:

10.3.2 Distance between the vantage points

Now you need to measure the distance between the two different vantage points, in this case, the distance between your two eyes. Have your partner measure this with a ruler. Since you see out of the pupil part of your eyes, you want to measure the distance between the centers of your two pupils.

1. What is the distance between your eyes? **(2 points)**

10.3.3 Using parallax measurements to determine the distance to an object

To determine the distance to an object for which you have a parallax measurement, you can construct an imaginary triangle between the two different vantage points and the object, as shown in Figure 10.1.

The angles you have measured correspond to the angle α on the diagram, and the distance between the vantage points (your pupils) corresponds to the distance b on the diagram. The distance to the object, which is what you want to figure out, is d.

The three quantities b, d, and α are related by a trigonometric function called the *tangent*. Now, you may have never heard of a *tangent*, if so don't worry–we will show you how to do this using another easy (but less accurate) way! But for those of you who are familiar with a little basic trigonometry, here is how you find the distance to an object using parallax: If you split your triangle in half (dotted line), then the tangent of $(\alpha/2)$ is equal to the quantity $(b/2)/d$:

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

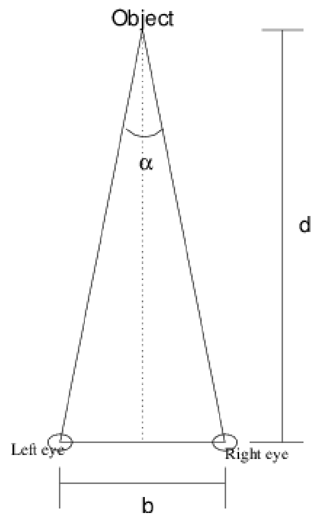


Figure 10.1: Parallax triangle

Rearranging the equation gives:

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

You can determine the tangent of an angle using your calculator by entering the angle and then hitting the button marked *tan*. There are several other units for measuring angles besides degrees (for example, radians), so you have to **make sure that your calculator is set up to use degrees** for angles before you use the tangent function.

Combine your measurements of angular distances and the distance between the vantage points to determine the three different distances to the parallax device. The units of the distances which you determine will be the same as the units you used to measure the distance between your eyes; if you measured that in inches, then the derived distances will be in inches.

Distance when object was at closest distance: **(2 points)**

Distance when object was at middle distance: **(2 points)**

Distance when object was at farthest distance: **(2 points)**

Now go and measure the actual distances to the locations of the objects using a yardstick, meterstick, or tape measure. How well did the parallax distances work? Can you think of any reasons why your measurements might not match up exactly? **(5 points)**

10.4 Using Parallax to measure distances on Earth, and within the Solar System

We just demonstrated how parallax works in the classroom, now let's move to a larger scale than the classroom.

10.4.1 The "Non-Tangent" way to figure out distances from angles

Because the angles in astronomical parallax measurement are very small, astronomers do not have to use the *tangent* function to determine distances from angles–they use something called the "small angle approximation formula":

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

In this equation, we have defined $\theta = \alpha/2$, where α is the same angle as in the earlier equations (and in Fig. 10.1). Rearranging the equation gives:

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

To use this equation your parallax angle "θ" **has to be in degrees.** Now you can proceed to the next step!

1. *Using the small angle formula*, and your measured pupil distance, what would be the parallax angle (in degrees) for Organ Summit, the highest peak in the Organ mountains, if the Organ Summit is located 12 miles (or 20 km) from this classroom? [Hint: there are 5280 feet in a mile, and 12 inches in a foot. There are 1,000 meters in a km.]: **(3 points)**

You should have gotten a tiny angle! The smallest angle that the best human eyes can resolve is about 0.02 degrees. Obviously, our eyes provide an inadequate baseline for measuring this large of a distance. How can we get a bigger baseline? Well surveyors use a "transit" to carefully measure angles to a distant object. A transit is basically a small telescope mounted on a (fancy!) protractor. By locating the transit at two different spots separated by 100 yards (and carefully measuring this baseline!), they can get a much larger parallax angle, and thus it is fairly easy to measure the distances to faraway trees, mountains, buildings or other large objects.

How about an object in the Solar System? We will use Mars, the planet that comes closest to Earth. At favorable oppositions, Mars gets to within about 0.4 AU of the Earth. Remember, 1 AU is the average distance between the Earth and Sun: 149,600,000 km.

2. Calculate the parallax angle for Mars (using the small angle approximation) using a baseline of 1000 km. **(3 points)**

10.5 Distances to stars using parallax, and the "Parsec"

Because stars are very far away, the parallax motion will be very small. For example, the nearest star is about 1.9×10^{13} miles or 1.2×10^{18} inches away! At such a tremendous distance, the apparent angular motion is very small. Considering the two vantage points of your two eyes, the angular motion of the nearest star corresponds to the apparent diameter of a human hair seen at the distance of the Sun! This is a truly tiny angle and totally unmeasurable by your eye.

Like a surveyor, we can improve our situation by using two more widely separated vantage points. The two points farthest apart we can use from Earth is to use two opposite points in the Earth's orbit about the Sun. In other words, we need to observe a star at two different times separated by six months. The distance between our two vantage points, b, will then be twice the distance between the Earth and the Sun: "2 AU". Figure 10.2 shows the idea.

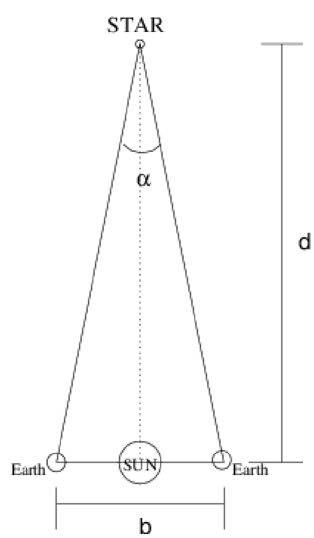


Figure 10.2: Parallax Method for Distance to a Star

Using 299.2 million km as the distance b, we find that the apparent angular motion (α) of even the nearest star is only about 0.0004 degrees. This is also unobservable using your naked eye, which is why we cannot directly observe parallax by looking at stars with our naked eye. However, this angle is relatively easy to measure using modern telescopes and instruments.

Time to talk about a new distance unit, the "Parsec". Before we do so, we have to review the idea of smaller angles than degrees. Your TA or professor might already have mentioned that a degree can be broken into 60 arcminutes. Thus, instead of saying the parallax angle is 0.02 degrees, we can say it is 1.2 arcminutes. But note that the nearest star only has a parallax angle of 0.024 arcminutes. We need to switch to a smaller unit to keep from having to use scientific notation: the arcsecond. There are 60 arcseconds in an arcminute, thus the parallax angle (α) for the nearest star is 1.44 arcseconds. To denote arcseconds astronomers append a single quotation mark (") at the end of the parallax angle, thus $\alpha = 1.44$" for the nearest star. But remember, in converting an angle into a distance (using the tangent or small angle approximation) we used the angle $\alpha/2$. So when astronomers talk about the parallax of a star they use this angle, $\alpha/2$, which we called "θ" in the small angle approximation equation.

How far away is a star that has a parallax angle of $\theta = 1$"? The answer is 3.26 light years, and this distance is defined to be "1 Parsec". The word Parsec comes from **Par**allax **Sec**ond. An object at 1 Parsec has a parallax of 1". An object at 10 Parsecs has a parallax angle of 0.1". Remember, the further away an object is, the smaller the parallax angle.

The nearest star (Alpha Centauri) has a parallax of $\theta = 0.78$", and is thus at a distance of $1/\theta = 1/0.78 = 1.3$ Parsecs.

Depending on your professor, you might hear the words Parsec, kiloparsec, Megaparsec and even Gigaparsec in your lecture classes. These are just shorthand methods of talking about distances in astronomy. A kiloparsec is 1,000 Parsecs, or 3,260 light years. A Megaparsec is one million parsecs, and a Gigaparsec is one billion parsecs. To convert to light years, you simply have to multiply by 3.26. The Parsec is a strange unit, but you have already encountered other strange units this semester!

Let's work some examples. Remember:

- **1 Parsec = 3.26 lightyears**
- **distance (in Parsecs) =** $\frac{1}{\theta}$**(in arcseconds)**

1. If a star has a parallax angle of $\theta = 0.25$", what is its distance in Parsecs? **(1 point)**

2. If a star is at a distance of 5 Parsecs, what is its parallax angle? **(1 point)**

3. If a star is at a distance of 5 Parsecs, how many light years away is it? **(1 point)**

10.6 Questions

1. How does the parallax angle change as an object is moved further away? Given that you can usually only measure an angular motion to some accuracy, would it be easier to measure the distance to a nearby star or a more distant star? Why? **(4 points)**

2. Relate the experiment you did in lab to the way parallax is used to measure the distances to nearby stars in astronomy. Describe the process an astronomer has to go through in order to determine the distance to a star using the parallax method. What do your two eyes represent in that experiment? **(5 points)**

3. Imagine that you did the classroom experiment by putting the object all the way at the front of the room (against the ruler). How big would the apparent motion be relative to the tick marks? What would you infer about the distance to the object? Why do you think this estimate is incorrect? What can you infer about where the background objects in a parallax experiment need to be located? **(7 points)**

4. Imagine that you observe a star field twice one year, separated by six months and observe the configurations of stars shown in Figure 10.3:

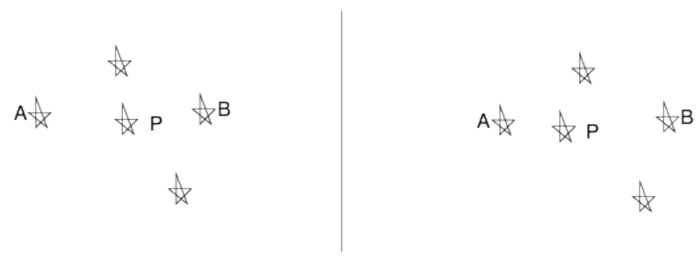


Figure 10.3: Star field seen at two times of year six months apart.

The star marked P appears to move between your two observations because of parallax. So you can consider the two pictures to be like our lab experiment where the left picture is what is seen by one eye and the right picture what is seen by the other eye. All the stars except star P do not appear to change position; they correspond to the background ruler in our lab experiment. If the angular distance between stars A and B is 0.5 arcminutes (remember, 60 arcminutes = 1 degree), then how far away would you estimate that star P is?

   (a) Determine the scale: Measure the distance (in cm) between stars A and B. (This distance corresponds to an angular separation of 0.5 arcminutes)

   (b) Measure how much star P moved (in cm)

   (c) Convert this measured distance to an angular distance in arcminutes (using the scale found in part a).

(d) Convert your angular distance from arcminutes to arcseconds (remember, there are 60 arcseconds in 1 arcminute).

(e) What is the value of θ? (Recall that $\theta = \frac{\alpha}{2}$)

(f) Using the parallax equation ($d = \frac{1}{\theta}$) find the distance to the star P.

(11 points)

10.7 Summary (35 points)

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

- A brief description on the basic principles of parallax and how astronomers can use parallax to determine the distance to nearby stars

Also think about and answer the following questions:

- Does the parallax method work for all stars we can see in our Galaxy and why?
- Why do you think it is important for astronomers to determine the distances to the stars which they study?

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

10.8 Possible Quiz Questions

1) How do astronomers measure distances to stars?
2) How can astronomers measure distances inside the Solar System?
3) What is an Astronomical Unit?
4) What is an arcminute?
5) What is a Parsec?

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

Use the web to find out about the planned GAIA Mission. What are the goals of GAIA? How accurately can it measure a parallax? Discuss the units of milliarcseconds ("mas") and microarcseconds. How much better is GAIA than the best ground-based parallax measurement programs?

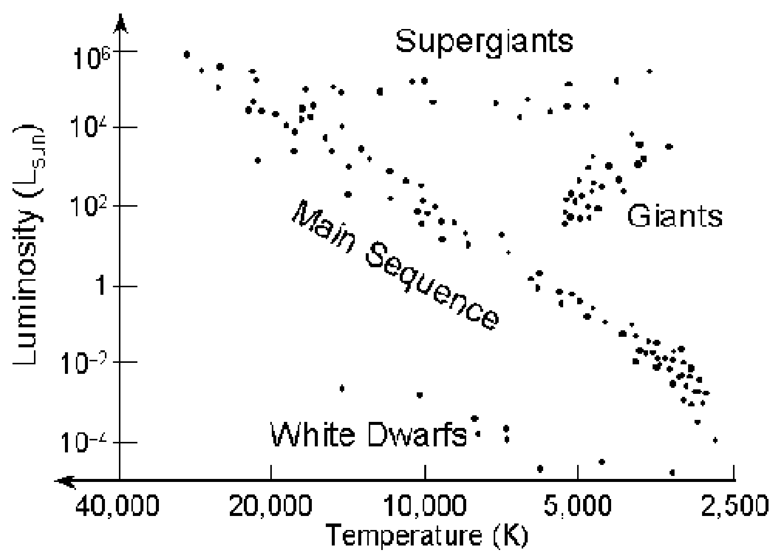
Name:______________________________

Date:______________________________

11 The Hertzsprung-Russell Diagram

11.1 Introduction

As you may have learned in class, the Hertzsprung-Russell Diagram, or the "HR diagram", is one of the most important tools used by astronomers: it helps us determine both the ages of star clusters and their distances. In your Astronomy 110 textbooks the type of HR diagram that you will normally encounter plots the Luminosity of a star (in solar luminosity units, L_{Sun}) versus its temperature (or spectral type). An example is shown here:



The positions of the various main types of stars are labeled in this HR diagram. The Sun has a temperature of 5,800 K, and a luminosity of 1 L_{Sun}. The Sun is a main sequence "G" star. All stars cooler than the Sun are plotted to the right of the Sun in this diagram. Cool main sequence stars (with spectral types of K and M) are plotted to the lower right of the Sun. Hotter main sequence stars (O, B, A, and F stars) are plotted to the upper left of the Sun's position. As the Sun runs out of hydrogen fuel in its center, it will become a red giant star–a star that is cooler than the Sun, but 100× more luminous. Red giants are plotted to the upper right of the Sun's position. As the Sun runs out of all of its fuel, it sheds its atmosphere and ends its days as a white dwarf. White dwarfs are hotter, and much less luminous than the Sun, so they are plotted to the lower left of the Sun's position in the HR diagram.

The HR diagrams for clusters can be very different depending on their ages. In the following examples, we show the HR diagram of a hypothetical cluster of stars at a variety of different ages. When the star cluster is very young, (see Fig. 11.1) only the hottest stars have made it to the main sequence. In the HR diagram below, the G, K, and M stars (stars that have temperatures below 6,000 K) are still not on the main sequence, while those stars hotter than 7,000 K (O, B, A, and F stars) are already fusing hydrogen into helium at their cores:

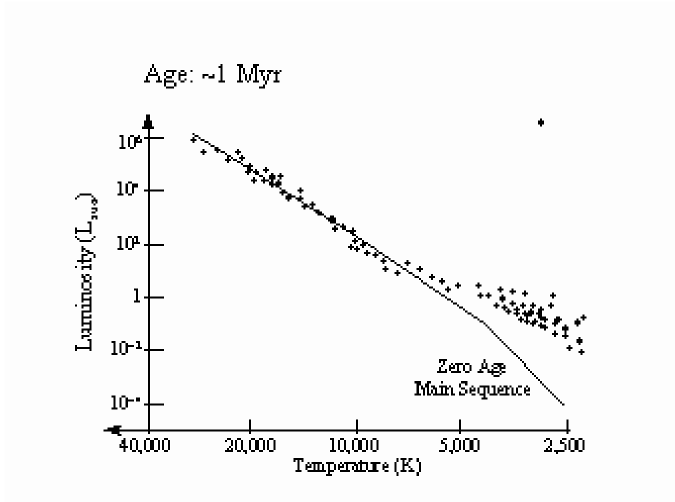


Figure 11.1: The HR diagram of a cluster of stars that is 1 million years old.

In the next HR diagram, Figure 11.2, we see a much older cluster of stars (100 million years = 100 Myr). In this older cluster, some of the hottest and most massive stars (the O and B stars) have evolved into red supergiants. The position of the "main sequence turn off" allows us to estimate the age of a cluster.

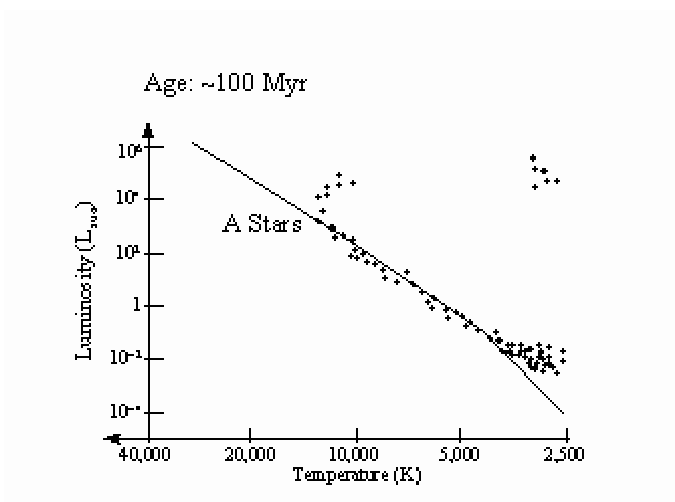


Figure 11.2: The HR diagram of a cluster of stars that is 100 million years old.

In the final HR diagram, Figure 11.3, we have a much older cluster (10 billion years old = 10 Gyr), now stars with one solar mass are becoming red giants, and we say the main sequence turn-off is at spectral type G (T = 5,500 K).

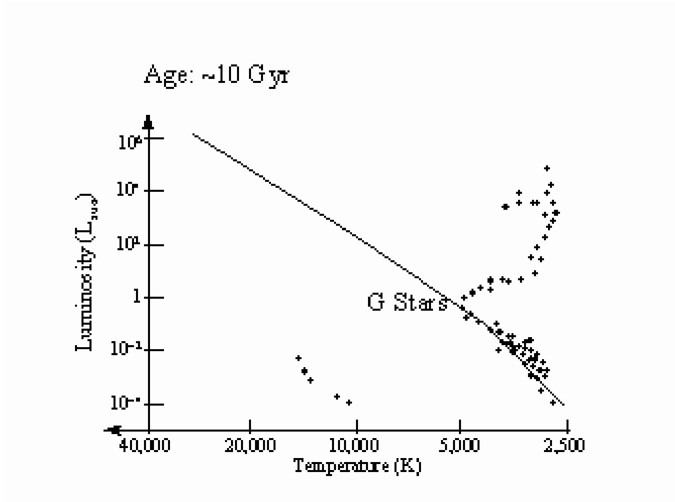


Figure 11.3: The HR diagram of a cluster of stars that is 10 billion years old.

Some white dwarfs (produced by evolved A and F stars) now exist in the cluster. Thus, the HR diagram for a cluster of stars is useful for determining its age.

11.2 Magnitudes and Color Index

While the HR diagrams presented in your class lectures or textbook allow us to provide a very nice description of the evolution of stars and star clusters, astronomers do not actually directly measure either the temperatures or luminosities of stars. Remember that luminosity is a measure the total amount of energy that a star emits. For the Sun it is 10^{26} Watts. But how much energy appears to be coming from an object depends on how far away that object is. Thus, to determine a star's luminosity requires you to know its distance. For example, the two brightest stars in the constellation Orion (see the "Constellation Highlight" for February from the Ast110 homepage link), the red supergiant Betelgeuse and the blue supergiant Rigel, appear to have about the same brightness. But Rigel is six more times luminous than Betelgeuse–Rigel just happens to be further away, so it appears to have the same brightness even though it is pumping out much more energy than Betelgeuse. The "Dog star" Sirius, located to the southeast of Orion, is the brightest star in the sky and appears to be about 5 times brighter than either Betelgeuse or Rigel. But in fact, Sirius is a nearby star, and actually only emits 22× the luminosity of the Sun, or about $1/2000^{th}$ the luminosity of Rigel!

Therefore, without a distance, it is impossible to determine a star's luminosity–and remember that it is very difficult to measure the distance to a star. We can, however, measure the relative luminosity of two (or more) stars if they are at the same distance: for example if they are both in a cluster of stars. If two stars are at the same distance, then the difference in their apparent brightness is a measurement of the true differences in their luminosities. To measure the apparent brightness of a star, astronomers use the ancient unit of "magnitude". This system was first developed by the Greek astronomer Hipparcos (*ca.* 190 to 120 BC). Hipparcos called the brightest stars "stars of the first magnitude". The next brightest were called "stars of the second magnitude". His system progressed all the way down to "stars of the sixth magnitude", the faintest stars you can see with the naked eye from a dark location.

Astronomers adopted this system and made it more rigorous by defining a five magnitude difference to be exactly equal to a factor of 100 in brightness. That is, a first magnitude star is 100X brighter than a sixth magnitude star. If you are good with mathematics, you will find that a difference of one magnitude turns out to be a factor of 2.5 ($2.5 \times 2.5 \times 2.5 \times 2.5 \times 2.5 = 100$, we say that the fifth root of $100 = 100^{1/5} = 2.5$). Besides this peculiar step size, it is also important to note that the magnitude system is upside down: usually when we talk about something being bigger, faster, or heavier, the quantity being measured increases with size (a car going 100 mph is going faster than one going 50 mph, etc.). In the magnitude system, the brighter the object, the smaller its magnitude! For example, Rigel has an apparent magnitude of 0.2, while the star Sirius (which appears to be 4.5 times brighter than Rigel) has a magnitude of -1.43.

Even though they are a bit screwy, and cause much confusion among Astronomy 110 students, astronomers use magnitudes because of their long history and tradition. So, when astronomers measure the brightness of a star, they measure its apparent magnitude. How bright that star appears to be on the magnitude scale. Usually, astronomers will measure the brightness of a star in a variety of different color filters to allow them to determine its temperature. This technique, called "multi-wavelength photometry", is simply the measurement of how much light is detected on Earth at a specific set of wavelengths from a star of interest. Most astronomers use a system of five filters, one each for the ultraviolet region (the "U filter"), the blue region (the "B filter"), the visual ("V", or green) region, the yellow-red region ("R"), and the near-infrared region ("I"). Generally, when doing real research, astronomers measure the apparent magnitude of a star in more than one filter. [Note: because the name of the filter can some times get confused with spectral types, filter names will be *italicized* to eliminate any possible confusion.]

To determine the temperature of a star, measurements of the apparent brightness in at least two filters is necessary. The difference between these two measurements is called the "color index". For example, the apparent magnitude in the B filter minus the apparent magnitude in the V filter, $(B - V)$, is one example of a color index (it is also the main color index used by astronomers to measure the temperature of stars, but any two of the standard filters can be used to construct a color index). Let us take Polaris (the "North Star") as an example. Its apparent B magnitude is 2.59, and its apparent V magnitude is 2.00, so the color index for Polaris is $(B - V) = 2.59 - 2.00 = 0.59$. In Table 11.1, we list the $(B-V)$ color index for main sequence stars. We see that Polaris has the color of a G star.

In Table 11.1, we see that O and B stars have negative $(B - V)$ color indices. We say that O and B stars are "Blue", because they emit more light in the B filter than in the V filter. We say that K and M stars are very red, as they emit much more V light than B

Table 11.1: The $(B - V)$ Color Index for Main Sequence Stars

Spectra Type	$(B - V)$	Spectral Type	$(B - V)$
O and B Stars	−0.40 to −0.06	G Stars	0.59 to 0.76
A Stars	0.00 to 0.20	K Stars	0.82 to 1.32
F Stars	0.31 to 0.54	M Stars	1.41 to 2.00

light (and even more light in the *R* and *I* filters!). A-stars emit the same amount of light at *B* and *V*, while F and G stars emit slightly more light at *V* than at *B* . With this type of information, we can now figure out the spectral types, and hence temperatures of stars by using photometry.

11.3 The Color-Magnitude HR Diagram

To construct HR diagrams of star clusters, astronomers measure the apparent brightness of stars in two different color filters, and then plot the data into a "Color-Magnitude" diagram, plotting the apparent *V* magnitude versus the color index $(B - V)$ as shown below. Figure 11.4 shows a color-magnitude diagram for a globular cluster. You might remember from class (or will soon be told!) that globular clusters are old, and that the low mass stars are evolving off the main sequence and becoming red giants. The main sequence turnoff for this globular cluster is at a color index of about $(B - V) = 0.4$, the color of F stars. An F star has a mass of about 1.5 M_{Sun}, thus stars with masses near 1.5 M_{Sun} are evolving off the main sequence to become red giants, so this globular cluster is about 7 billion years old.

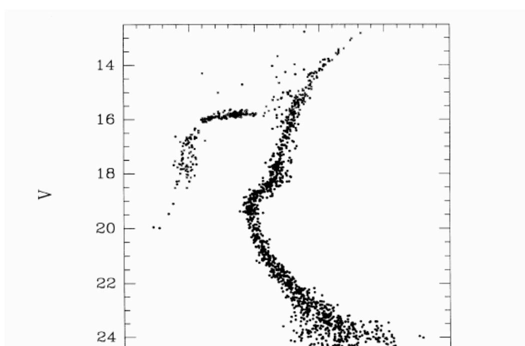


Figure 11.4: The HR diagram for the globular cluster M15.

11.4 The Color-Magnitude Diagram for the Pleiades

In today's lab, you and your lab partners will construct a color magnitude diagram for the Pleiades star cluster. The Pleiades, sometimes known as the "Seven Sisters" (see the constellation highlight for January at the back of this lab manual), is a star cluster located in the wintertime constellation of Taurus, and can be seen with the naked eye. A wide-angle photograph of the Pleiades is shown below (Fig. 11.4). Many people confuse the Pleiades with the Little Dipper because the brightest stars form a small dipper-like shape.

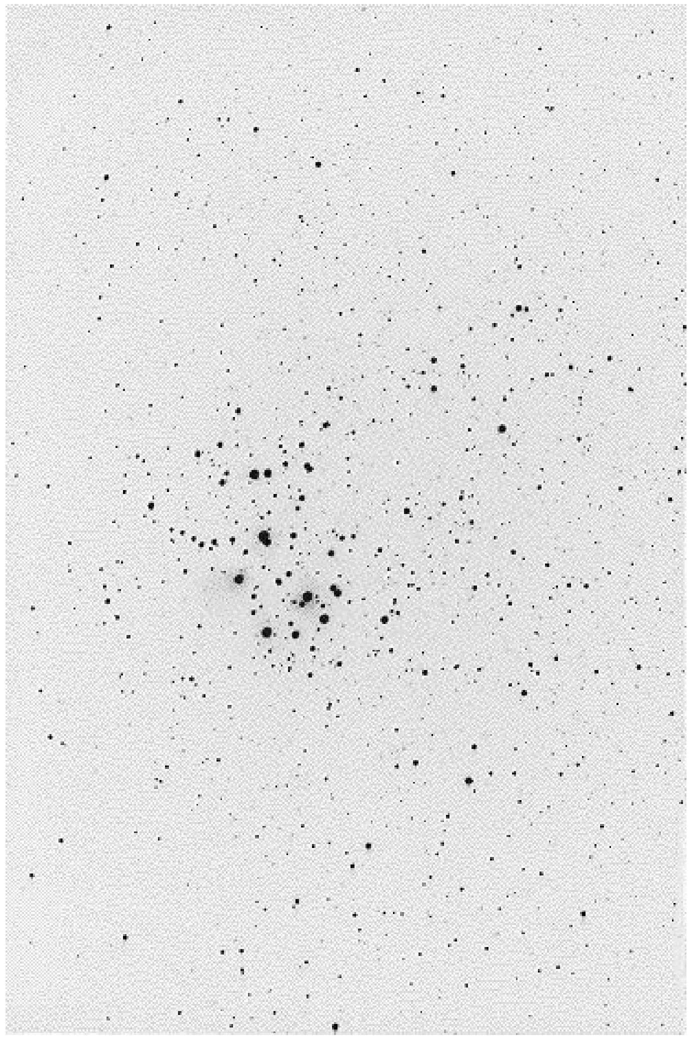
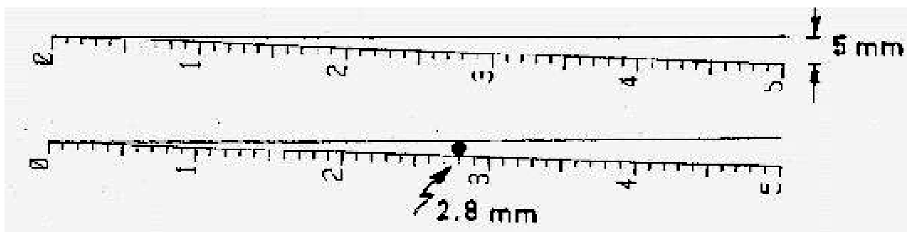


Figure 11.5: A photograph of the Pleiades.

As you will find out, the Pleiades is a relatively young group of stars. We will be using photographs of the Pleiades taken using two different color filters to construct a Color-Magnitude diagram. If you look closely at the photograph of the Pleiades, you will notice that the brighter stars are larger in size than the fainter stars. Note: you are not seeing the actual disks of the stars in these photographs. Brighter stars appear bigger on photographs because more light from them is detected by the photograph. As the light from the stars accumulates, it spreads out. Think of a pile of sand. As you add sand to a pile, it develops a conical, pyramid shape. The addition of more sand to the pile raises the height of the sand pile, but the *base* of the sand pile has to spread more to support this height. The same thing happens on a photograph. The more light there is, the larger the spread in the *image* of the star. In reality, *all* of the stars in the sky are much to far away to be seen as little disks (like those we see for the planets in our solar system) when viewed/imaged through *any existing telescope*. We would need to have a space-based telescope with a mirror 1.5 miles across to actually be able to see the stars in the Pleiades as little, resolved disks! [However, there are some special techniques astronomers have developed to actually measure the diameters of stars. Ask your TA about them if you are curious.]

Thus, we can use the sizes of the stars on a photograph to figure out how bright they are, we simply have to measure their diameters! A special tool, called a "dynameter", is used to measure sizes of circles. You will be given a clear plastic dynameter in class. A replica of this dynameter is shown here:



As demonstrated, a dynameter allows you to measure the diameter of a star image by simply sliding the dynameter along until the edges of the star just touch the lines. In the example above, the star image is 2.8 mm in diameter. On the following two pages are digitized scans of two photographs of the Pleiades taken through *B* and *V* filters. These photographs were digitized to allow us to put in an X-Y scale so that you can keep track of which star is which in the two different photographs. You should be able to compare the digitized photographs with the actual photo shown above and see that most of the brighter stars are on all three images.

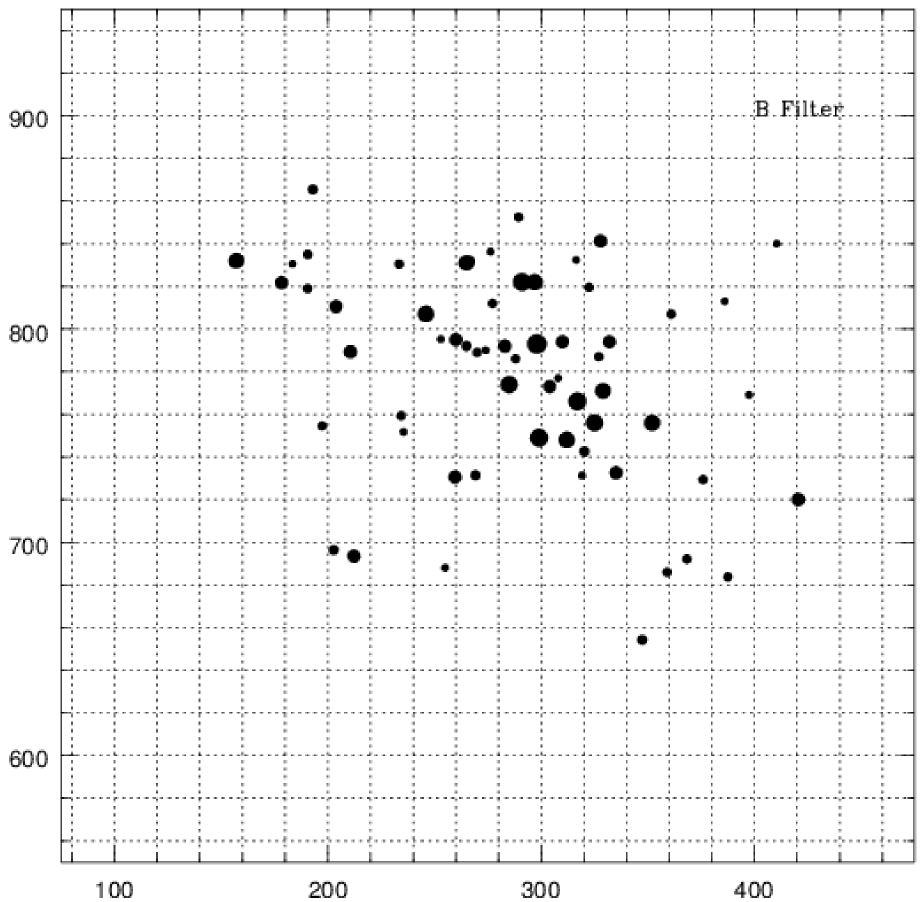


Figure 11.6: This is not the right figure for use in this lab–your TA will give you the correctly scaled version. (Go to: http://astronomy.nmsu.edu/astro/hrlabB.ps)

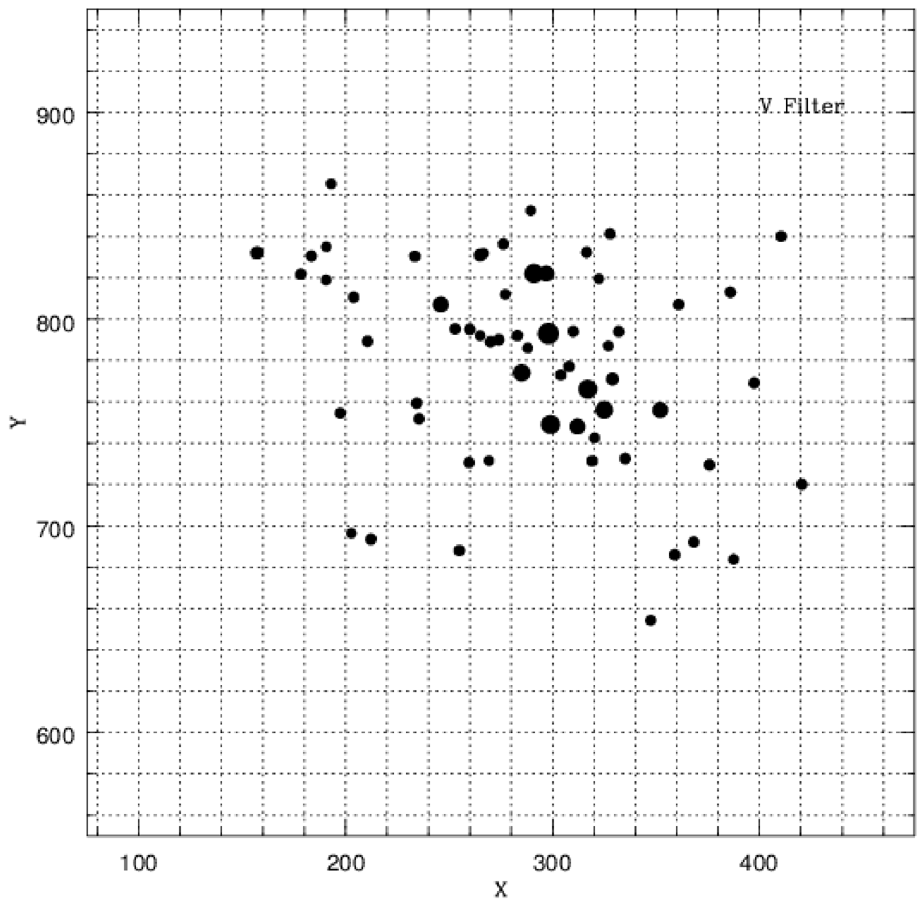


Figure 11.7: This is not the right figure for use in this lab–your TA will give you the correctly scaled version. (Go to: http://astronomy.nmsu.edu/astro/hrlabB.ps)

11.4.1 Procedure

The first task for this lab is to collect your data. What you need to do for this lab is to measure the diameters of ten of the 63 stars on both digitized photographs. At the end of this lab there is a data table that has the final data for 53 of the 63 stars. It is missing the information for ten of the stars (#'s 7, 8, 13, 18, 30, 39, 53, 55, 61, and 63). You must collect the data for these ten stars.

Task #1: First, identify the stars with the missing data on *both* of the digitized photographs (use their X,Y positions to do this). Then measure their diameters of these ten stars on both photographs using the dynameter. Write the V and B diameters into the appropriate spaces within the data table. [Note: You will probably not be able to measure the diameters to the same precision as shown for the other stars in the data table. Those diameters were measured using a computer. Do the best you can—make several measurements of each star and average the results.] (**15 points**)

11.4.2 Converting Diameters to Magnitudes

Obviously, the diameter you measure of a star on a photograph has no obvious link to its actual magnitude. For example, we could blow the photograph up, or shrink it down. The diameters of the stars would change, but the relative change in size between stars of different brightnesses would stay the same. To turn diameters into magnitudes requires us to "calibrate" the two photographs. For example, the brightest star in the Pleiades, "Alcyone" (star #35), has a V magnitude of 2.92, and has a V diameter of 4.4 mm. We have used this star to calibrate our data. Once you have completed measuring the diameters of the stars, you must convert those diameters (in millimeters) into V magnitudes and $(B - V)$ color index. To do so, requires you to use the following two equations:

$$V(\text{mag}) = -2.95\times(\text{V mm}) + 15.9 \text{ (Eq. \# 1)}$$

and

$$(B - V) = -1.0\times(\text{B mm} - \text{V mm}) + 0.1 \text{ (Eq. \#2)}$$

These equations might seem confusing to you because of the negative number in front of the diameters. But if you remember, the brighter the star, the smaller its magnitude. Brighter stars appear bigger, so bigger diameters mean smaller magnitudes! That is why there is a negative sign. Using the example of Alcyone, its V diameter is 4.4 mm and it has a B diameter of 4.7 mm. Putting the V diameter into equation #1 gives: $V\text{ (mag)} = -2.95\times(4.4\text{ mm}) + 15.9 = -13.0 + 15.9 = 2.9$. So, the V magnitude of Alcyone is correct: $V = 2.9$, and we have calibrated the photograph. Its color index can be found using Eq. #2: $(B - V) = -\,1.0\times(4.7 - 4.4) + 0.1 = -1.0\times(0.4) + 0.1 = -0.20$. Alcyone is a B star!

Task #2: Convert all of the B and V diameters into V magnitudes and $(B - V)$ color index, entering them into the proper column in your data table. Use any of the other stars in the table to see how it is done. Make sure all students in your group have complete tables with all of the data entered. **(15 points)**

11.4.3 Constructing a Color-Magnitude Diagram

The collection of the data is now complete. In this lab you are getting exactly the same kind of experience in "reducing data" that real astronomers do. Aren't you glad you didn't have to measure the diameters of all 63 stars? Obtaining and reducing data can be very tedious, tiring, or even boring. But it is an essential part of the scientific process. Because of the possibility of mis-measurement of the star diameters, a real astronomer doing this lab would probably measure all of the star diameters at least three times to insure that they had not made any errors. Today, we will assume you did everything exactly right, but we will provide a check shortly.

Now we want to finally get to the goal of the lab: constructing a Color-Magnitude diagram. In this portion of the lab, we will be plotting the V magnitudes vs. the $(B - V)$ color index. On the following page is a blank grid that has V magnitude on the Y axis, and the $(B - V)$ color index on the X axis. Now we want to plot your data onto this blank Color-Magnitude diagram to closely examine what kind of stars are in the Pleiades.

Task #3: For each star in your table, plot its position where the $(B - V)$ color index is the X coordinate, and the V magnitude is the Y coordinate. Note that some stars will have very similar magnitudes and colors because they are the same types of star. When this happens, simply plot them as close together as possible, making sure they are slightly separated for clarity. All students must complete their own Color-Magnitude diagram. (**15 points**)

Error checking: All of your stars should fit within the boundaries of the Color-Magnitude diagram! If not, go back and re-measure the problem star(s) to see if you have made an error in the B or V diameter or in the calculations.

11.5 Results

If you have done everything correctly, you should now have a Color-Magnitude diagram in which your plotted stars trace out the main sequence for the Pleiades. Use your Color-Magnitude diagram to answer the following questions:

1. Are there more B stars in the Pleiades, or more K stars? (**5 points**)

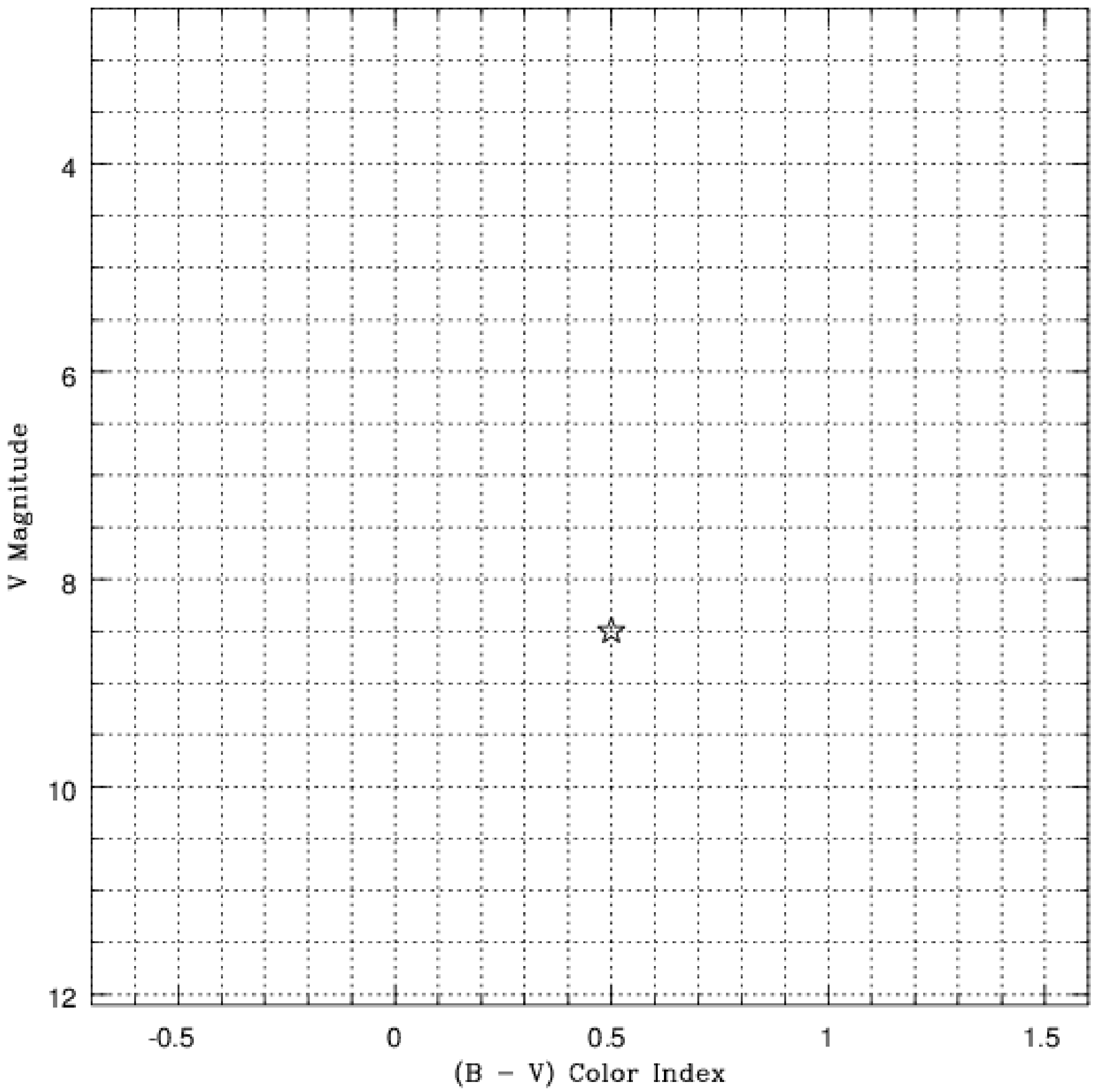


Figure 11.8: The Color-Magnitude Diagram for the Pleiades

2. Given that the Sun is a main sequence G star, draw an “X” to mark the spot where the Sun would be in your Color-Magnitude diagram for the Pleiades (**5 points**)

3. The faintest stars that the human eye can see on a clear, dark night is $V = 6.0$. If the Sun was located in the Pleiades, could you see it with the naked eye? (**5 points**)

4. Are there any red giants or supergiants in the Pleiades? What does this tell you about the age of the Pleiades? (**5 points**)

11.6 Summary (35 points)

Please summarize the important concepts of this lab.

- Describe how an HR diagram is constructed.
- If you have plotted your HR Diagram for the Pleiades correctly, you will notice that the faint, red stars seem to have a spread when compared to the brighter, bluer stars. Why do you think this occurs? How might you change your observing or measuring procedure to fix this problem? [Hint: is it harder or easier to measure big diameters vs. small diameters?]
- Why are HR diagrams important to astronomers?

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

11.7 Possible Quiz Questions

1. What is a magnitude? Which star is brighter, a star with V = -2.0, or one with V = 7.0?
2. In an HR Diagram, what are the two quantities that are plotted?
3. What are the properties of a white dwarf?
4. What are the properties of a red giant?
5. What is a Color Index, and what does it tell you about a star?

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

White dwarfs are 100× less luminous than the Sun, but are hot, and have a negative color index $(B - V) = -0.2$. Given that a factor of 100 = 5 magnitudes, is it possible to plot the positions of white dwarfs on your Color-Magnitude diagram for the Pleiades?

Table 11.2: Data Table

#	X	Y	V(mm)	B(mm)	V(mag)	$(B-V)$
01	157.00	832.00	3.10	2.89	6.76	0.31
02	157.61	832.20	2.49	2.00	8.50	0.59
03	178.33	821.70	2.37	1.70	8.91	0.77
04	183.40	830.51	2.32	1.60	9.06	0.82
05	190.53	818.94	2.24	1.52	9.29	0.82
06	190.62	834.99	2.23	1.52	9.32	0.81
07	192.98	865.44				
08	197.37	754.50				
09	202.78	696.35	2.23	1.46	9.32	0.87
10	203.87	810.57	2.36	1.72	8.94	0.74
11	210.57	789.29	2.32	1.62	9.06	0.80
12	212.22	693.49	2.48	1.97	8.58	0.61
13	233.44	830.40				
14	234.34	759.27	2.35	1.57	8.97	0.88
15	235.50	751.74	2.40	1.85	8.82	0.65
16	246.00	807.00	3.26	3.07	6.28	0.29
17	252.95	795.24	2.75	2.35	7.78	0.50
18	254.95	688.02				
19	259.60	730.54	2.39	1.74	8.85	0.75
20	260.00	795.00	2.35	1.77	8.97	0.68
21	265.00	792.00	2.24	1.48	9.29	0.86
22	265.00	831.00	2.95	2.65	7.20	0.40
23	266.66	831.82	2.20	1.36	9.41	0.94
24	269.27	731.47	2.18	1.33	9.47	0.95
25	270.00	789.00	2.31	1.62	9.09	0.79
26	274.00	790.00	2.32	1.70	9.06	0.72
27	276.28	836.35	2.50	1.98	8.53	0.62
28	277.19	811.96	2.22	1.55	9.35	0.77
29	283.00	792.00	2.35	1.75	8.97	0.70
30	285.00	774.00				
31	288.00	786.00	2.20	1.42	9.41	0.88
32	289.50	852.50	2.18	1.54	9.47	0.74
33	291.00	822.00	4.24	4.46	3.39	−0.12
34	297.00	822.00	3.46	3.38	5.69	0.18
35	298.00	793.00	4.40	4.70	2.92	−0.20
36	299.00	749.00	4.09	4.23	3.83	−0.04
37	304.00	773.00	2.39	1.79	8.85	0.70
38	308.00	777.00	2.31	1.67	9.09	0.74
39	310.00	794.04				
40	312.00	748.00	3.35	3.20	6.02	0.25

Table 11.3: Data Table (cont.)

#	X	Y	V(mm)	B(mm)	V(mag)	$(B-V)$
41	316.46	832.35	2.52	2.01	8.47	0.61
42	317.00	766.00	3.93	4.00	4.31	0.03
43	319.14	731.31	2.38	1.81	8.88	0.67
44	320.29	742.55	2.17	1.46	9.50	0.81
45	322.43	819.50	2.17	1.52	9.50	0.75
46	325.00	756.00	3.62	3.57	5.22	0.15
47	327.00	787.00	2.20	1.47	9.41	0.83
48	327.80	841.25	2.34	1.68	8.99	0.76
49	329.00	771.00	2.87	2.52	7.43	0.45
50	332.00	794.00	2.62	2.14	8.17	0.58
51	335.13	732.56	2.28	1.54	9.17	0.84
52	347.41	654.23	2.15	1.43	9.55	0.82
53	352.00	756.00				
54	359.05	685.95	2.35	1.70	8.97	0.75
55	361.00	807.00				
56	368.31	692.12	2.35	1.69	8.96	0.76
57	375.90	729.41	2.20	1.50	9.41	0.80
58	375.90	729.41	2.36	1.73	8.94	0.73
59	386.00	813.00	2.37	1.72	8.91	0.75
60	387.50	683.69	2.20	1.54	9.41	0.76
61	397.48	769.11				
62	410.49	839.98	2.34	1.62	8.99	0.82
63	420.52	720.04				

Name:________________________________
Date:_________________________________

12 Characterizing Exoplanets

12.1 Introduction

Exoplanets are a hot topic in astronomy right now. As of December 19th, 2024, there were over 5811 known exoplanets with several thousand candidates waiting to be confirmed. These exoplanets and exoplanet systems are of great interest to astronomers as they provide information on planet formation and evolution, as well as the discovery of a variety of types of planets not found in our solar system. A small subset of these planetary systems are of interest for another reason: They may support life. In this lab you will analyze observations of exoplanets to fully characterize their nature. At the end, you will then compare your results with simulated images of these exoplanets to see how well you performed. Note that the capabilities required to intensely study exoplanets have not yet been built and launched into space. But we know enough about optics that we can envision a day when advanced space telescopes, like those needed for the conclusion of today's lab, will be in Earth orbit and will directly image these objects, as well as obtain spectra to search for the chemical signatures of life.

12.2 Types of Exoplanets

As you have learned in class this semester, our solar system has two main types of planets: Terrestrial (rocky) and Jovian (gaseous). Because these were the only planets we knew about, it was hard to envision what other kinds of planets might exist. Thus, when the first exoplanet was discovered, it was a shock for astronomers to find out that this object was a gas giant like Jupiter, but had an orbit that was even smaller than that of Mercury! This lead to a new kind of planet called "Hot Jupiters". In the two decades since the discovery of that first exoplanet, several other new types of planets have been recognized. Currently there are six major classes that we list below. We expect that other types of planets will be discovered as our observational techniques improve.

12.2.1 Gas Giants

Gas giants are planets similar to Jupiter, Saturn, Uranus, and Neptune. They are mostly composed of hydrogen and helium with possible rocky or icy cores. Gas giants have masses greater than 10 Earth masses. Roughly 25 percent of all discovered exoplanets are gas giants.

12.2.2 Hot Jupiters

Hot Jupiters are gas giants that either formed very close to their host star or formed farther out and "migrated" inward. If there are multiple planets orbiting a star, they can interact through their gravity. This means that planets can exchange energy, causing their orbits to expand or to shrink. Astronomers call this process migration, and we believe it happened early in the history of our own solar system. Hot Jupiters are found within 0.05-0.5 AU of their host star (remember that the Earth is at 1 AU!). As such, they are extremely hot (with temperatures as high as 2400 K), and are the most common type of exoplanet found; about 50 percent of all discovered exoplanets are Hot Jupiters. This is due to the fact that the easiest exoplanets to detect are those that are close to their host star and very large. Hot Jupiters are both.

12.2.3 Water Worlds

Water worlds are exoplanets that are completely covered in water. Simulations suggest that these planets actually formed from debris rich in ice further from their host star. As they migrated inward, the water melted and covered the planet in a giant ocean.

12.2.4 Exo-Earths

Exo-Earths are planets just like the Earth. They have a similar mass, radius, and temperature to the Earth, orbiting within the "habitable zone" of their host stars. Only a very small number of Exo-Earth candidates have been discovered as they are the hardest type of planet to discover.

12.2.5 Super-Earths

Super-Earths are potentially rocky planets that have a mass greater than the Earth, but no more than 10 times the mass of the Earth. "Super" only refers to the mass of the planet and has nothing to do with anything else. Therefore, some Super Earths may actually be gas planets similar to (slightly) smaller versions of Uranus or Neptune.

12.2.6 Chthonian Planets

"Chthonian" is from the Greek meaning "of the Earth." Chthonian Planets are exoplanets that used to be gas giants but migrated so close to their host star that their atmosphere was stripped away leaving only a rocky core. Due to their similarities, some Super Earths may actually be Chthonian Planets.

12.3 Detection Methods

There are several methods used to detect exoplanets. The most useful ones are listed below.

12.3.1 Transit Method/Light Curves

The transit method attempts to detect the "eclipse" of a star by a planet that is orbiting it. Because planets are tiny compared to their host stars, these eclipses are very small, requiring extremely precise measurements. This is best done from space, where observations can be made continuously, as there is no night or day, or clouds to get in the way. This is the detection method used by the *Kepler* Space Telescope. *Kepler* stared at a particular patch of sky and observed over a hundred thousand stars continuously for more than four years.

It measured the amount light coming from each star. It did this over and over, making a new measurement every 30 minutes. Why? If we were looking back at the Sun and wanted to detect the Earth, we would only see one transit per year! Thus, you have to continuously stare at the star to insure you do not miss this event (as you need at least three of these events to determine that the exoplanet is real, and to measure its orbital period). The end result is something called a "light curve", a graph of the brightness of a star over time. The entire process is diagrammed in Figure 12.9. We will be exclusively using this method in lab today.

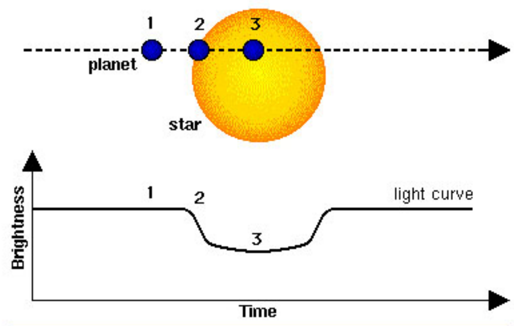


Figure 12.9: The diagram of an exoplanet transit. The planet, small, dark circle, crosses in front of the star as seen from Earth. In the process, it blocks out some light. The light curve, shown on the bottom, is a plot of brightness versus time, and shows that the star brightness is steady until the exoplanet starts to cover up some of the visible surface of the star. As it does so, the star dims. It eventually returns back to its normal brightness only to await the next transit.

In Figure 12.9, there is a dip in the light curve, signifying that an object passed between the star and our line of sight. If, however, *Kepler* continues to observe that star and sees the same sized dip in the light curve on a periodic basis, then it has probably detected an exoplanet (we say "probably" because a few other conditions must be met for it to be a confirmed exoplanet). The amount of star light removed by the planet is very small, as all planets are much, much smaller than their host stars (for example, the radius of Jupiter is 11 times that of the Earth, but it is only 10% the radius of the Sun, *or 1% of the area = how much the light dims*). Therefore, it is much easier to detect planets that are larger because they block more of the light from the star. It is also easier to detect planets that are close to their host star because they orbit quickly so *Kepler* could observe several dips in the light curve each year.

12.3.2 Direct Detection

Direct detection is exactly what it sounds like. This is the method of imaging (taking a picture) of the planets around another star. But we cannot simply point a telescope at a star and take a picture because the star is anywhere from 100 million (10^8) to 100 billion (10^{11})

times brighter than its exoplanets. In order to combat the overwhelming brightness of a star, astronomers use what is called a "coronagraph" to block the light from the star in order to see the planets around it. You may have already seen images made with a coronagraph to see the "corona" of the Sun in the Sun lab.

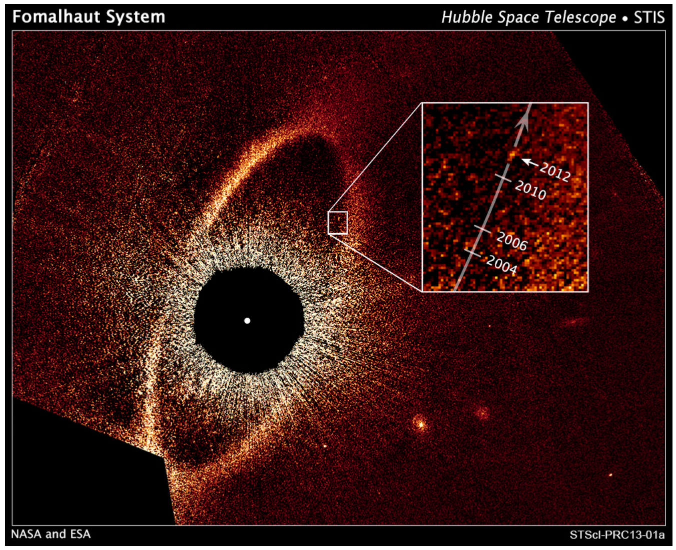


Figure 12.10: A coronagraphic image of an exoplanet orbiting the star Fomalhaut (inside the box, with the arrow labeled "2012"). This image was obtained with the Hubble Space Telescope, and the star's light has been blocked-out using a small metal disk. Fomalhaut is also surrounded by a dusty disk of material—the broad band of light that makes a complete circle around the star. This band of dusty material is about the same size as the Kuiper belt in our solar system. The planet, "Fomalhaut B", is estimated to take 1,700 years to orbit once around the star. Thus, using Kepler's third law ($P^2 \propto a^3$), it is roughly about 140 AU from Fomalhaut (remember that Pluto orbits at 39.5 AU from the Sun).

So if astronomers can block the light from the Sun to see its corona, they should be able to block the light from distant stars to see the exoplanets right? While this is true, directly seeing exoplanets is difficult. There are two problems: the exoplanet only shines by reflected light, and it is located very, very close to its host star. Thus, it takes highly specialized techniques to directly image exoplanets. However, for some of the closest stars this can be done. An example of direct exoplanet detection is shown in Figure 12.10. A new generation of space-based telescopes that will allow us to do this for many more stars is planned. Eventually, we should be able to take both spectra (to determine their composition) and direct images of the planets themselves. We will pretend that we can obtain good images of exoplanets later in lab today.

12.3.3 Radial Velocity (Stellar Wobble)

The radial velocity or "stellar wobble" method involves measuring the Doppler shift of the light from a particular star and seeing if the lines in its spectrum oscillate periodically between a red and blue shift. As a planet orbits its star, the planet pulls on the star gravitationally just as the star pulls on the planet. Thus, as the planet goes around and around, it slightly tugs on the star and makes it wobble, causing a back and forth shift in its radial velocity, the motion we see towards and away from us. Therefore, if astronomers see a star wobbling back and forth on a repeating, periodic timescale, then the star has at least one planet orbiting around it. The size of the wobble allows astronomers to calculate the mass of the exoplanet.

12.4 Characterizing Exoplanets from Transit Light Curves

Quite a bit of information about an exoplanet can be gleaned from its transit light curve. Figure **??** shows how a little bit of math (from Kepler's laws), and a few measurements, can tell us much about a transiting exoplanet.

The equations shown in Figure **??** are complicated by the fact that exoplanets do not orbit their host stars in perfect circles, and that the transit is never exactly centered. Today we are going to only study planets that have circular orbits, and whose orbital plane is edge-on. Thus, all of the terms with "cos$i$" ("i" is the inclination of the orbit to our sight line, and $i = 0°$ for edge on), cosδ or sinδ (δ is the transit latitude, here $\delta = 90°$), and "e" (which is the eccentricity, the same orbital parameter you have heard about in class for our solar system planets, or in the orbit of Mercury lab, for circular orbits e= 1.0) are equal to "1" or "0".

First, let's remember Kepler's third law $P^2 \propto a^3$, where P is the orbital period, and a is the semi-major axis. For Earth, we have P = 1 yr, a = 1 AU. By taking ratios, you can figure out the orbital periods and semi-major axes of other planets in *our* solar system. Here we cannot do that, and we need to use Isaac Newton's reformulation of Kepler's third law:

$$P^2 = \frac{4\pi^2 a^3}{G(M_{star} + M_{planet})} \tag{1}$$

"G" in this equation is the gravitational constant (G = 6.67 x 10^{-11} Newton-m^2/kg^2), and $\pi = 3.14$.

We also have to estimate the size of the planet. As detailed in Fig. **??**, the depth of the "eclipse" gives us the ratio of the radius of the planet to that of the star:

$$\frac{\Delta F}{F} = \left(\frac{R_{planet}}{R_{star}}\right)^2 \tag{2}$$

Now we have everything we need to use transits to characterize exoplanets. We will have to re-arrange equations 1 and 2 so as to extract unknown parameters where the other variables are known from measurements.

12.5 Deriving Parameters from Transit Light Curves

The orbital period of the exoplanet is the easiest parameter to measure. In Figure 12.11 is the light curve of "Kepler 1b", the first of the exoplanets examined by the *Kepler* mission. Kepler 1b is a Hot Jupiter, so it has a deep transit. You can see from the figure that transits recur every 2.5 days. That is the orbital period of the planet. It is very easy to figure out orbital periods, so we will not be doing that in this lab today.

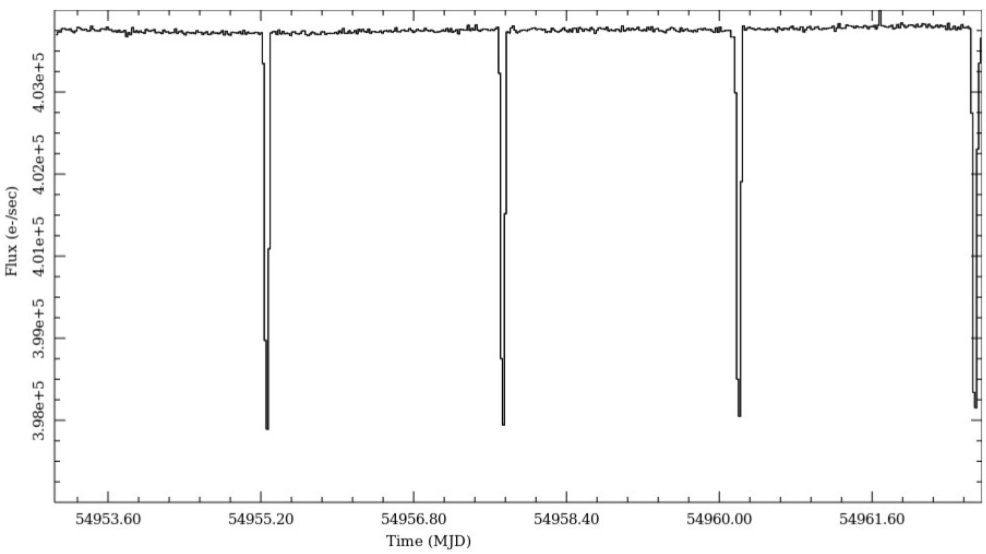


Figure 12.11: The light curve of Kepler 1b as measured by the *Kepler* satellite. The numbers on the y-axis are the total counts (how much light was measured), while the x-axis is "modified Julian days". This is a system that simply makes it easy to figure out periods of astronomical events since it is a number that increases by 1 every day (instead of figuring out how many days there were between June 6^{th} and November 3^{rd}). Thus, to get an orbital period you just subtract the MJD of one event from the MJD of the next event.

In the following eight figures are the light curves of eight different transiting exoplanets. Today you will be using these light curves to determine the properties of transiting exoplanets. To help you through this complicated process, the data for exoplanet #8 will be worked out at each step below. You will do the same process for one of the other seven transiting exoplanets. Your TA might assign one to you, or you will be left to choose one. Towards the end of today's exercise your group will classify both of these exoplanets. Each panel lists the orbital period of the exoplanets ("xxx day orbit"), ranging from 3.89 days for exoplanet #3, to 3.48 years for exoplanet #2. You should be able to guess what that means already: one is close to its host star, the other far away. The other information contained in these figures is a measurement of "t", the total time of the transit ("eclipse takes xxx hours"). When working with the equations below, all time units must be in seconds! Remember, 3600 seconds per hour, 24 hours per day, 365 days per year (there are 3.15×10^7 seconds per year).

Exercise #1:

1. The first quantity we need to calculate is the size of the planet with respect to the host star. How do we do that? Go back to Figure **??**. We need to measure "ΔF/F". The data points in the exoplanet light curves have been fit with a transit model (the solid line fit to the data points) to make it easy to measure the *minimum*. For both of the transits, take a ruler and determine the value on the y axis by drawing a line across the model fit to the light curve minimum. Estimate this number as precisely as possible, then subtract this number from 1, and you get ΔF/F. (**2 points**)

ΔF/F for transit # __________ = __________________________

ΔF/F for transit #8 = 0.00153

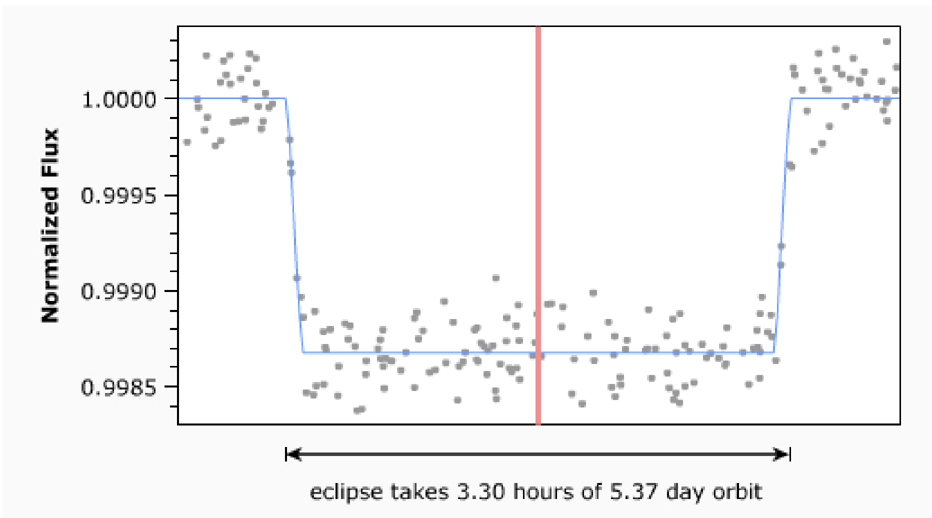


Figure 12.12: Transiting exoplanet #1. The vertical line in the center of the plot simply identifies the center of the eclipse.

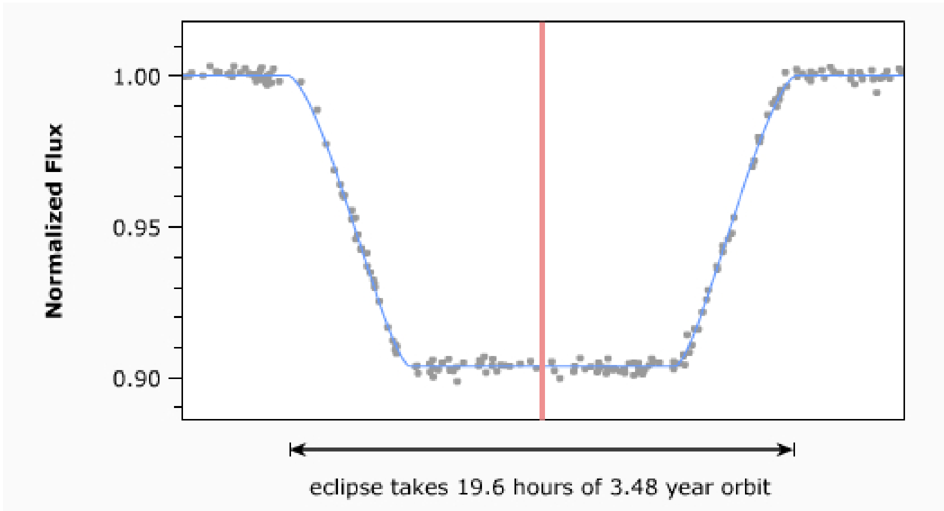


Figure 12.13: Transiting exoplanet #2.

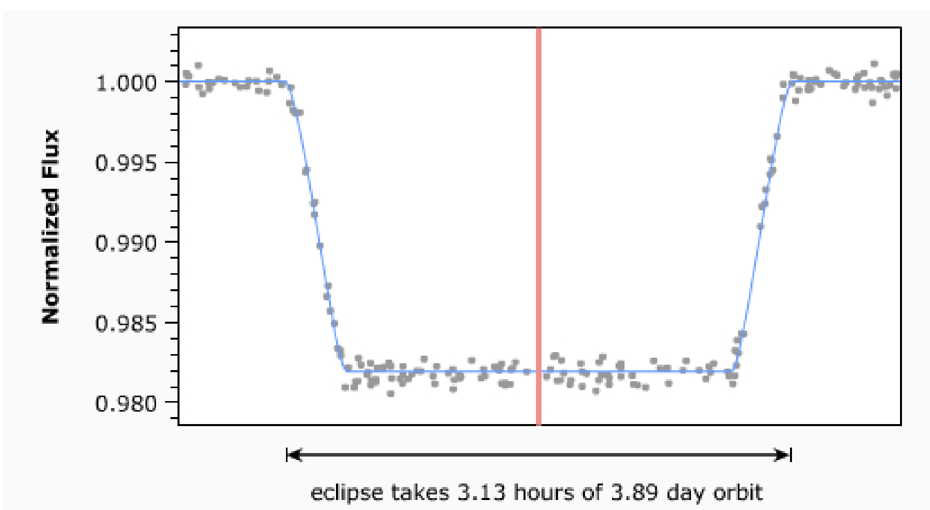


Figure 12.14: Transiting exoplanet #3.

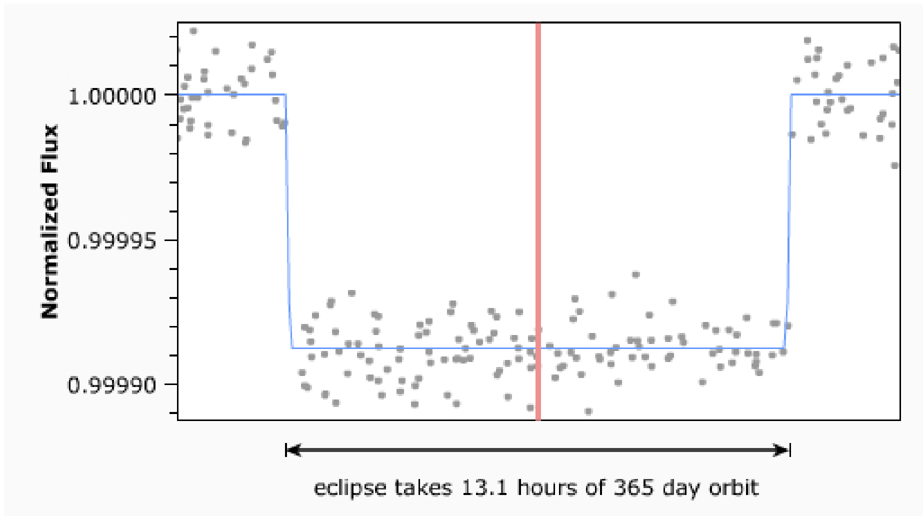


Figure 12.15: Transiting exoplanet #4.

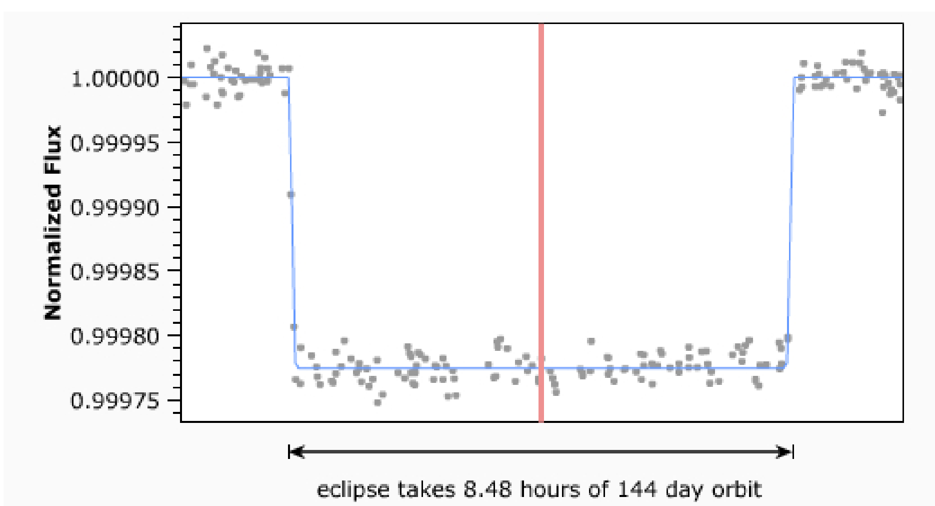


Figure 12.16: Transiting exoplanet #5.

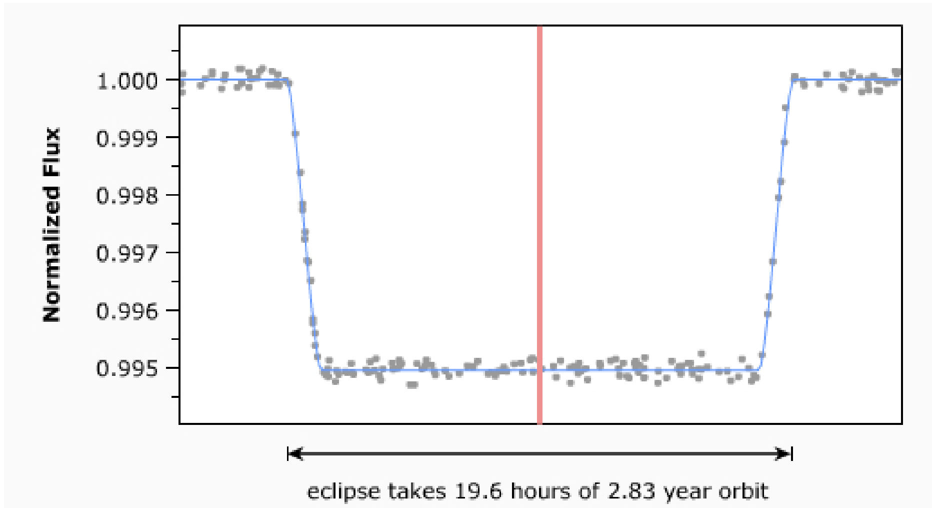


Figure 12.17: Transiting exoplanet #6.

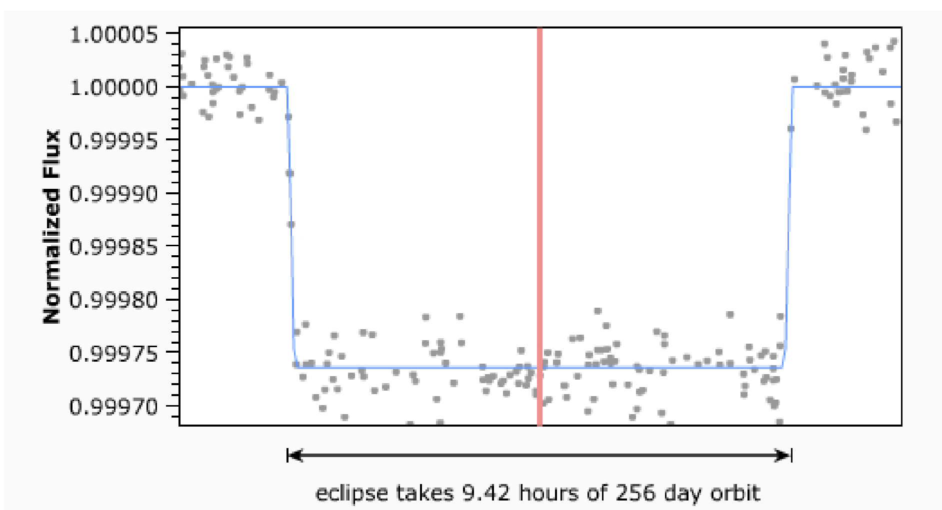


Figure 12.18: Transiting exoplanet #7.

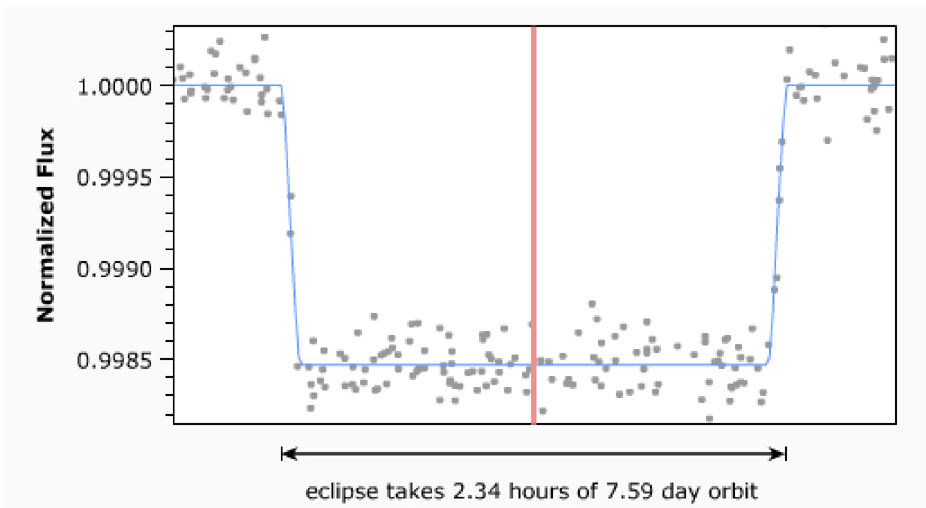


Figure 12.19: Transiting exoplanet #8.

Going back to equation #2, we have:

$$\frac{\Delta F}{F} = \left(\frac{R_{planet}}{R_{star}}\right)^2 \quad or \quad R_{planet} = \left(\frac{\Delta F}{F}\right)^{1/2} (\times\ R_{star})$$

2. Taking the square roots of the ΔF/F from above, fill in the following blanks (**4 points**):

   R_{planet} for transit # __________ = _________________________($\times\ R_{star}$)

   R_{planet} for transit ___#8___ = __________0.0391__________($\times\ R_{star}$)

You just calculated the relative sizes of the planets to their host stars. To turn these into real numbers, we have to know the sizes of the host stars. Astronomers can figure out the masses, radii, temperatures and luminosities of stars by combining several techniques (photometry, parallax, spectroscopy, and interferometry). Note that stars can have dramatically different values for their masses, radii, temperatures and luminosities, and these directly effect the parameters derived for their exoplanets. The data for the eight exoplanet host stars are listed in Table 12.4. The values for our Sun are $M_\odot = 2 \times 10^{30}$ kg, $R_\odot = 7 \times 10^8$ m, $L_\odot = 4 \times 10^{26}$ Watts.

Table 12.4: Exoplanet Host Star Data

Object	**Mass** (kg)	**Radius** (meters)	**Temperature** (K)	**Luminosity** (Watts)
#1	2.0×10^{30}	7.00×10^{8}	5800	4.0×10^{26}
#2	1.3×10^{30}	4.97×10^{8}	4430	2.8×10^{25}
#3	2.2×10^{30}	7.56×10^{8}	6160	1.2×10^{27}
#4	2.0×10^{30}	7.00×10^{8}	5800	4.0×10^{26}
#5	1.6×10^{30}	5.88×10^{8}	5050	2.4×10^{26}
#6	2.0×10^{30}	7.00×10^{8}	5800	4.0×10^{26}
#7	1.4×10^{30}	5.25×10^{8}	4640	4.8×10^{25}
#8	1.0×10^{30}	3.99×10^{8}	3760	4.0×10^{24}

3. Now that you calculated the radius of the exoplanet with respect to the host star radius, use the data in Table 12.4 to convert the radii of your planet into meters, and put this value in the correct row and column in Table 12.5. (**5 points**)

4. Astronomer Judy, and her graduate student Bob, used the spectrograph on the Keck telescope in Hawaii to measure the masses of your planets using the radial velocity technique mentioned above. So we have entered their values for the masses for all of the exoplanets in Table 12.5. You need to calculate the density of your exoplanet and enter it in the correct places in Table 12.5. Remember that density = mass/volume,

Table 12.5: Exoplanet Data

Object	**Radius** (m)	**Semi-major axis** (m)	**Mass** (kg)	**Density** (kg/m^3)	**Temperature** (K)
#1			1.9×10^{26}		
#2			1.9×10^{28}		
#3			5.7×10^{27}		
#4			6.0×10^{24}		
#5			1.5×10^{25}		
#6			8.0×10^{26}		
#7			4.0×10^{24}		
#8	1.6×10^{7}	9.0×10^{9}	5.5×10^{25}	3205	555

and the volume of all of the planets is $V = 4\pi R^3/3$, as we know that they all must be spherical. (**5 points**)

5. By calculating the density, you already know something about your planets. Remember that the density of Jupiter is 1326 kg/m^3 and the density of the Earth is 5514 kg/m^3. If you did the Density lab this semester, we used the units of gm/cm^3, where water has a density of 1.00 gm/cm^3. This is the "cgs" system of units. To get from kg/m^3 to gm/cm^3, you simply divide by 1000. Describe how the densities of your two exoplanets compare with the Earth and/or Jupiter. (**5 points**)

The next parameter we want to calculate is the semi-major axis "a". While we now know the size and densities of our planets, we do not know how hot or cold they are. We need to figure out how far away they are from their host stars. To do this we re-arrange equation #1, and we get this:

$$a = \left(\frac{P^2 G(M_{star} + M_{planet})}{4\pi^2} \right)^{1/3} = (1.69 \times 10^{-12} P^2 M_{star})^{1/3}$$

6. You must use seconds for P, and kg for the mass of the star (note: you can ignore the mass of the planet since it will be very small compared to the star). We have simplified the equation by bundling G and $4\pi^2$ into a single constant. Note that you have to take the cube root of the quantity inside the parentheses. We write the cube root as an exponent of "1/3". Ask your TA for help on this step. Fill in the column for semi-major axis in Table 12.5 for your exoplanet. (**5 points**)

12.6 The Habitable Zone

The habitable zone is the region around a star in which the conditions are just right for a planet to have liquid water on its surface. Here on Earth, all life must have access to liquid water to survive. Therefore, a planet is considered "habitable" if it has liquid water. This zone is also colloquially know as the "Goldilocks Zone".

To figure out the temperature of a planet is actually harder than you might think. We know how much energy the exoplanet host stars emit, as that is what we call their luminosities. We also know how far away your exoplanets are from this energy source (the semi-major axis). The formula to estimate the "equilibrium temperature" of an exoplanet with a semi-major axis of a around a host star with known parameters is:

$$T_{planet} = T_{star}(1.0 - A)^{1/4}\left(\frac{R_{star}}{2a}\right)^{1/2} \tag{3}$$

The "A" in this equation is the "Albedo," how much of the energy intercepted by a planet is reflected back into space. Equation #3 is not too hard to derive, but we do not have enough time to explain how it arises. You can ask your professor, or search Wikipedia using the term "Planetary equilibrium temperature" to find out where this comes from. The big problem with using this equation is that different atmospheres create different effects. For example, Venus reflects 67% of the visible light from the Sun, yet is very hot. The Earth reflects 39% of the visible light from the Sun and has a comfortable climate. It is how the atmosphere "traps heat" that helps determine the surface temperature. Alternatively, a planet might not even have an atmosphere and could be bright or dark with no heat trapping (for example, the Albedo of the moon is 0.11, as dark as asphalt, and the surface is boiling hot during the day, and extremely cold at night).

Let's demonstrate the problem using the Earth. If we use the value of A = 0.39 for Earth, equation #3 would predict a temperature of T_{Earth} = 247 K. But the mean temperature on the Earth is actually T_{Earth} = 277 K. Thus, the atmosphere on Earth keeps it warmer than the equilibrium temperature. This is true for just about any planet with a significant atmosphere. To account for this effect, let's go backwards and solve for "A". With $R_{\odot} = 7.0 \times 10^8$ m, $a = 1.50 \times 10^{11}$ m, T_{Earth} = 277 K, and $T_{\odot}$ = 5800 K, we find that A = 0.05. Thus, the Earth's atmosphere makes it seem like we absorb 95% of the energy from the Sun. We will presume this is true for all of our planets.

If we assume A = 0.05, equation #3 simplifies to:

$$T_{planet} = 0.70\left(\frac{R_{star}}{a}\right)^{1/2} T_{star} \tag{4}$$

[To understand what we did here, note that (1.0 − A) = 0.95. The fourth root of 0.95 = $0.95^{1/4}$ = 0.99 (remember the fourth root is two successive square roots: $\sqrt{0.95} = 0.95^{1/2}$ = 0.97, and $0.97^{1/2}$ = 0.99). We then divided 0.99 by $\sqrt{2}$ (= 1.41) to have a single constant out front.]

7. Calculate the temperature of your exoplanet using equation #4 and enter it into Table 12.5. (**5 points**)

As we said, the habitable zone is the region around a star of a particular luminosity where water might exist in a liquid form somewhere on a planet orbiting that star. The Earth (a = 1 AU) sits in the habitable zone for the Sun, while Venus is too close to the Sun (a = 0.67 AU) to be inside the habitable zone, while Mars (a = 1.52 AU) is near the outer edge. As we just demonstrated, the atmosphere of a planet can radically change the location of the habitable zone. Mars has a very thin atmosphere, so it is very cold there and all of its water is frozen. If Mars had the thick atmosphere of Venus, it would probably have abundant liquid water on its surface. As we noted, the mean temperature of Earth is 277 K, but the polar regions have average temperatures well below freezing (32°F = 273 K) with an average annual temperature at the North pole of 263 K, and 228 K at the South pole. The equatorial regions of Earth meanwhile have average temperatures of 300 K. So for just about every planet there will be wide ranges in surface temperature, and liquid water could exist somewhere on that planet.

8. Given that your temperature estimates are not very precise, we will consider your planet to be in the habitable zone if its temperature is between 200K and 350 K. Is either of your planets in the habitable zone? (**4 points)**

12.7 Classifying Your Exoplanets

At the beginning of today's lab we described the several types of exoplanet classes that currently exist. We now want you to classify your exoplanet into one of these types. To help you decide, in Table 12.6 we list the parameters of the planets in our solar system. After you have classified them, you will ask your TA to see "images" of your exoplanets to check to see how well your classifications turned out.

9. Compare the radii, the semi-major axes, the masses, densities and temperatures you found for your two exoplanets to the values found in our solar system. For example, if the radius of one of your exoplanets was 8×10^7, and its mass was 2.5×10^{27} it is similar in "size" to Jupiter. But it could have a higher or lower density, depending on composition, and it might be hotter than Mercury, or colder than Mars. Fully describe your two exoplanets. (**10 points**)

Table 12.6: Solar System Data

Object	**Radius** (m)	**Semi-major axis** (m)	**Mass** (kg)	**Density** (kg/m^3)	**Temperature** (K)
Mercury	2.44×10^6	5.79×10^{10}	3.3×10^{23}	5427	445
Venus	6.05×10^6	1.08×10^{11}	4.9×10^{24}	5243	737
Earth	6.37×10^6	1.49×10^{11}	5.9×10^{24}	5514	277
Mars	3.39×10^6	2.28×10^{11}	6.4×10^{23}	3933	210
Jupiter	6.99×10^7	7.78×10^{11}	1.9×10^{27}	1326	122
Saturn	6.03×10^7	1.43×10^{12}	5.7×10^{26}	687	90
Uranus	2.54×10^7	2.87×10^{12}	8.7×10^{25}	1270	63
Neptune	2.46×10^7	4.50×10^{12}	1.0×10^{26}	1638	50
Pluto	1.18×10^6	5.87×10^{12}	1.3×10^{22}	2030	43

As Table 12.6 shows you, there are two main kinds of planets in our solar system: the rocky Terrestrial planets with relatively thin atmospheres, and the Jovian planets, which are gas giants. Planets with high densities (> 3000 kg/m^3) are probably like the Terrestrial planets. Planets with low densities (< 3000 kg/m^3) are probably mostly gaseous or have large amounts of water (Pluto has a large fraction of its mass in water ice).

10. Given your discussion from the previous question, and the discussion of the types of exoplanets in the introduction, classify your two exoplanets into one of the following categories: 1) Gas giant, 2) Hot Jupiter, 3) Water world, 4) Exo-Earth, 5) Super-Earth, or 6) Chthonian. What do you expect them to look like? (**10 points**)

11. Your TA has images for all eight exoplanets of this lab obtained from NASA's "Exoplanet Imager" mission that was successfully launched in 2040. Were your predictions correct? Yes/no. If no, what went wrong? [The TA also has the data for all of the exoplanets to help track down any errors.] (**10 points**)

Name:______________________________
Date:_______________________________

12.8 Take Home Exercise (35 points total)

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

- Discuss the different types of exoplanets and their characteristics.
- What are the measurements required for you to determine the most important parameters of an exoplanet?
- What requirement for an exoplanet gives it the possibility of harboring life?

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

12.9 Possible Quiz Questions

1. What are some of the different types of exoplanets?
2. What are some different exoplanet detection methods?
3. What is the habitable zone?

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

Your TA has the data for all of the exoplanets for today's lab. With that data, go back and answer questions #8 and #9 for all of the exoplanets.

Acknowledgement: This lab was made possible using the Extrasolar Planets Module of the Nebraska Astronomy Applet Project.

Name:______________________________
Date:_______________________________

13 Appendix 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: ____

____

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

____

____

____

Campus Observatory Observation Sheet

Your Name: ____________________ T.A.: ____________________

Date & Time: __________________ Telescope: ______________

Type of Object: ________________ Object Name: __________

Object Description: ______________________________________

____

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

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