DEPARTMENT OF
ASTROPHYSICAL AND PLANETARY SCIENCES

ASTR 1010 Laboratory

Introductory Astronomy I

Fall 2019

University of Colorado Boulder

LECTURE

Class Time: Mon. Wed. Fri. 9:00 – 9:50 am
Location: Duane G1B20

Instructor: Dr. Doug Duncan (aka D^3 or Dr. Doug)
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LABORATORY

Section Number:
Lab Time:
Lab Location: ***Sommers-Bausch Observatory Room S-175***
Lab Instructor/TA:
Office Location:
Office Hours:
E-mail:
Telephone:

NIGHT OBSERVING SESSIONS

Dates and Times: Posted on class website

Front Cover: Comet Hale-Bopp over the Flatirons courtesy Niescja Turner and Carter Emmart
Back Cover: CCD Mosaic of the Full Moon contributed by Keith Gleason

TABLE OF CONTENTS

Clear skies are required for this exercise - Or for a portion of the exercise

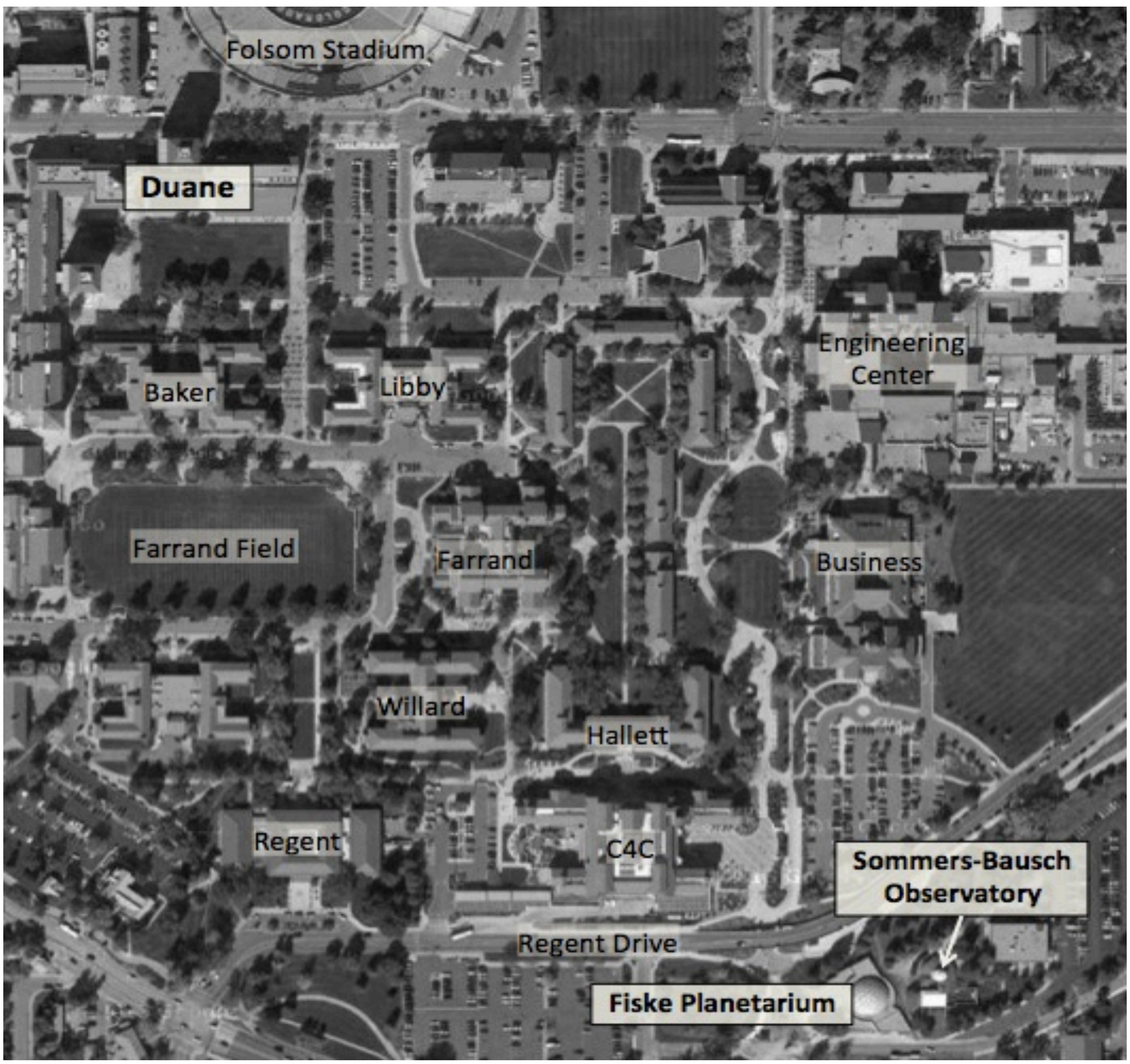
GENERAL INFORMATION

You *must* enroll for *both* the lecture section *and* a laboratory section.

Your **lecture** section will usually be held in the classroom in Duane Physics & Astrophysics Building (just south of Folsom Stadium). An occasional lecture may be held instead at the Fiske Planetarium (at the intersection of Regent Drive and Kittridge Loop; see map below).

Your **laboratory** section will meet once per week during the daytime in Room S175 at Sommers-Bausch Observatory (just east of the Fiske Planetarium). Follow the walkway around the south side of Fiske and up the hill to the Observatory.

You will also have **night time observing sessions** using the Sommers-Bausch Observatory telescopes to view and study the constellations, the moon, planets, stars, and other celestial objects.



MATERIALS

The following materials are needed:

- **ASTR 1010 Astronomy Lab Manual** (*this booklet*), available from the CU Bookstore. Replacement (or print-your-own) copies are available in PDF format downloadable from the SBO website. You *must* have your own paper copy of the lab manual.

  https://www.colorado.edu/sbo/aps-courses

- **Calculator**. All students should have access to a scientific calculator that can perform scientific notation, exponentials, and trig functions (sines, cosines, etc.).

- **A 3-ring binder** to hold this lab manual, your lab notes, and lab write-ups.

THE LABORATORY SECTIONS

Your laboratory session will meet for 1 hour and 45 minutes in the daytime once each week in the Sommers-Bausch Observatory (SBO), Classroom S175. Each lab section will be run by a lab Teaching Assistant (TA) who will also grade your lab exercises and assign you scores for the work you hand in with the assistance of an undergraduate Learning Assistant (LA). Your lab TA will give you organizational details and information about grading at the first lab session.

The lab exercises do not exactly follow the lectures or the textbook. The emphasis of most of these labs is on *how* we know what we know; thus we spend more time making and interpreting observations. Modern astronomers, in practice, spend almost no time at the eyepiece of a telescope. They work with photographs, satellite data, computer images, or computer simulations. In our laboratory we will explore both the traditional and more modern techniques.

You are expected to attend all lab sessions. Most lab exercises can *only* be done using the equipment and facilities in the SBO classroom. Therefore, if you do not attend the daytime lab sessions, you *cannot* complete those experiments and cannot get credit. Most observational exercises can *only* be done at night using the Observatory telescopes. If you do not attend the nighttime sessions, you *cannot* complete these either.

While your final grade in ASTR1010 is based on both lab (25%) and lecture (75%) components, you cannot receive a passing grade in the class as a whole without passing the lab portion.

NIGHTTIME OBSERVING

You are expected to attend nighttime observing labs. Due to the availability of Saturn this semester, many of these nights are in the first month of the semester. Plan on attending at least one of these. Prof. Duncan and your Lab TA will keep you appraised of upcoming night lab opportunities. The telescopes are not in a heated area, so dress warmly for the night observing sessions later in the semester!

If you have a job or other commitments that conflict with the nighttime sessions, it is *your* responsibility to make arrangements with your instructor to attend at different times.

THE LABORATORY WRITE-UPS

You are expected to turn in lab assignments of *collegiate* quality. This means that they must be neat and easy to read, well organized, and demonstrating a mastery of the English language (grammar and spelling), as well as mastery of the subject matter. For most labs, you will turn in your lab report by simply removing the appropriate pages from this manual and turning in your answers at the end of the lab period.

HONOR CODE

The University of Colorado Honor Code will be strictly enforced. Plagiarism (including "cut-and-paste" electronic plagiarism) *will not be tolerated* and can result in academic and/or non-academic sanctions. Specifically, we point out the following guideline regarding your laboratory assignments:

All work turned in *must* be your own. You should understand all work that you write on your paper. We encourage you to work in groups if it is helpful, but you *must not copy* the work of someone else. We encourage you to consult friends for help in understanding problems. However, if you copy answers blindly, it will be considered a breach of the Honor Code. *Work together, write separately.*

SOMMERS-BAUSCH OBSERVATORY

Sommers-Bausch Observatory (SBO), on the University of Colorado campus, is operated by the Department of Astrophysical and Planetary Sciences (APS). SBO provides hands-on observational experience for CU undergraduate students, and research opportunities for University of Colorado astronomy graduate students and faculty. ASTR1010 students will utilize a pair of state-of-the-art 20-inch Cassegrain reflectors as well as some smaller, portable telescopes.

In its teaching role, the Observatory is used by approximately 1500 undergraduate students each year to view celestial objects that might otherwise only be seen on the pages of a textbook or discussed in classroom lectures. All major astronomical telescope control systems use a PC-Windows platform that incorporates planetarium-style "click-and-go" pointing. Objects are selected from an extensive catalogue of double stars, star clusters, nebulae, and galaxies. Both 20-inch telescopes are equipped with research-grade CCD cameras which enable students to image celestial objects for easy digital analysis.

In addition to the standard laboratory room, the Observatory has a computer lab that includes a server system running a Unix/Linux environment. This system provides computing power and internet access for all introductory astronomy students. It was originally made possible through a grant from Dr. Dick McCray of the APS department.

The 10.5-inch aperture **heliostat** is equipped for viewing sunspots, measuring the solar rotation, implementing solar photography, and studying the solar spectrum. A unique optical system called SCRIBES permits simultaneous observations of the photosphere (using white light) and the solar chromosphere (using red light from hydrogen atoms, and ultraviolet light from calcium atoms which absorb and emit light within the upper solar atmosphere).

The **24-inch telescope** is used primarily for upper-division observational astronomy (ASTR 3510/3520), graduate student training, and research projects not feasible with larger telescopes due to time constraints or scheduling limitations. In the fall of 1999, the telescope was upgraded from to a modern DFM computerized telescope control system, and integrated with planetarium-style control software for "click-and-go" pointing. All three major SBO telescopes now use nearly identical controls and software, simplifying user training and increasing observer productivity and proficiency.

Easy-to-operate, large-format SBIG ST-8 and ST1001E CCD cameras are used for graduate and advanced undergraduate work on the 24-inch telescope. These recent improvements and additions have all been made possible by the funding provided by the student laboratory fees.

Open Houses for free public viewing through the 20-inch deck telescopes are held every Friday evening that school is in session. Students are encouraged to attend. Call 303-492-5002 for starting times; call 303-492-6732 for general astronomical information.

See our website located at https://www.colorado.edu/sbo/ for additional information about the Sommers-Bausch Observatory, including schedules, information on how to contact your lab instructor, and examples of images taken by students in the introductory astronomy classes.

FISKE PLANETARIUM

The Fiske Planetarium and Science Center is used as a teaching facility for classes in astronomy, planetary science, and other courses that can take advantage of this unique audiovisual environment. The star theater seats 210 under a 62-foot dome that serves as a projection screen, making it the largest planetarium between Chicago and California. In August 2013, Fiske underwent a major renovation and now houses a Megastar star projector and has the ability to project stunning 8K HD video across the entire dome.

Astronomy programs designed to entertain and to inform are presented to the public on Fridays and Saturdays, and to schoolchildren on weekdays. Laser-light shows rock the theater late Friday nights as well. Following the Friday evening star show presentations, visitors are invited next door to view the celestial bodies at Sommers-Bausch Observatory, weather permitting.

The Planetarium provides students with employment opportunities to assist with show production and presentation, and in the daily operation of the facility.

Fiske is located west of the CU Events Center on Regent Drive on the Boulder campus of the University of Colorado. For recorded program information call 303-492-5001; to reach the business office call 303-492-5002.

You can also check out the upcoming schedules and events on the Fiske website at:

https://www.colorado.edu/fiske/

UNITS AND CONVERSIONS

You are probably familiar with the fundamental units of length, mass, and time in the English System: the yard (yd), the pound (lb), and the second (s). The other common units of this measurement system are typically strange multiples of these fundamental units such as the ton (2000 lbs), the mile (1760 yd), the inch (1/36 yd) and the ounce (1/16 lb). Most of these units arose from accidental conventions, and so have few fundamental relationships.

Outside of the United States, most of the world uses the more sensible **metric system** (the SI, *Systeme International d'Unites*, internationally agreed upon system of units) with the following fundamental units:

- The **meter** (m) for length.
- The **kilogram** (kg) for mass. (Note: kilogram, not gram, is the fundamental unit.)
- The **second** (s) for time.

Since the primary units are the **m**eter, **k**ilogram, and **s**econd, this is sometimes called the **mks system**. (Less commonly, some people use another metric system based on the centimeter, gram, and second as its fundamental units, called the **cgs** system.)

All of the unit relationships in the metric system are based on multiples of 10, so it is very easy to multiply and divide. This system uses prefixes to make multiples of the units. All of the prefixes represent powers of 10. The table below provides prefixes used in the metric system, along with their abbreviations and values.

Metric Prefixes

Prefix	Abbre-viation	Value
deci-	d	10^{-1}
centi-	c	10^{-2}
milli-	m	10^{-3}
micro-	m	10^{-6}
nano-	n	10^{-9}
pico-	p	10^{-12}
femto-	f	10^{-15}
atto-	a	10^{-18}

Prefix	Abbre-viation	Value
decka-	da	10^{1}
hecto-	h	10^{2}
kilo-	k	10^{3}
mega-	M	10^{6}
giga-	G	10^{9}
tera-	T	10^{12}
peta-	P	10^{15}

The United States, unfortunately, is one the few countries in the world that has not yet made a complete conversion to the metric system. (Even Great Britain has adopted the SI system; so what are called "English" units are now better termed "American.") As a result, Americans must convert between English and metric units, because all science and international commerce is transacted in metric units. Fortunately, converting units is not difficult. Most of the lab exercises here (as well as most conversions you will ever need in science, business, and other applications) by using just the four conversions between English and metric units listed on the next page (coupled with your own recollection of the relationships between various English units).

Units Conversion Table

English to metric		
1 inch	=	2.54 cm
1 mile	=	1.609 km
1 lb	=	0.4536 kg
1 gal	=	3.785 liters

metric to English		
1 m	=	39.37 inches
1 km	=	0.6214 mile
1 kg	=	2.205 pound
1 liter	=	0.2642 gal

Strictly speaking, the conversion between kilograms and pounds is valid only on the Earth, because kilograms measure *mass* while pounds measure *weight*. However, since most of you will be remaining on the Earth for the foreseeable future, we will not yet dwell on this detail here. (Strictly, the unit of weight in the metric system is the *Newton*, and the unit of mass in the English system is the *slug*.)

Using the "Well-Chosen 1"

Many people have trouble converting between units because, even with the conversion factor at hand, they are not sure whether they should *multiply* or *divide* by that number. The problem becomes even more confusing if there are multiple units to be converted, or if there is need to use intermediate conversions to bridge two sets of units. We offer a simple and foolproof method for handling the problem.

We all know that any number multiplied by 1 equals itself, and also that the reciprocal of 1 equals 1 (i.e., 1/1=1). We can exploit these simple properties by choosing our 1's carefully so that they will perform a unit conversion for us, so long as we remember to always include our units.

Suppose we wish to know how many kilograms a 170-pound person weighs. We know that 1 kg = 2.205 pounds, and can express this fact in the form of 1's:

$$1 = \frac{1\text{ kg}}{2.205\text{ pounds}} \qquad \text{or its reciprocal} \qquad 1 = \frac{2.205\text{ pounds}}{1\text{ kg}}$$

Note that the 1's on the left of each equation are *dimensionless*. In other words, the quantity (number *with* units) in the numerator is exactly equal to the quantity (number *with* units) in the denominator. If we took a shortcut and omitted the units, we would be writing nonsense: of course, without units, neither 1 divided by 2.205, nor 2.205 divided by 1, equals "1"! Now we can multiply any other quantity by these 1's, and the quantity will remain unchanged (even though it will look considerably different).

In particular, we want to *multiply* the quantity "170 pounds" by 1 so that it will still be equivalent to 170 pounds, but will be expressed in kg units. But which "1" do we choose? Very simply, *if the unit we want to "get rid of" is in the numerator, we choose the "1" that has that same unit appearing in the denominator* (and vice versa), so that the unwanted units will cancel. In our example, we can write:

$$170 \text{ lbs} \times 1 \quad = \quad 170 \text{ lbs} \times \frac{1 \text{ kg}}{2.205 \text{ lbs}} \quad = \quad \frac{170 \times 1}{2.205} \times \frac{\cancel{\text{lbs}} \times \text{kg}}{\cancel{\text{lbs}}} \quad = \quad 77.1 \text{ kg}$$

Be certain not to omit the units, but multiply and divide them just like ordinary numbers. If you have selected a "well-chosen" 1 for your conversion, then your units will nicely cancel, assuring you that the numbers themselves will also have been multiplied or divided properly. This is what makes this method foolproof: if you accidentally used a "poorly-chosen" 1, the expression itself will immediately let you know about it:

$$170 \text{ lbs} \times 1 \quad = \quad 170 \text{ lbs} \times \frac{2.205 \text{ lbs}}{1 \text{ kg}} \quad = \quad \frac{170 \times 2.205}{1} \times \frac{\text{lbs} \times \text{lbs}}{\text{kg}} \quad = \quad 375 \times \frac{\text{lbs}^2}{\text{kg}} \qquad ?!$$

Strictly speaking, this is not really incorrect: 375 lbs^2/kg *is* the same as 170 lbs, but this is not a very useful way of expressing this, and it is certainly not what you were trying to do…

Example: As a passenger on the Space Shuttle, you notice that the inertial navigation system shows your orbital velocity to be 8,042 meters per second. You remember from your astronomy course that a speed of 17,500 miles per hour is the minimum needed to maintain an orbit around the Earth. Should you be worried?

$$8042 \frac{\text{m}}{\text{s}} \quad = \quad \frac{8042}{1}\frac{\text{m}}{\text{s}} \times \frac{1 \text{ km}}{1000 \text{ m}} \times \frac{1 \text{ mile}}{1.609 \text{ km}} \times \frac{60 \text{ s}}{1 \text{ min}} \times \frac{60 \text{ min}}{1 \text{ hr}}$$

$$= \quad \frac{8042 \times 1 \times 60 \times 60}{1 \times 1000 \times 1.609 \times 1 \times 1} \times \frac{\cancel{\text{m}} \times \cancel{\text{km}} \times \text{mile} \times \cancel{\text{s}} \times \cancel{\text{min}}}{\cancel{\text{s}} \times \cancel{\text{m}} \times \cancel{\text{km}} \times \cancel{\text{min}} \times \text{hr}}$$

$$= \quad 17{,}993 \ \frac{\text{miles}}{\text{hour}}$$

Your careful analysis using "well-chosen 1's" indicates that you are fine, and so will be able to perform more unit conversions!

Temperature Scales

Scales of temperature measurement are referenced to the freezing point and boiling point of water. In the United States, the Fahrenheit (F) scale is the one commonly used; water freezes at 32 °F and boils at 212 °F. In Europe, the Celsius system is usually used: water freezes at 0 °C and boils at 100 °C. In scientific work, it is common to use the Kelvin temperature scale. The Kelvin degree is exactly the same "size" increment as the Celsius degree, but it is based on the idea of **absolute zero**, the unattainable temperature at which all random molecular motions would cease. Absolute zero is defined as 0 K, water freezes at 273 K, and water boils at 373 K. Note that the degree mark is not used with Kelvin temperatures, and the word "degree" is commonly not even mentioned: we say that "water boils at 373 Kelvin."

To convert among these three systems, recognize that 0 K = -273 °C = -459 °F, and that the Celsius and Kelvin degree is larger than the Fahrenheit degree by a factor of 180/100 = 9/5. The relationships between the systems are:

$$K = °C + 273 \qquad °C = 5/9\ (°F - 32) \qquad °F = 9/5\ K - 459$$

Energy and Power: Joules and Watts

The SI metric unit of *energy* is called the *joule* (abbreviated J). Although you may not have heard of joules before, they are simply related to other units of energy with which you may be more familiar. For example, 1 food *Calorie* is 4,186 joules. House furnaces are rated in *btu* (British thermal units), indicating how much heat energy they can produce: 1 btu = 1,054 joules. Thus, a single potato chip (with an energy content of about 9 Calories) could be said to possess 37,674 joules or 35.7 btu of energy.

The SI metric unit of *power* is called the *watt* (abbreviated W). Power is defined to be the *rate* at which energy is used or produced, and is measured as energy per unit time. The relationship between joules and watts is:

$$1 \text{ watt} = 1 \frac{\text{joule}}{\text{second}}$$

For example, a 100-watt light bulb uses 100 joules of energy (about 1/42 of a Calorie or 1/10 of a btu) each second it is turned on. Weight watchers might be more motivated to stick to their diet if they realized that one potato chip contains enough energy to operate a 100-watt light bulb for over 6 minutes!

You are probably familiar with the unit of power called the *horsepower*; one horsepower equals 746 watts, which means that energy is consumed or produced at the rate of 746 joules per second. You can calculate (using unit conversions) that if your car has "fifty horsepower" under the hood, they need to be fed 37,300 joules, or the equivalent energy of one potato chip every second, in order to pull you down the road.

To give you a better sense of the joule as a unit of energy (and of the convenience of scientific notation, our next topic), some comparative energy outputs are listed on the next page.

Energy Source	**Energy (joules)**
Big Bang	~ 10^{68}
Radio galaxy	~ 10^{55}
Supernova	10^{44} - 10^{46}
Sun's radiation for 1 year	10^{34}
U.S. annual energy consumption	10^{20}
Volcanic explosion	10^{19}
H-bomb (20 megaton)	10^{17}
Earthquake	2.5×10^{16}
Thunderstorm	10^{15}
Fission of 1 kg of Uranium-235	5.6×10^{13}
Lightening strike	10^{10}
Burning 1 liter of oil	1.2×10^{7}
Daily energy needs of average adult	10^{7}
Kinetic energy of a car at 60 mph	10^{6}
Energy expended by a 1 hour walk	10^{6}
Solar energy at Earth (per m^2 per sec)	10^{3}
Baseball pitch	10^{2}
Hitting keyboard key	10^{-2}
Hop of a flea	10^{-7}

Labeling Units

In 1999, a NASA spacecraft, the Mars Climate Orbiter, was en route to the planet Mars carrying instruments intended to map the planet's surface and profile the structure of the atmosphere. Unfortunately, while it was trying to maneuver itself into orbit, the orbiter burned up in Mars' atmosphere. In the end, a rather simple problem was discovered to have caused the accident: software on-board the spacecraft reported a critical value in pounds (English units) rather than the newtons (metric unit) that the scientists were expecting. This little error caused a big difference in the calculations of the scientists and resulted in the loss of the $125 million spacecraft. Moral of the story: **A number without units is meaningless. Always label your units!**

SCIENTIFIC NOTATION

What Is Scientific Notation?

Astronomers deal with quantities ranging from the truly microcosmic to the hugely macrocosmic. It would be very inconvenient to always have to write out the age of the universe as 15,000,000,000 years or the distance to the Sun as 149,600,000,000 meters. For simplicity, powers-of-ten notation is used, in which the exponent tells you how many times to multiply by 10. For example, 10 = 10^1, and 100 = 10^2. As another example, 10^{-2} = 1/100; in this case the exponent is negative, so it tells you how many times to divide by 10. The only trick is to remember that $10^0 = 1$. (See the section on **Powers and Roots**, p. 20.) Using powers-of-ten notation, the age of the universe is 1.5×10^{10} years and the distance to the Sun is 1.496×10^{11} meters.

- The general form of a number in scientific notation is $a \times 10^n$, where a (called the coefficient) is a number less than or equal to 1 and less than 10, and n (called the exponent) is an integer.

  Correct scientific notation: 6×10^2, 4.8×10^5, 8.723×10^{-3}, -2.4×10^2.

  *In*correct scientific notation: 34×10^5, $4.8\times10^{0.5}$, 0.2×10^3.

- If the coefficient is between 1 and 10, so that it would be multiplied by 10^0 (=1), then it is not necessary to write the power of 10. For example, the number 4.56 already is in scientific notation (it is not necessary to write it as 4.56×10^0, but you could write it this way if you wish).

- If the number is already a power of 10, then it is not necessary to write that it is multiplied by 1. For example, the number 100 can be written in scientific notation either as 10^2 or as 1×10^2. (Note, however, that the latter form should be used when entering numbers on a calculator.)

The use of scientific notation has several advantages, even for use outside of the sciences:

- Scientific notation makes the expression of very large or very small numbers much simpler. For example, it is easier to express the U.S. federal debt as $\$7\times10^{12}$ rather than as $7,000,000,000,000.

- Because it is so easy to multiply powers of ten in your head (by adding the exponents), scientific notation makes it easy to do "in your head" estimates of answers.

- Use of scientific notation makes it easier to keep track of significant figures; that is, does your answer really need all of those digits that pop up on your calculator?

Converting from "Normal" to Scientific Notation:

Place the decimal point after the first non-zero digit, and count the number of places the decimal point has moved. If the decimal place has moved to the *left* then multiply by a positive power of 10; to the right will result in a negative power of 10.

Example: To write 3040 in scientific notation, we must move the decimal point 3 places to the left, so it becomes 3.04×10^3.

Example: To write 0.00012 in scientific notation, we must move the decimal point 4 places to the right: 1.2×10^{-4}.

Converting from Scientific to "Normal" Notation:

If the power of 10 is positive, then move the decimal point to the right; if it is negative, then move it to the left.

Example: Convert 4.01×10^2. We move the decimal point two places to the right, making 401.

Example: Convert 5.7×10^{-3}. We move the decimal point three places to the left, making 0.0057.

Addition and Subtraction with Scientific Notation:

When adding or subtracting numbers in scientific notation, their powers of 10 must be equal. If the powers are *not* equal, then you must first write the numbers so that they all have the same power of 10.

Example: $(6.7 \times 10^9) + (4.2 \times 10^9) = (6.7+4.2) \times 10^9 = 10.9 \times 10^9 = 1.09 \times 10^{10}$. (Note that the last step is necessary in order to put the answer into proper scientific notation.)

Example: $(4 \times 10^8) - (3 \times 10^6) = (4 \times 10^8) - (0.03 \times 10^8) = (4-0.03) \times 10^8 = 3.97 \times 10^8$.

Multiplication and Division with Scientific Notation:

It is very easy to multiply or divide just by rearranging so that the powers of 10 are multiplied together.

Example: $(6 \times 10^2) \times (4 \times 10^{-5}) = (6 \times 4) \times (10^2 \times 10^{-5}) = 24 \times 10^{2-5} = 24 \times 10^{-3} = 2.4 \times 10^{-2}$. (Note that the last step is necessary in order to put the answer in scientific notation.)

Example: $(9 \times 10^8) \div (3 \times 10^6) = \dfrac{9 \times 10^8}{3 \times 10^6} = (9/3) \times (10^8/10^6) = 3 \times 10^{8-6} = 3 \times 10^2$.

Approximation with Scientific Notation:

Because working with powers of 10 is so simple, use of scientific notation makes it easy to estimate *approximate* answers. This is especially important when using a calculator since, by doing mental calculations, you can verify whether your answers are reasonable. To make approximations, simply round the numbers in scientific notation to the nearest integer, then do the operations in your head.

Example: Estimate 5,795 x 326. In scientific notation the problem becomes (5.795 x 10^3) x (3.26 x 10^2). Rounding each to the nearest integer makes the approximation (6 x 10^3) x (3 x 10^2), which is 18 x 10^5, or 1.8 x 10^6. (The exact answer is 1.88917 x 10^6.)

Example: Estimate (5 x 10^{15}) + (2.1 x 10^9). Rounding to the nearest integer this becomes (5 x 10^{15}) + (2 x 10^9). We can see that the second number is nearly $10^{15}/10^9$, or one million, times smaller than the first. Thus, it can be ignored in the addition, and our approximate answer is 5 x 10^{15}. (The exact answer is 5.0000021 x 10^{15}.)

Significant Figures:

Numbers should be given only to the accuracy that they are known with certainty, or to the extent that they are important to the topic at hand. For example, your doctor may say that you weigh 130 pounds, when in fact at that instant you might weigh 130.16479 pounds. The discrepancy is unimportant and anyway will change as soon as a blood sample has been drawn.

If numbers are given to the greatest accuracy that they are known, then the result of a multiplication or division with those numbers cannot be determined any better than to the number of digits in the *least* accurate number.

Example: Find the circumference of a circle measured to have a radius of 5.23 cm using the formula: $C = 2\pi R$. Because the value of *pi* stored in your calculator is probably 3.141592654, the calculator's numerical solution will be

$$(2 \times 3.141592654 \times 5.23 \text{ cm}) = 32.86105916 = 3.286105916 \times 10^1 \text{ cm}.$$

If you write down all 10 digits as your answer, you are implying that you know, with absolute certainty, the circle's circumference to an accuracy of one part in 10 billion! That would require that your measurement of the radius was in error by no more than 0.000000001 cm. That is, its actual value was at least 5.229999999 cm, but no more than 5.230000001 cm.

In reality, because your measurement of the radius is known to only three decimal places, the circle's circumference is also known to only (at best) three decimal places as well. You should round the fourth digit and give the result as 32.9 cm or 3.29 x 10^1 cm. It may not look as impressive, but this is an honest representation of what you know about the figure.

Because the value of "2" was used in the formula, you may wonder why we are allowed to give the answer to *three* decimal places rather than just one: 3 x 10^1 cm. The reason is because the number "2" is *exact* - it expresses the fact that a diameter is *exactly* twice the radius of a circle - no uncertainty about it at all. Without any exaggeration, the number could have been represented as 2.0000000000000000000, but the shorthand "2" is used for simplicity. This does not violate the rule of using the least accurately-known number.

USEFUL MATH FOR ASTRONOMY

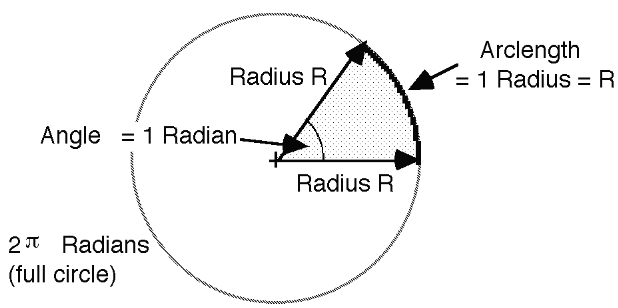
Dimensions of Circles and Spheres

- The circumference of a circle of radius R is $2\pi R$.
- The area of a circle of radius R is πR^2.
- The surface area of a sphere of radius R is given by $4\pi R^2$.
- The volume of a sphere of radius R is $4/3\ \pi R^3$.

Measuring Angles - Degrees and Radians

- There are 360° in a full circle.
- There are 60 minutes of arc in one degree. (The shorthand for arcminute is the single prime (‘), so we can write 3 arcminutes as 3’.) Therefore, there are 360 x 60 = 21,600 arcminutes in a full circle.
- There are 60 seconds of arc in one arcminute. (The shorthand for arcsecond is the double prime (“), so we can write 3 arcseconds as 3”.) Therefore, there are 21,600 x 60 = 1,296,000 arcseconds in a full circle.

We sometimes express angles in units of *radians* instead of degrees. If we were to take the radius (length R) of a circle and bend it so that it conformed to a portion of the circumference of the same circle, the angle covered by that radius is defined to be an angle of *one radian*.



Because the circumference of a circle has a total length of $2\pi R$, we can fit exactly 2π radii (6 full lengths plus a little over 1/4 of an additional length) along the circumference. Thus, a full 360° circle is equal to an angle of 2π radians. In other words, an angle in radians equals the arclength of a circle intersected by that angle, divided by the radius of that circle. If we imagine a *unit* circle (where the radius = 1 unit in length), then an angle in radians equals the actual curved distance along the portion of its circumference that is “cut” by the angle.

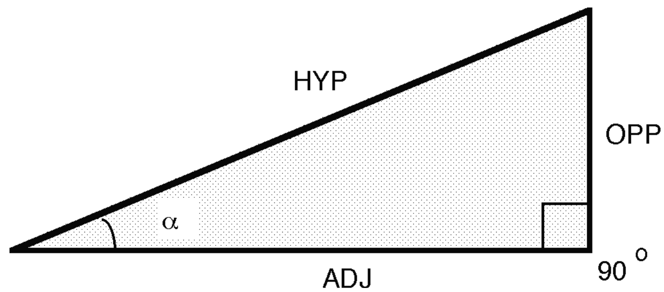
The conversion between radians and degrees is

$$1 \text{ radian} = \frac{360}{2\pi} \text{ degrees} = 57.3^\circ \qquad 1^\circ = \frac{2\pi}{360} \text{ radians} = 0.01745 \text{ radians}$$

Trigonometric Functions

In this course, we will make occasional use of the basic trigonometric (or "trig") functions: sine, cosine, and tangent. Here is a quick review of the basic concepts.

In any *right triangle* (where one angle is 90°), the longest side is called the *hypotenuse*; this is the side that is opposite the right angle. The trigonometric functions relate the lengths of the sides of the triangle to the other (i.e., not the 90°) enclosed angles. In the right triangle figure below, the side *adjacent* to the angle α is labeled "adj," the side *opposite* the angle α is labeled "opp." The hypotenuse is labeled "hyp."



- The Pythagorean theorem relates the lengths of the sides of a right triangle to each other:

$$(\text{opp})^2 + (\text{adj})^2 = (\text{hyp})^2 \quad .$$

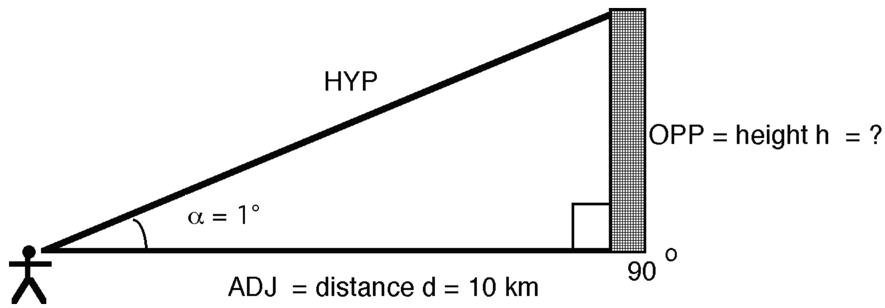
- The trig functions are just ratios of the lengths of the different sides:

$$\sin\alpha = \frac{(\text{opp})}{(\text{hyp})} \qquad \cos\alpha = \frac{(\text{adj})}{(\text{hyp})} \qquad \tan\alpha = \frac{(\text{opp})}{(\text{adj})} \quad .$$

Angular Size, Physical Size and Distance

The *angular* size of an object (the angle it "subtends," or appears to occupy from our vantage point) depends on both its true *physical* size and its *distance* from us. For example, if you stand with your nose up against a building, it will occupy your entire view; as you back away from the building it will cover a smaller and smaller angular size, even though the building's physical size is unchanged. Because of the relations between the three quantities (angular size, physical size, and distance), we need know only two in order to calculate the third.

Suppose a tall building has an angular size of 1° (that is, from our location its height appears to span one degree of angle), and we know from a map that the building is located precisely 10 km away. How can we determine the actual physical size (height) of the building?



We imagine that we are standing with our eye at the apex of a triangle, from which point the building covers an angle $\alpha = 1°$ (greatly exaggerated in the drawing). The building itself forms the *opposite* side of the triangle, which has an unknown height that we will call h. The distance d to the building is 10 km, corresponding to the *adjacent* side of the triangle.

Because we want to know the opposite side, and already know the adjacent side of the triangle, we only need to concern ourselves with the *tangent* relationship:

$$\tan\alpha = \frac{(\text{opp})}{(\text{adj})} \qquad \text{or} \qquad \tan 1° = \frac{h}{d}$$

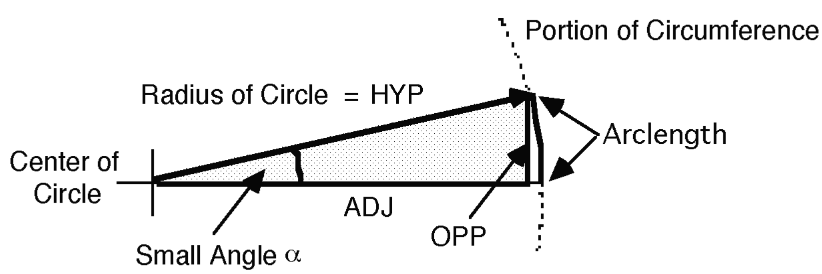
which we can reorganize to give

$$h = d \times \tan 1° \qquad \text{or} \qquad h = 10 \text{ km} \times 0.017455 = 0.17455 \text{ km} = 174.55 \text{ meters.}$$

Small Angle Approximation

We used the *adjacent* side of the triangle for the distance instead of the *hypotenuse* because it represented the smallest separation between the building and us. It should be apparent, however, that because we are 10 km away, the distance to the top of the building is only very slightly farther than the distance to the base of the building. A little trigonometry shows that the hypotenuse in this case equals 10.0015 km, or less than 2 meters longer than the adjacent side of the triangle.

In fact, *the hypotenuse and adjacent sides of a triangle are always of similar lengths whenever we are dealing with angles that are "not very large."* Thus, we can substitute one for the other whenever the angle between the two sides is small.



Now imagine that the apex of a small angle α is located at the center of a circle that has a radius equal to the hypotenuse of the triangle, as illustrated above. The *arclength* of the circumference covered by that small angle is only very slightly longer than the length of the corresponding straight ("opposite") side. In general, then, *the opposite side of a triangle and its corresponding arclength* *are always of nearly equal lengths whenever we are dealing with angles that are "not very large."* We can substitute one for the other whenever the angle is small.

Now we can go back to our equation for the physical height of our building:

$$h = d \times \tan\alpha = d \times \frac{\text{(opp)}}{\text{(adj)}} \quad .$$

Because the angle α is small, the opposite side is approximately equal to the "arclength" covered by the building. Likewise, the adjacent side is approximately equal to the hypotenuse, which is in turn equivalent to the radius of the inscribed circle. Making these substitutions, the above (exact) equation can be replaced by the following (approximate) equation:

$$h \approx d \times \frac{\text{(arclength)}}{\text{(radius)}} \quad .$$

But remember that the ratio (arclength)/(radius) is the definition of an angle expressed in *radian* units rather than degrees, so we now have the very useful **small angle approximation**:

> *For small angles*, the physical size h of an object can be determined directly from its distance d and angular size in radians by
>
> $$h \approx d \times \text{(angular size in radians)} \quad .$$
>
> Or, *for small angles*, the physical size h of an object can be determined from its distance d and its angular size α in degrees by
>
> $$h \approx d \times \frac{2\pi}{360°} \times \alpha \quad .$$

Using the small angle approximation, the height of our building 10 km away is calculated to be 174.53 meters high, an error of only about 2 cm (less than 1 inch)! And best of all, *the calculation did not require trigonometry*, just multiplication and division!

When can the approximation be used? Surprisingly, the angles do not really have to be very small. For an angle of 1°, the small angle approximation leads to an error of only 0.01%. Even for an angle as great as 10°, the error in your answer will only be about 1%.

Powers and Roots

We can express any *power* or *root* of a number in *exponential notation*, in which we say that b^n is the "*n*th power of *b*", or "*b* to the *n*th power." The number represented here as *b* is called the *base*, and *n* is called the *power* or *exponent*.

The basic definition of a number written in exponential notation states that the base should be multiplied by itself the number of times indicated by the exponent. That is, b^n means *b* multiplied by itself *n* times. For example: $5^2 = 5 \times 5$; $b^4 = b \times b \times b \times b$.

From the basic definition, certain properties automatically follow:

- **Zero Exponent:** Any nonzero number raised to the zero power is 1. That is, $b^0 = 1$.

  Examples: $2^0 = 10^0 = -3^0 = (1/2)^0 = 1$.

- **Negative Exponent:** A negative exponent indicates that a *reciprocal* is to be taken. That is,

$$b^{-n} = \frac{1}{b^n} \qquad \frac{1}{b^{-n}} = b^n \qquad \frac{a}{b^{-n}} = a \times b^n.$$

  Examples: $4^{-2} = 1 / 4^2 = 1/16$; $10^{-3} = 1 / 10^3 = 1/1000$; $3 / 2^{-2} = 3 \times 2^2 = 12$.

- **Fractional Exponent:** A fractional exponent indicates that a *root* is to be taken.

$$b^{1/n} = \sqrt[n]{b}\,; \qquad b^{m/n} = \sqrt[n]{b^m} = \left(\sqrt[n]{b}\right)^m$$

Examples: $8^{1/3} = \sqrt[3]{8} = 2$ $\qquad 8^{2/3} = \left(\sqrt[3]{8}\right)^2 = 2^2 = 4$

$2^{4/2} = \sqrt{2^4} = \sqrt{16} = 4$ $\qquad x^{1/4} = \left(x^{1/2}\right)^{1/2} = \sqrt{\sqrt{x}}$

PROPORTIONALITY

How to use the “$\propto$” (proportional to) to simplify math

The $\propto$ symbol means “is proportional to”. This shorthand way of working with equations is important because it

- Saves time
- Prevents calculator mistakes
- Lets you check the answer – *“Does This Make Sense?”*

Here is how it works.

Example:

Volume of a sphere of radius R, is $V = 4/3\pi R^3$

Planet Able has a radius twice the radius of planet Bable. Compare their volumes.

$V = 4/3\pi R^3$ so $V \propto R^3$

To compare quantities we take a ratio:

$$V_A / V_B = [4/3\pi R_A^3] / [4/3\pi R_B^3]$$

$$= R_A^3 / R_B^3$$

$$= [R_A / R_B]^3$$

$$= [2/1]^3$$

$$= 2^3$$

$$= 8$$

So, the planet Able has a volume 8 times that of planet Bable. **Notice that the π ALWAYS cancels out. Since it does, you can leave it out whenever you use RATIOS.**

The $\propto$ sign lets you cut this down to a simpler expression:

$V \propto R^3$

So if R increases by ×2 then V increases by $2^3 = 8$. **Simpler, eh?!**

ASTRONOMICAL WEBSITES

Celestial Objects – Fall 2019:
Information on what is where and when in the sky can be obtained from the following websites:

Sun, Moon, Eclipses, Some Celestial Objects:
http://www.usno.navy.mil/USNO/astronomical-applications/data-services
Lunar Phases: https://svs.gsfc.nasa.gov/4604
Meteor Showers: http://www.theskyscrapers.org/meteors/
Night Sky Viewing Guide: http://www.seasky.org/astronomy/astronomy-calendar-2019.html
Eclipses and Transits of Solar System Objects
http://eclipse.gsfc.nasa.gov/eclipse.html
https://www.nasa.gov/eclipse

Sky & Telescope's what's-up-in-the-sky-now

http://www.skyandtelescope.com/observing/ataglance

Constellations from the Hawaiian Astronomical Society

http://www.hawastsoc.org/deepsky/constellations.html

What Satellites are Orbiting Overhead that you can See Tonight? When Can You See the International Space Station, with humans aboard?

https://www.heavens-above.com/

Astronomy Picture of the Day:

http://apod.nasa.gov/

Space News:

The Planetary Society http://www.planetary.org

Bad Astronomy http://www.slate.com/blogs/bad_astronomy.html

Sky & Telescope http://www.skyandtelescope.com

Space Weather http://www.swpc.noaa.gov

NASA TV http://www.nasa.gov/multimedia/nasatv

Daily Space News http://www.space.com

More Daily Space News http://www.spacedaily.com

Some Current Missions:

Mars Reconnaissance Orbiter http://mars.jpl.nasa.gov/mro/

Mars Exploration Rovers http://mars.nasa.gov/mer/

Mars Odyssey http://mars.jpl.nasa.gov/odyssey/

MAVEN (at Mars) http://lasp.colorado.edu/home/maven/

Dawn (to Vesta and Ceres) http://dawn.jpl.nasa.gov/
Cassini-Huygens Mission (to Saturn) http://saturn.jpl.nasa.gov/
New Horizons Mission (to Pluto) http://pluto.jhuapl.edu/
Juno (to Jupiter) http://missionjuno.swri.edu
Hubble Space Telescope http://hubblesite.org/
Spitzer Space Telescope http://www.spitzer.caltech.edu/
Kepler Space Telescope http://kepler.nasa.gov/

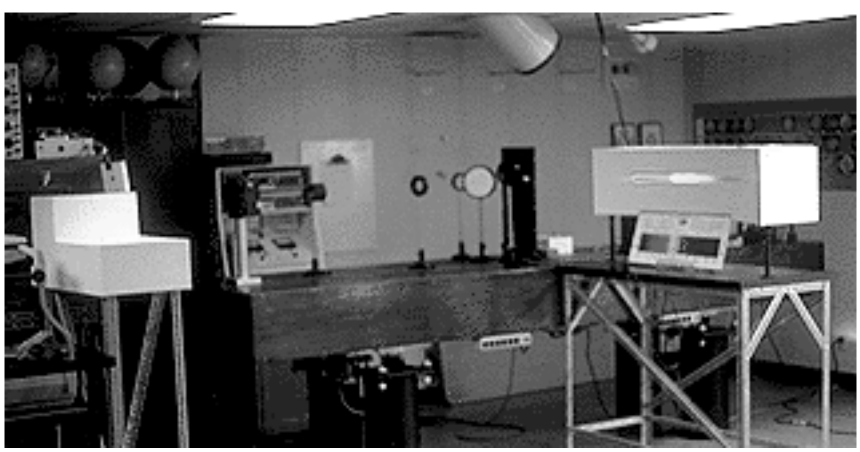
Planets, Near and Far:

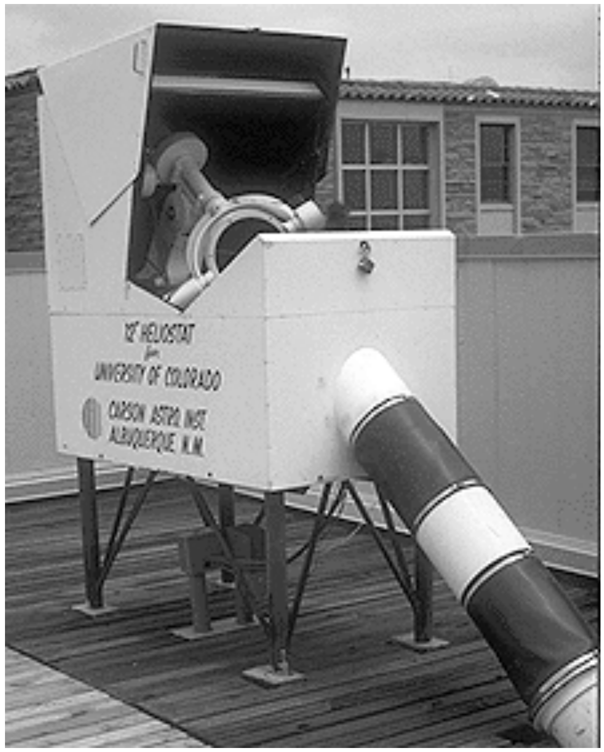
Solar System Simulator http://space.jpl.nasa.gov/
Super Planet Crash http://www.stefanom.org/spc/
Planet Hunters https://www.planethunters.org/
Exoplanets https://exoplanets.nasa.gov/

Beyond Our Solar System:

Interactive Sky Chart http://www.skyandtelescope.com/observing/skychart/
Constellations (SEDS site) http://www.seds.org/Maps/Stars_en/Fig/const.html
More Constellations http://www.hawastsoc.org/deepsky/constellations.html
Messier Web site http://www.seds.org/messier/

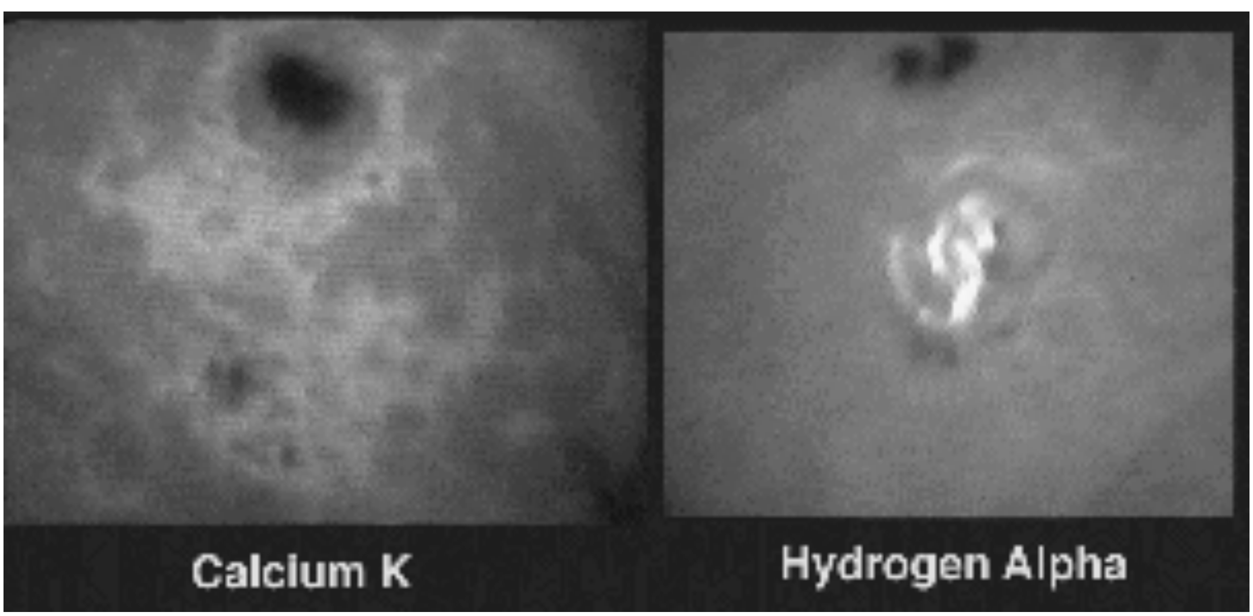
DAYTIME LABORATORY EXPERIMENTS





The SBO Heliostat …

… and a television image of a solar flare observed with it



Measuring the Height of a Building

Measure to the roof here

Name 1: _____________

Name 2: _____________

Name 3: _____________

Your Instructor will ask you to work in a group on this exercise. Write down all names, but you only need to turn in one paper. (note there are 4 pages to look at)

What's the Big Idea of this activity?

Science involves using creativity and imagination to figure things out. In Astronomy we often have to measure things we can't touch because they are so far away. Also, whenever you measure something it is important to understand the how accurate the measurement is.

Learning Goals

- Measure something (The roof height of the Center for Community or C4C building) you cannot touch. ****Use creativity in devising your own method to do this****

- Learn how to estimate the accuracy of your measurement.

IMPORTANT NOTE: Many labs are like cookbooks –they tell you what to do. That is not the way real science works. *Real science* (as opposed to boring classroom science) is all about using your imagination. That's why we don't tell you a specific method. You will invent one…

Activity: (The pre-lab for this activity is to read it beforehand and start to plan…)

Learning Goal I: Measure the size of something (the roof height of the C4C building) that you cannot touch.

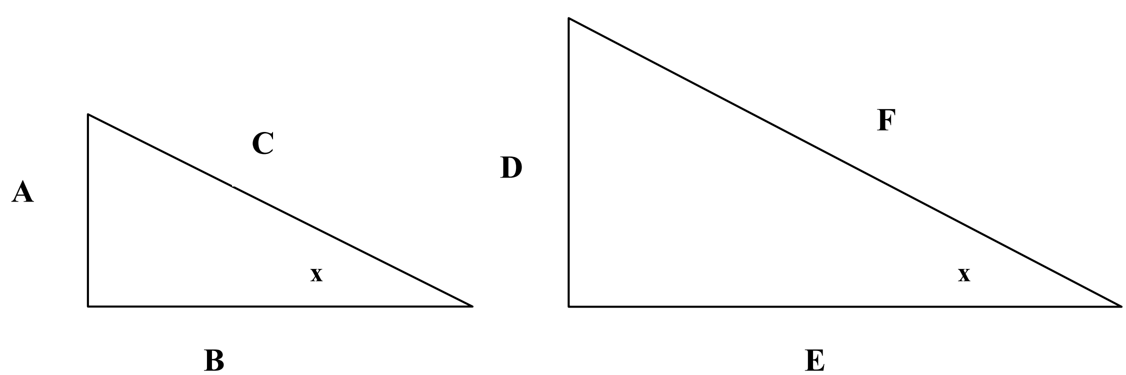
Experimentation

Part 1: Your apparatus includes a **meter stick** and a large cardboard triangle whose **sides are in a ratio of 2 to 1.**

- Use creativity in devising your method. Discuss your ideas with the others in your group of three. Start with the following hint, that reminds you of the properties of ratios:

- **HINT:** The following two triangles are *similar* and the sides are in the ratio of 2 to 1. Triangles are similar if the *corresponding angles are equal,* and that's true here. So the ratios of any two sides in the first triangle are equal to the ratios of the corresponding sides in the second triangle. If A=1' how large is B? Answer: B=2' If D = 50 feet, how large is E? **Write your answer here and show it to**

  your Instructor: _________



Mathematically, A/B = D/E. If you know 3 parts of a ratio, you can find the 4^{th}.

You could also use trigonometry if you measured the angle x. The ratios A/C and B/C are called the *sine* and *cosine* of the angle x, and A/B is the *tangent*. So you could measure one side, and an angle (if you had a protractor) and figure out the other side. <u>However, you don't need to, because we've already told you the sides are in a ratio of 2 to 1.</u>

Notes and Observations:

Sketch your method of measuring the building here. Include the building in your drawing. Draw in 2 dimensions, not 3.

Show the drawing to your instructor and explain your plan BEFORE you do your measurements!

Question(s):

I.1) What is the height of The C4C building? ____________________________

(units)

Learning Goal II: Learn how to estimate the accuracy of a measurement.

Question(s):

II.1) What do you think is the accuracy of your measurement? Think about this carefully, please.

____________________ **(units)**

II.2) How did you estimate your uncertainty?

Part of a **scientific attitude** means understanding data and the errors that come with it. When someone makes a claim, you *always* should ask, "What data or evidence supports that claim?" *and* "How good is that data?"

II.3) If you compared your measurement of the height of The C4C building to the measurement of another group, how different would you expect them to be?

II.4) How does that compare to your estimate of uncertainty?

Discussion Question:

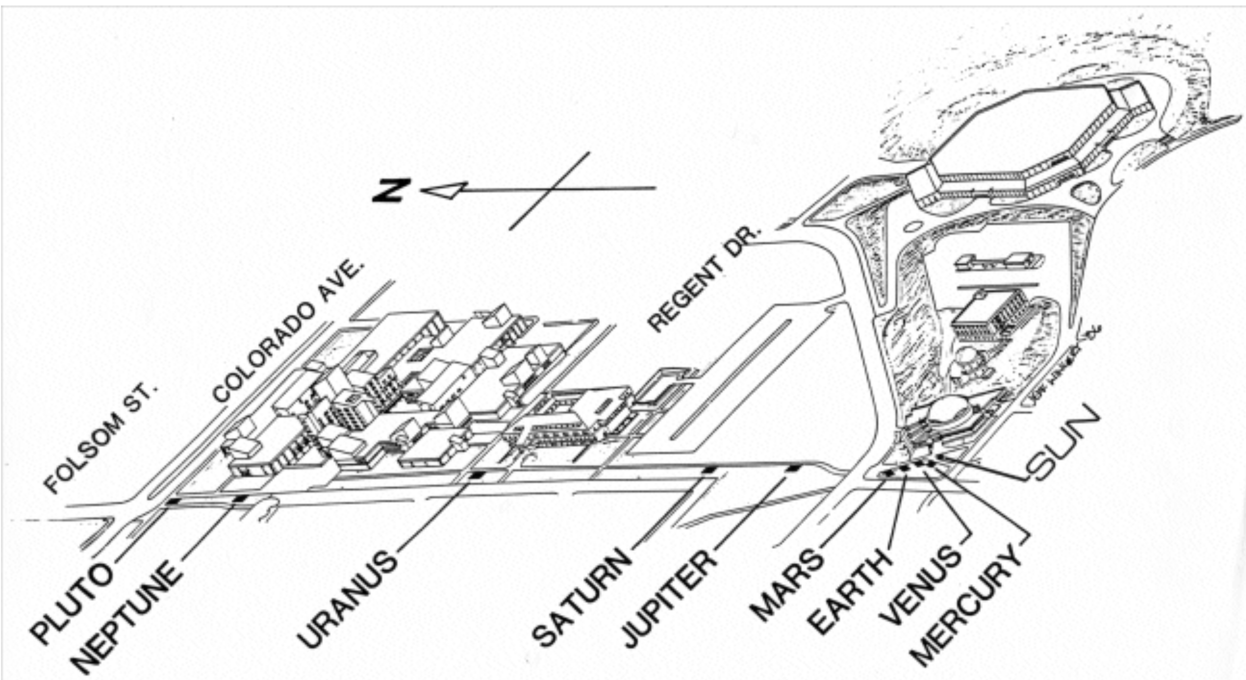
How do astronomers use geometry and trigonometry to measure distances? What do they measure distances to this way?

1 - THE COLORADO MODEL SOLAR SYSTEM

SYNOPSIS: A walk through a model of our own solar system will give you an appreciation of the immense size of our own local neighborhood and a sense of astronomical distances.

EQUIPMENT: This lab write-up, a pencil, a calculator, eclipse view glasses, and walking shoes. *(Since this lab involves walking outside, you should bring a coat if necessary.)*

Astronomy students and faculty have worked with CU to lay out a scale model solar system along the walkway from Fiske Planetarium northward to the Engineering complex (see figure below). The model is a memorial to astronaut Ellison Onizuka, a CU graduate who died in the explosion of the space shuttle *Challenger* in January 1986.



The Colorado Scale Model Solar System is on a scale of **1 to 10 billion (10^{10}).** That is, for every meter (or foot) in the scale model, there are 10 billion meters (or feet) in the real solar system.

Note: A review of scientific notation can be found on page 13 of this manual.

All of the *sizes* of the objects within the solar system (where possible), as well as the distances between them, have been reduced by this same scale factor. As a result, the apparent *angular sizes* and separations of objects in the model are accurate representations of how things truly appear in the real solar system.

The model is unrealistic in one respect, however. All of the planets have been arranged roughly in a straight line on the same side of the Sun; hence, the separation from one planet to the next is as small as it can possibly be. The last time all nine planets were lined up this well in the *real* solar system, the year was 1596 BC.

In a more accurate representation, the planets would be scattered in all different directions (but still at their properly-scaled distances) from the Sun. For example, rather than along the sidewalk to our north, Jupiter could be placed in Kittridge Commons to the south; Uranus might be found on the steps of Regent Hall; Neptune could be in the Police Building (for its crimes?); and Pluto in Folsom Stadium. Of course, the inner planets (Mercury, Venus, Earth, and Mars) will still be in the vicinity of Fiske Planetarium, but could be in any direction from the model Sun.

Before you go out to explore the planets, make some estimates. You won't be marked off if you are wrong (but WILL if you leave them blank!)

I.1 In this model, the Sun is the size of a grapefruit (13.9 cm or 5.5 inches in diameter). How large do you predict the Earth will be in this model? What common object (e.g speck of dust, grain of sand, marble, baseball, softball, volleyball, etc…) do you think will be approximately the same size as the Earth?

I.2 Which planet do you think is most similar to Earth in size?

I.3 Which planet do you think is most similar to Earth in length of day (rotation period)?

I.4 Jupiter is the largest planet in our solar system. What common object do you think you will be able to use to represent Jupiter?

I.5 How long (in Earth-hours or Earth-days) do you think it takes Jupiter to rotate once (i.e. experience one complete Jupiter-day)?

I.6 Which planet has the most moons? Which has the least?

As you pass each of the four innermost planets, you'll need to jot down some of the important properties of each planet AND record the number of steps you took between each planet.
(Hint: you should look at the next page to see what things you should be writing down)

Mercury (Steps from the Sun: _____)	**Venus** (Steps from Mercury: _____)
Earth (Steps from Venus: _____)	**Mars** (Steps from Earth: _____)

I.7 Were you right in your estimate for what object you could use to represent Earth? If not, pick a new object now.

I.8 Based on the planets encountered so far:

(a) Which planet is most like the Earth in temperature?

(b) Which planet is most similar to the Earth in size?

(c) Which is the smallest planet?

(d) Which planet has a period of rotation (its day) very much like the Earth's?

(e) Which planet(s) has/have the least moons?

The *real* Earth orbits about 93 million miles (150 million km) from the Sun. This distance is known as an *astronomical unit*, or *AU* for short. The AU is very convenient for comparing relative distances in the solar system by using the average Earth-Sun separation as a standard distance.

I.9 What fraction of an AU does one of your steps correspond to in the model? How many miles do you cover in each step?

II. The View From Earth

Stand next to the model Earth and take a look at how the rest of the solar system appears from our vantage point. (Remember, because everything is scaled identically, the apparent angular sizes of objects in the model are the same as they appear in the real solar system).

II.1 (a) Stretch out your hand at arm's length, close one eye, and see if you can cover the model Sun with your index finger. Are you able to completely block it from your view?

(b) The width of your index finger at arm's length is about 1 degree. Estimate the angle, in degrees, of the diameter of the model Sun as seen from Earth.

Caution! Staring at the Sun with unprotected eyes can injure your eyes.

For the next question, be sure your finger covers the disk of the Sun!

You may also borrow the eclipse glasses available from SBO.

II.2 If it is not cloudy, you can use the same technique to cover the real Sun with your outstretched index finger. Is the apparent size of the *real* Sun as seen from the *real* Earth the same as the apparent size of the *model* Sun as seen from the distance of *model* Earth?

III. Journey to the Outer Planets

As you cross under Regent Drive heading for Jupiter, you will also be crossing the region of the *asteroid belt*, where thousands of "minor planets" can be found crossing your path. The very largest of these is Ceres, which is 760 km (450 miles) in diameter (slightly larger than 1/10th the size of Mars).

III.1 Assuming the asteroids were to be scaled like the rest of the solar system model, would you likely be able to see most of the asteroids as you passed by them? Why or why not?

As you continue your journey through the solar system, be sure to continue to jot down the important properties of all the planets.

Jupiter (Steps from Mars: _____)	**Saturn** (Steps from Jupiter: _____)

Uranus (Steps from Saturn: _____)	**Neptune** (Steps from Uranus: _____)	**Pluto** (Steps from Neptune: _____)

Jupiter contains over 70% of all the mass in the solar system outside of the Sun, but this is still less that one-tenth of one percent of the mass of the Sun itself.

III.2 Were you right in your estimate for what object you could use to represent Jupiter? If not, pick a new object now.

III.3 (a) How many times larger (in radius or diameter) is Jupiter than the Earth?

(b) How many times more massive is Jupiter than the Earth?

(c) How does the distance between Saturn and Jupiter compare to the entire distance from the Sun to Mars? *(We're not looking for exact answers here, just make a general comparison.)*

IV. Travel Times

IV.1 Based on the *total* steps you took from the Sun to Pluto, how long (in seconds) would it take to walk the scale model solar system from the Sun to Pluto if you took 1 step per second?

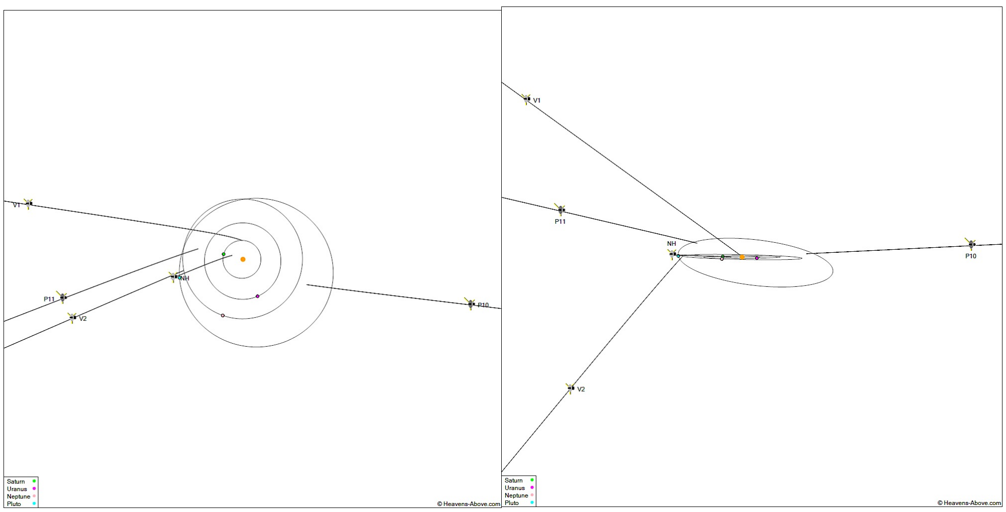
IV.2 Based on the same 1 step/second rate, how long would it take (in years) to walk from the Sun to Pluto in the REAL solar system? *(Ignore the fact that you can't actually WALK between planets.) (Hint: There are ~*3.16×10^7 *seconds in a year.)*

V. Beyond Pluto

Although we have reached the edge of the solar system as we typically describe it that does not mean that the solar system actually ends here. It does not mean that our exploration of the solar system ends here, either.

Over on Pearl Street Mall to your north, about 125 AU from the Sun, Voyager 1 is still travelling outwards towards the stars, and still sending back data to Earth. It is currently in an area known as the *heliosheath* (where the Sun's wind pressure is almost balanced by space pressure itself).

Spacecraft exiting the Solar System (as of August 2016)



In 2000 years, Comet Hale-Bopp (which was visible from Earth in 1997, and is shown on the cover of this lab manual) will reach its farthest distance from the Sun (*aphelion*), just north of the city of Boulder at our scale. Comet Hyakutake, which was visible from Earth in 1996, will require 23,000 years more to reach *its* aphelion distance, which is 15 miles to the north in our scale model, near the town of Lyons.

Beyond Hyakutake's orbit is a great repository of comets-yet-to-be: the *Oort cloud*, a collection of a billion or more microscopic (at our scale) "dirty snowballs" scattered across the space between Wyoming and the Canadian border. Each of these icy worldlets is slowly orbiting our grapefruit-sized model of the Sun, waiting for a passing star to jostle it into a million-year plunge into the inner solar system.

Other Solar Systems

And *there* is where our solar system really ends. Beyond that, you'll find nothing but empty space until you encounter Proxima Centauri, a tiny star the size of a cherry, 4,000 km (2,400 miles) from our model Sun (still staying at our 1-to-10 billion scale)! This puts it at about the distance of Fairbanks, Alaska. At this scale, Proxima orbits 160 kilometers (100 miles) around *two other stars* collectively called Alpha Centauri: one is the size and brightness as the Sun, and the other only half as big (the size of an orange) and one-fourth as bright. The two stars of Alpha Centauri orbit each other at a distance of only 1000 feet (0.3 km) in our scale model.

Now you know why we call it SPACE!

2 - MOTIONS OF THE SUN & MOON

SYNOPSIS: The goal is to investigate some of the apparent motions of the Sun & Moon in the sky. You will then use these results to explain why Earth experiences both seasons and phases of the Moon.

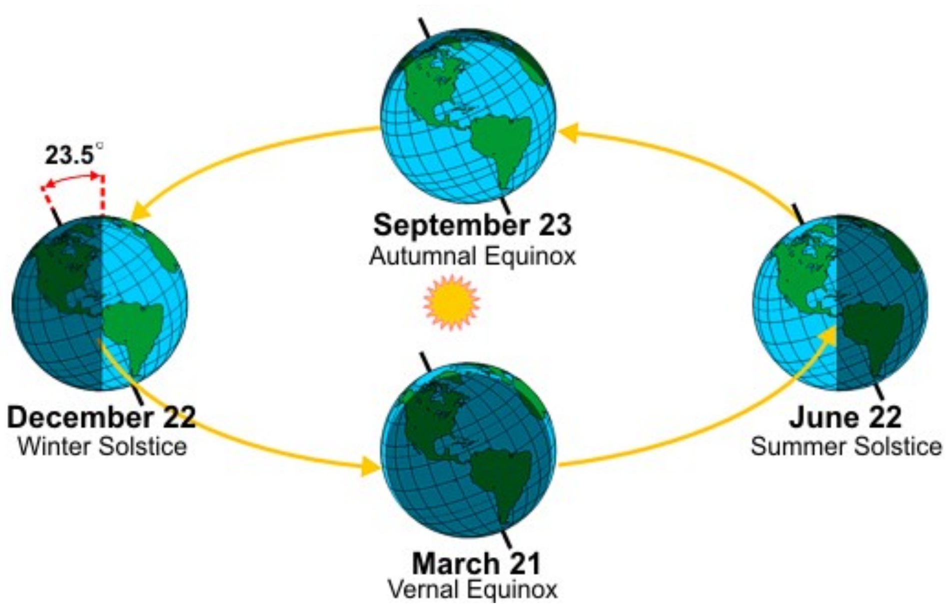
EQUIPMENT: A globe of the Earth, a bright light, foam Moon ball.

PRELAB QUESTIONS:

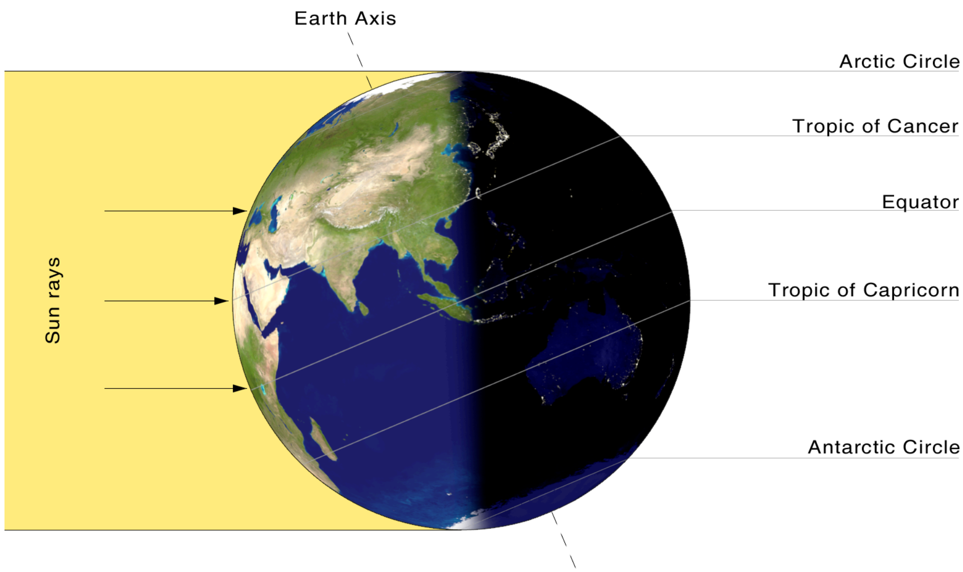
1) What is the difference between latitude and longitude? What are the latitude and longitude of Boulder?
2) At noon today in Boulder, where should you look to see the Sun in the sky? (In the northern, eastern, southern, or western part of the sky?)
3) What is the period of the Moon's orbit around the Earth?
4) How can the Sun and the Moon have the same apparent angular size in our sky?

Part I. The Annual Motion of the Sun

The position of the Sun in the sky appears to change as the Earth orbits around the Sun. *This motion is not to be confused with the daily motion of the Sun (rising and setting)!* If you think of the plane of the Earth's orbit- the ecliptic plane- being horizontal (parallel to the ground or table top) then the Earth's spin axis does not point directly upwards but is tilted 23.5°. This tilt is fixed in direction in space (always pointing towards Polaris) but as the Earth orbits the Sun, the tilt affects the angle of the North pole to the Sun (as in the diagram below). As a consequence, different parts of the Earth receive different amounts of sunlight depending on where the Earth is in its orbit. (Note: The Earth's orbit is nearly circular, but it appears very non-round in this diagram only because we are viewing at an angle across the plane of the Earth's orbit.)



(Image courtesy of NOAA)



(Image courtesy of [User:Blueshade](#) / [Wikimedia Commons](#) / [CC-BY-SA-2.0](#))

I.1 We know the Sun (and stars) rises in the east and sets in the west. Use your globe to determine which direction the Earth spins when viewed from above the North Pole. Does it rotate clockwise or counterclockwise?

The illustration above shows the Earth at the summer solstice (for the Northern Hemisphere). Position your globe such that Boulder is at noon *and* it is the summer solstice.

At noon, the Sun is high in the sky in Boulder and shining (almost) directly down on us. So it is summer for us. At the end of the semester, you'll investigate this phenomena in more detail. For today, you'll look at a few other locations on the globe and compare them to Boulder.

I.2 Find a city somewhere in Asia at the same latitude as Boulder. List the city (and country) that you've chosen. What season is this part of the world experiencing? (You might want to spin your globe (*don't change the direction of the tilt!*) to simulate daytime in that country.)

I.3 The **Tropic of Cancer** (23.5° north latitude) marks the latitude where the Sun is at the **zenith** (i.e. directly overhead) at noon on the summer solstice. Can the Sun ever be seen at the zenith (at noon) from here in Boulder? If so, when? If not, why not? Use your globe to confirm your answer.

I.4 Is there anywhere in all of the fifty United States where you could see the Sun at the zenith at some time of the year? If so, where?

I.5 The **Arctic Circle** lies at a latitude of 66.5° north. North of the Arctic Circle, the Sun is above the horizon for 24 continuous hours at least once per year and below the horizon for 24 continuous hours at least once per year. Find the town of Barrow, Alaska. On the summer solstice at what times will the Sun rise and set in Barrow?

Without changing the orientation (tilt) of the globe, rotate it so it is noon in Australia. Study what is happening “down under” in Melbourne, Australia.

I.6 On the Northern Hemisphere's summer solstice is the Sun in the northern or southern portion of the sky, as seen from Melbourne?

I.7 Is it high in their sky or low? *(Hint: think about where their zenith point is.)*

I.8 What season is Melbourne (and all of Australia) experiencing? Explain.

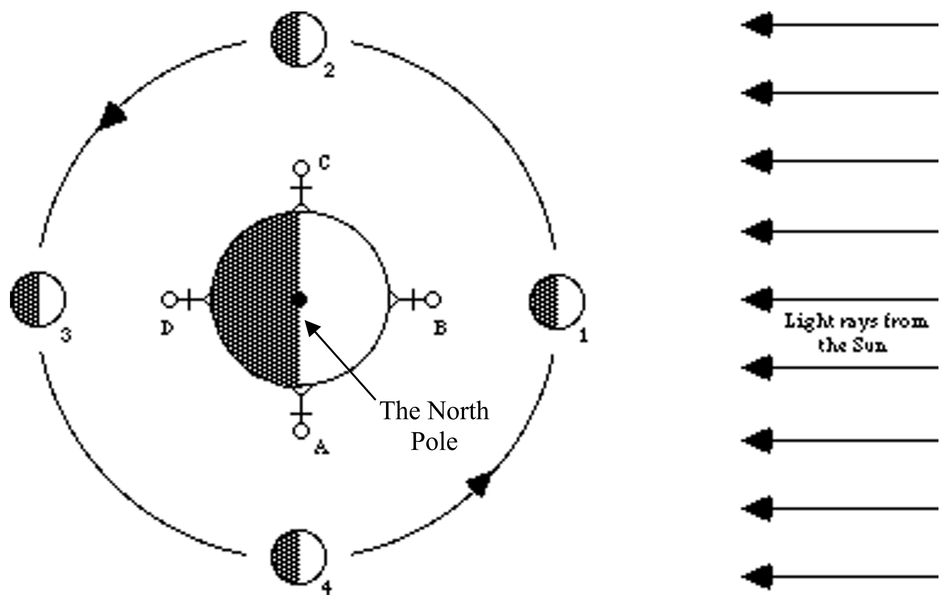
I.9 The **Antarctic Circle** is the southern equivalent of the Arctic Circle. On our summer solstice what time does the Sun rise at the South Pole?

I.10 The **Tropic of Capricorn** lies at 23.5° south latitude. Find Lake Disappointment in the Great Sandy Desert of Australia. Is the Sun ever directly overhead there? If so, when?

I.11 In Australia, do the stars still rise in the east and set in the west? (Hint: Use your globe to verify!) Explain the reason for your answer.

Part II. The Moon's Orbit

Now let's think about the Moon's movement around the Earth. The diagram below shows the overhead view of the Earth and Moon with the Sun off to the right. Depending on where you are sitting in the lab room, the Sun (bright light in the center of the classroom) may be coming from a different direction, but the Moon still orbits the Earth ***counterclockwise*** when viewed from above the North Pole. *For this activity, you can assume that sunrise is at 6am and sunset is at 6pm.*



Note that half of the Moon is always illuminated (just like the Earth); even though it may not appear to be from our view here on Earth.

II.1 How long (roughly) does it take the Moon to orbit the Earth once? How many times does the Earth rotate in that same period?

Imagine that your head is the Earth and that you live on the tip of your nose. Position yourself such that your head is pointing directly at the "Sun" (the light).

II.2 What time is it for the mini-you living on the tip of your nose?

Slowly turn your head around counterclockwise to simulate the daily cycle: sunrise, noon, sunset, midnight, and back to sunrise. This should give you a feel of what direction in space you are looking during the different times of the day.

II.3 Assuming your head is the Earth and the United States stretches from your right eye to your left eye, which eye represents the East Coast?

Hold your "Moon" (foam ball) out at arm's length. Start with the Moon pointed in the direction of the Sun. While keeping the Moon out in front of your nose, slowly spin your entire body (including the Moon) counterclockwise (to your left). Keep your eyes on the Moon the entire time. Stop turning when the portion of the Moon you can see is more than a sliver but not quite half lit. We call this a **crescent moon**.

II.4 Which side of the Moon (that you can see) is illuminated (right or left)?

II.5 Draw the alignment between the Moon (foam ball), the Earth (your head) and the Sun (light). It may look similar to the diagram on page 42 but there should only be one Moon and one person (and it is likely not in any of the places shown on that diagram).

II.6 What is the (closest) angle between the Moon, the Earth and the Sun: 0°, 45°, 90°, 135°, or 180°?

II.7 What time is it for mini-you on the tip of your nose? (This is the time you would see that Moon phase highest in the sky.) Explain your reasoning.

If the illuminated portion of the Moon is getting bigger as it progresses through its phases, we call it "**waxing**." If it is getting smaller, we call it "**waning**."

II.8 Are you looking at a waxing crescent or waning crescent moon?

Continue to turn slowly to your left until the illuminated portion of the Moon you can see, is exactly half lit. Your alignment should match one of the numbered positions in the diagram on page 42.

II.9 Which numbered position do you match?

Continue to turn slowly to your left until the Sun is directly behind you. (You may have to lift the Moon above your head a bit so your head doesn't block the sunlight.)

II.10 What do we call this phase of the Moon?

If you lower the Moon a little you will probably move it behind the shadow of your head. This is a **lunar eclipse,** when the shadow of the Earth (in this case, the shadow from your head) covers the Moon. In Part IV, you'll discover why there isn't a lunar eclipse every time there is a full moon.

Continue to turn counterclockwise, holding the Moon at arm's length. Stop when the illuminated portion of the Moon you can see is no longer full but not yet half illuminated. This is known as a **"gibbous" moon**.

II.11 Which side of the Moon is now illuminated?

II.12 Draw the alignment between the Moon, the Earth, and the Sun. It may look similar to the diagram on page 42 but there should only be one Moon (and it is likely again not in any of the places shown on that diagram).

II.13 Is this a waxing gibbous or waning gibbous moon? Explain your answer.

II.14 When you are facing directly towards your moon, what time is it for mini-you on the tip of your nose? (This is the time you would see that moon phase highest in the sky.)

Part III. Moonrise and Moonset

In reality, the Moon doesn't orbit as fast as the Earth rotates. So when you've been moving your head *with* the Moon, you've been making the Moon orbit way too fast. (A day is 24 hours, how long was the Moon's orbit?) Let's investigate moonrise and moonset.

If your mini-you (living on the tip of your nose) had a horizon, it could be simulated as an imaginary plane that cuts down through your head and goes through both ears. North on the horizon would be the top of your head and south on the horizon would be below your chin.

III.1 Which ear represents the western point of the horizon (your right or left)? (*Hint: You might think back to your answer to question II.2.)*

While keeping your arm in the same place it was for QII.14 (i.e. don't move the Moon in its orbit) continue to turn your head to the left (simulating the Earth's rotation). Stop when the Moon is even with your *right* ear.

III.2 The Moon is about to cross your horizon. Is this rising or setting?

III.3 What time is it for mini-you on the tip of your nose?

III.4 Circle the correct responses in parentheses: You have just discovered what time a ________ (waxing or waning) gibbous moon __________ (rises or sets)!

You should check your answer with your TA/LA before moving on to make sure you have this concept correct.

III.5 Use everything you have learned in this section, draw a picture below similar to what you drew for II.5 and II.12 but this time show the configuration for a waning crescent moon. Also, add a stick figure on the Earth (like in the image shown on page 42) that would be seeing the moon *rise.*

III.6 What time does a waning crescent moon rise?

III.7 Even though it is usually regarded as a nighttime object, you have just learned that some phases of the Moon can be seen during the day. Go outside to see if the Moon is visible right now (your TA/LA can help). If it is up (and it is sunny), hold up your foam Moon ball at arm's length in the direction of the real Moon. The foam Moon ball should have the same phase as the Moon! Even if you can't see the Moon, explain why this is (or would be) so.

Part IV. Solar and Lunar Eclipses

Because the Sun and Moon have roughly the same angular size (as viewed from Earth), it is possible for the Moon to block out the Sun from our view, causing a **solar eclipse**.

IV.1 Hold the foam Moon ball at arm's length and move it through its phases. There is only one phase of the Moon when it is possible for it to block your view of the Sun, causing a solar eclipse. Which phase is this?

IV.2 Now simulate this arrangement with the Moon, the Earth globe, and the Sun. Does the Moon's shadow eclipse the entire Earth, or does only a portion of the Earth lie in the Moon's shadow?

IV.3 Does this mean that *all* people on the sunlit side of the Earth can see a solar eclipse when it happens, or only *some* people in certain locations? Explain your answer.

The Moon's orbit is not quite circular. The Earth-Moon distance varies between 28 and 32 Earth diameters. If a solar eclipse occurs when the Moon is at the point in its orbit where the distance from Earth is "just right," then the Moon's apparent size can *exactly* match the Sun's apparent size.

IV.4 If the Moon were at its *farthest* point to the Earth during a solar eclipse, would it appear bigger or smaller than the Sun as seen from Earth?

IV.5 Describe what the eclipse would look like from the Earth in the case described above.

It is also possible for the shadow of the Earth to block the sunlight reaching the Moon, causing a **lunar eclipse.**

IV.6 Once again, move the Moon through its phases around your head and find the one phase where the shadow from the Earth (your head) can fall on the Moon, causing a lunar eclipse. What phase is this? (Or what phase was it *just* before the eclipse?)

IV.7 During a lunar eclipse, is it visible to *everyone* on the (uncloudy) nighttime side of the Earth, or can only a portion of the people see it? Explain your answer.

Many people mistakenly think that a lunar and solar eclipse should occur every time that the Moon orbits the Earth. This misconception is due to the fact that we usually show the Moon *far* closer to the Earth than it actually is, making it appear that an eclipse is unavoidable. However, the Moon's actual distance is roughly 30 Earth-diameters away. Additionally, the Moon's orbit is tilted slightly (~5°) to the ecliptic plane. *(Your TA may have a demo set up in the lab room demonstrating the Moon's orbit around the Earth. If you are having trouble visualizing the tilt of the Moon's orbit, ask your TA/LA to show you the demo.)*

IV.8 Position the foam Moon ball in the full phase and hold it at a properly-scaled distance from the globe of the Earth (30 Earth-diameters away). How much of the Moon's orbit would the shadow of the Earth cover at this distance? (A general answer is all that is required here. A larger or smaller fraction of the Moon's orbital path?)

IV.9 First using the foam Moon ball, and then by making a sketch below showing the view of the Sun-Earth-Moon system from the side (edge-on), show how the Earth's shadow can miss the Moon, so that a lunar eclipse does not occur.

3 - THE ERATOSTHENES CHALLENGE

(or: A Pilgrimage to the Fortieth Parallel)

SYNOPSIS: The purpose of this observing project is to measure the circumference of the Earth in your paces and then in yards and miles using the ancient methods of Eratosthenes. We will use the results to have you discuss why measurement errors are *not* mistakes and why systematic errors sometimes *are* mistakes. If you want to make this a more accurate historical re-enactment, we will (hopefully) give you the opportunity to calibrate your paces in the *CU football stadium* (since the ancient Greeks measured distances in *stadia*).

PRELAB QUESTIONS:

1) If the Sun was directly above Syene on the summer solstice, at what latitude was Syene?
2) In your own words, explain the difference between a measurement (random) uncertainty and a systematic error.
3) Why must you measure the distance between SBO and Baseline road in an exactly north-south direction?
4) Estimate the distance (in either paces or yards) from Sommers-Bausch Observatory to the south sidewalk of Baseline Road. (Try to come up with as accurate an estimate as you can. You will not be penalized if you are wrong.) How did you come up with your estimate?

Background:

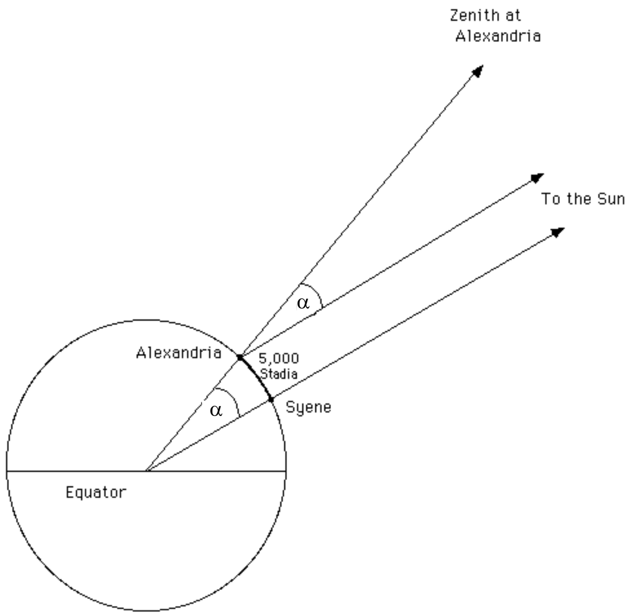
Eratosthenes of Cyrene:

Born: 276 BC in Cyrene, North Africa (now Shahhat, Libya)
Died: 194 BC in Alexandria, Egypt

He was student of Zeno's (founder of the Stoic school of philosophy), invented a mathematical method for determining prime numbers … and made the first accurate measurement for the circumference of the Earth!

Details were given in his treatise "On the Measurement of the Earth" which is now lost. However, some details of these calculations appear in works by other authors. Apparently, Eratosthenes compared the noon shadow at Midsummer (June 21st) between Syene (now Aswan on the Nile in Egypt) and Alexandria, 500 miles to the North on the Mediterranean Sea. He assumed that the Sun was so far away that its rays were essentially parallel, and then with a knowledge of the distance between Syene and Alexandria, he gave the length of the circumference of the Earth as 250,000 stadia (1 stadium = the length of a Greek stadium).

We still do not know how accurate this measurement is because we still do not know the exact length of a Greek stadium. However, scholars of the history of science have suggested an accurate value for the stadium and estimate that Eratosthenes' measurement was 17% too small. Unfortunately, in Renaissance times, the length of a Greek stadium was under-estimated as well, yielding an even smaller circumference for the Earth. This small value led Columbus to believe that the Earth was not nearly as large as it is … so when he sailed to the New World, he was quite confident that he had sailed far enough to reach India.



Here is how Eratosthenes made his measurement (see figure). He had heard that on the **summer solstice** the Sun at noon stood directly over Syene, at the **zenith**, so that the Sun's light penetrated all the way down to the bottom of a well at Syene casting no shadow. Eratosthenes measured the angle of the Sun off the zenith (called the **zenith angle**; angle "α" in the figure) from Alexandria on that same day. (Unfortunately, his measurement of α was ~6% too small.) As shown in the figure, α is also the difference in **latitudes** of these two locations. (This point will be explained in detail by your TA or LA if you ask.)

From here on, it's all arithmetic.

Logically, Angle α is to 360 degrees (a full circle) as the distance between Alexandria and Syene is to the full circumference of the Earth. Eratosthenes had a measurement for the distance between Syene and Alexandria of 5000 stadia (now thought to be ~24% too low). Mathematically:

$$\frac{\alpha}{360^\circ} = \frac{5{,}000 \text{ Stadia}}{\text{Circumference of the Earth}}$$

and so (rearranging):

$$\text{Circumference of the Earth} = \frac{360^\circ}{\alpha} \times 5{,}000 \text{ Stadia}$$

What We Need to Know to Make a Modern "Eratosthenes Measurement":

We need to know the equivalent of the two measurements Eratosthenes had:

1. The difference in latitude between two locations on Earth.
2. The difference in distance (we will use paces, then yards, then miles and then, possibly, CU stadia, but the idea is the same) between these same two locations in an **exactly** north-south direction.

Eratosthenes measured #1 and had obtained from others a value for #2.

We will measure #2 (in paces, then in yards and miles) and obtain a value from others for #1 (see, we are following his footsteps virtually exactly!)

#1. Changes in Latitude:
Conveniently, we have two nearby locations with well-known latitudes.

> Location 1: When Colorado was surveyed in the 1800s, Baseline Road was determined to be at precisely 40 degrees North Latitude.
>
> Location 2: More recently than that, an astronomical measurement at the **Sommers-Bausch Observatory** (SBO) 24-inch telescope (located here at CU just north of Baseline Road) determined the latitude of SBO to be:
>
> 40.00372 degrees (+40° 00' 13.4") North

Local Diversions:

Unfortunately in recent years due to traffic control necessity, the course of Baseline Road has been altered just south of campus. As shown in the photograph from space on page 46, Baseline Road curves gently north between Broadway Blvd and 30th Street. The white line is our best estimate for exactly 40 degrees latitude based on the course of Baseline Road east and west of this bend. Perhaps realizing that they had altered a geographically (and astronomically) important landmark, the city of Boulder (or maybe RTD?) has painted a red line on the sidewalk near the bus stop in order to mark the exact location of the 40^{th} parallel. (Notice how it splits the rock to the east.)

YOUR CHALLENGE

REPEAT THE ERATOSTHENES MEASUREMENT USING YOUR PACES, AND CONVERT YOUR PACES TO YARDS AND THEN MILES, USING THE TAPE MEASURE.

We will provide a 100-yard tape measure for your conversions. Additionally, we have arranged time for you to make measurements down on the field inside Folsom Stadium since the original measurement was made in stadia. See below for details on this optional portion.

<u>Each</u> member of your lab group must make these measurements (both pacing between SBO and Baseline and "calibrating" their paces by stepping off 100 yards). Each participant will then use the Eratosthenes Equation to determine how many paces you would need to walk to get all the way around the Earth. By calibrating your paces you will then determine the number of miles around the Earth.

As an *optional* component, you can measure (in paces) the size of the actual CU Stadium in order to convert your measurements to modern day stadia. (What part of the stadium you use is up to you. But you must justify your choice!) Your TA/LA will tell you the times when the stadium will be available. You may enter the stadium through Gate 5. (You are allowed to make your measurements on the sidelines next to the field but ***please stay off the field grass!***)

That's IT! That's all we are going to tell you, but if you need help be sure to ask the LAs or TA for some pointers. Each individual in each group must make their own measurements using the method agreed to by the group.

Good luck. KEEP THINKING AND STAY SAFE! Especially when crossing Baseline and other streets... the cars do not know that you are conducting an historical reenactment.

East


30th St
Aurora Ave
28th St / US 36
Baseline
←SBO
Broadway
40th Parallel

West

Part I. Make Your Measurements

As stated in the previous instructions, you will need to come up with a plan with your lab group to make your measurements. Be sure to record all your measurements and calculations and turn them in with your lab report.

I.1 Describe the general route you took. You may want to mark your route on the map on the previous page as part of your description, although *you must still explain your route in words*.

I.2 There are many possible routes you could have taken. How did your group decide on this particular route? What procedures did you use to make sure your measurements were as accurate as possible?

Part II. Explaining your measurements

The central equation for this lab is:

$$\frac{\alpha}{360°} = \frac{Distance}{Circumference}$$

II.1 Explain in words why the fraction on the left side of the equation (α / 360°) must equal the fraction on the right side of the equation (Distance/Circumference). Feel free to include drawings in your explanation.

II.2 How did ***Eratosthenes*** get a value for α? How did he get a value for the distance?

II.3 How did ***you*** get a value for α? How did you get a value for the distance?

II.4 Calculate the circumference of the Earth in yards and miles (note: 1 mile = 1760 yards = 5280 feet) based on your count of the number of paces between SBO and Baseline. *Show all your work.*

II.5 Write down what the other members of your group calculated for the circumference based on their paces. *You do not need to show the calculations again.*

Name:_________________ Circumference (in miles): _____________________________

Name:_________________ Circumference (in miles): _____________________________

Name:_________________ Circumference (in miles): _____________________________

Name:_________________ Circumference (in miles): _____________________________

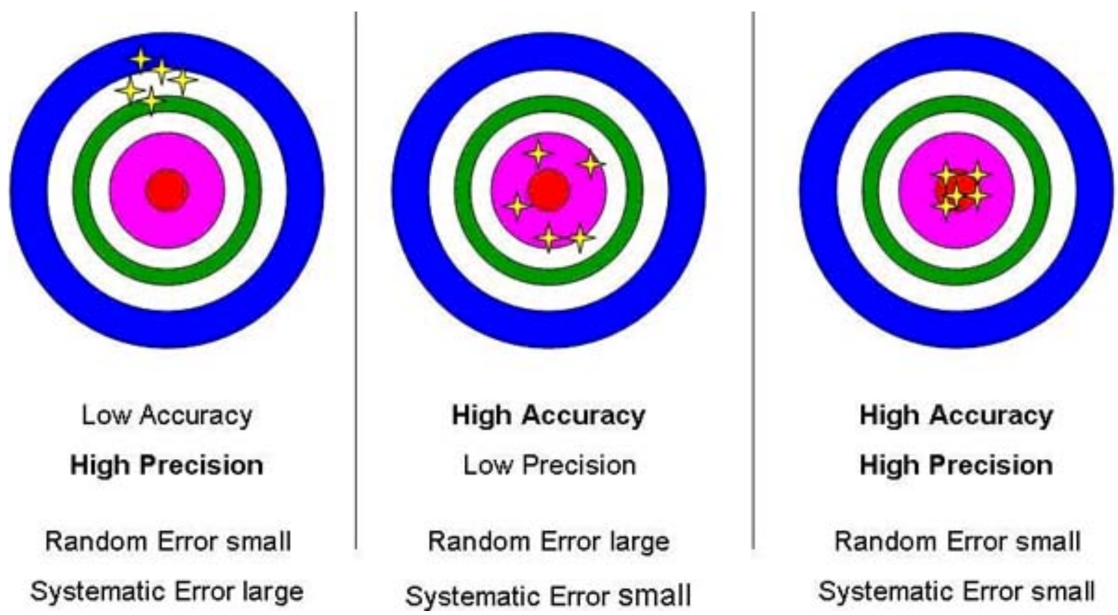
II.6 Calculate your group's average value for the circumference of the Earth. Show all your work.

Part III. Error Analysis

Webster's dictionary defines **error** as "the difference between an observed or calculated value and the true value". We don't know the true value; otherwise there would be no reason to make the measurement. We wish our measurements to be both ACCURATE and PRECISE.

Accuracy relates to how closely the results of the experiment are to the true result. Thus, accuracy speaks to whether our chosen methods actually work to allow a measurement of the quantity we seek to determine, whether all assumptions have been accounted for and whether these assumptions do not compromise the measurement. Errors in setting up an accurate experiment are called **systematic errors**, and more and more precise measurements cannot reduce these types of errors.

Precision, on the other hand, refers to the actual measurement process itself. Greater precision in measurement can be accomplished by using a more accurate measuring device or by repeating measurements several times. Uncertainties in precision are called **measurement (random) uncertainties** and repeated measurement can reduce these uncertainties (e.g., independent measurements by equally precise measuring tools or people) but never eliminate them. However, be warned, precise measurements do not yield an accurate result if the experimental setup is inaccurate; i.e., systematic and measurement errors are independent of one another and both must be dealt with to obtain the best value for the true result.



*** Any scientific measurement has inherent uncertainties and errors (precision in measurement and errors in experimental setup) which limit the ultimate precision of the result. All scientific experiments have these limitations, which must be quoted with the result (e.g., even political polling reports results and uncertainties… 54% with an uncertainty of 3 points (3%)…but beware, systematic errors are not reported and can be much larger in some cases; e.g., what if only women were polled, only rich people were polled, etc.) In this experiment, think about the experimental setup, the specific methods that you and your group employed and the uncertainties and errors which may have limited the ultimate precision of your result.

1) Precision (Measurement Uncertainty)

III.1 Typically, an experimental result is listed as: [value obtained] +/- [precision], e.g. 25,000 +/- 1000 miles for the circumference of the Earth. Through a comparison of your final results on the circumference of the Earth with the results from the other members of your group, estimate the **precision** of your measurement. List your group's result as [value] +/- [precision] *(Don't forget your units!)*

III.2 Think back to how you got your data for this lab. List at least two measurement errors in how you got your data.

	Brief Description of Measurement Error	Estimate of Size of Error
1		
2		
3		

III.3 Why does averaging many results reduce the measurement uncertainty (i.e. produce a more *precise* measurement)?

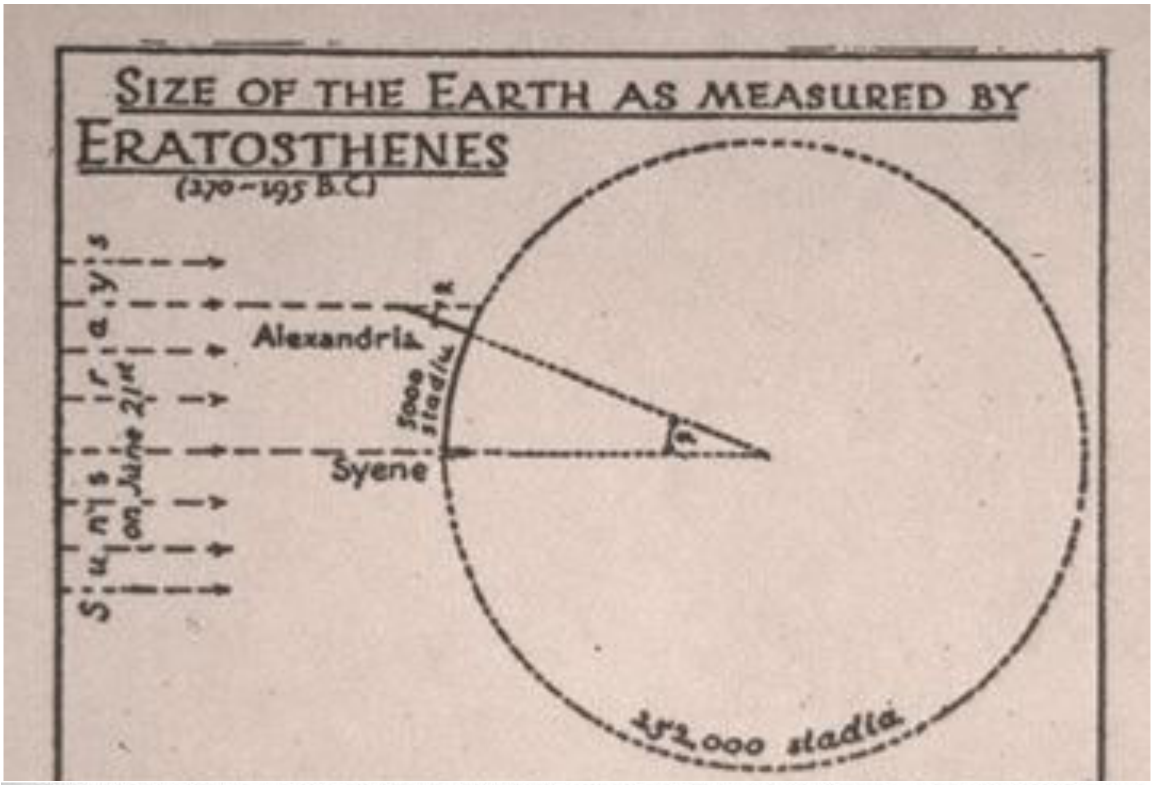
2) Accuracy (Systematic Error)

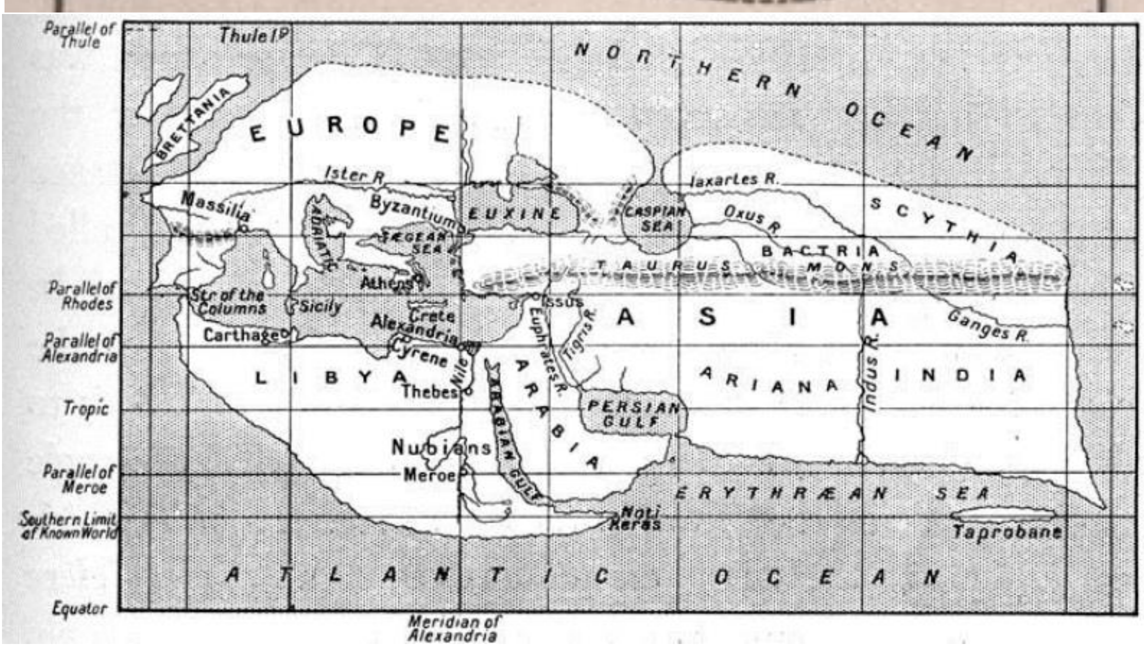
III.4 A systematic error is a factor that prevents you from obtaining a 100% accurate result, even if you perfectly executed your method for getting your data.

	Brief Description of Systematic Error	**Estimate of Size of Error**
1		
2		
3		

A **minimum** of two entries are required on each chart. (*Note:* A listing of "human error" is insufficient… be specific!)

III.5 Why does averaging many results *not* reduce the effects of systematic errors (i.e. not produce a more *accurate* measurement)?


SIZE OF THE EARTH AS MEASURED BY ERATOSTHENES
(270–195 B.C.)
Sun's rays on June 21st
Alexandria
Syene
5000 stadia
252,000 stadia


Parallel of Thule
Thule I?
NORTHERN OCEAN
BRETTANIA
EUROPE
Ister R.
Massilia
ADRIATIC
Byzantium
EUXINE
CASPIAN SEA
Iaxartes R.
Oxus R.
SCYTHIA
ÆGEAN SEA
BACTRIA
TAURUS MONS
Athens
Parallel of Rhodes
Str. of the Columns
Sicily
Crete
Issus
ASIA
Ganges R.
Parallel of Alexandria
Carthage
Alexandria
Cyrene
Nile
Euphrates R.
Tigris R.
LIBYA
Thebes
ARABIA
ARIANA
Indus R.
INDIA
Tropic
PERSIAN GULF
ARABIAN GULF
Nubians
Parallel of Meroe
Meroe
ERYTHRÆAN SEA
Southern Limit of Known World
Noti Keras
Taprobane
ATLANTIC OCEAN
Equator
Meridian of Alexandria

4 - KEPLER'S LAWS

SYNOPSIS: Johannes Kepler formulated three laws that described *how* the planets orbit around the Sun. His work paved the way for Isaac Newton, who derived the underlying physical reasons *why* the planets behave as Kepler had described. In this exercise, you will use computer simulations of orbital motions to experiment with various aspects of Kepler's three laws of motion. The learning goal of this lab is to understand what factors control a planet's motion around the Sun.

EQUIPMENT: Computer with internet connection, stopwatch.

PRELAB QUESTIONS:

1) Which law states that planets orbit in an ellipse?
2) What is the semi-major axis of an ellipse?
3) Explain why the following statement is false: The orbital period of Mars is longer than the Earth's orbital period because its orbit is less circular.
4) Mathematically, solve Kepler's 3rd Law for <u>period</u>.

Getting Started

Here's how you get your computer up and running:

(1) Launch an internet browser. (If you are using the computers in the scorpius computer lab, click the globe at the bottom of the screen to launch a browser.)

(2) Go to the website **http://astro.unl.edu/naap/pos/animations/kepler.html**

Note: We intentionally do not give you "cook-book" how-to instructions here, but instead allow you to explore the various available windows to come up with the answers to the questions asked.

Part I. Kepler's First Law

Kepler's First Law states that a planet moves on an ellipse around the Sun with the Sun at one focus.

If it is not already running, launch the NAAP *Planetary Orbit Simulator* described in the previous section.

- Click on the Kepler's 1st Law tab if it is not already highlighted (it's open by default)
- One-by-one, enable all 5 check boxes. Make sure you understand what each one is showing.
- The white dot is the "simulated planet." You 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 (planet and star sizes don't change despite zooming in or out.)
- Change the eccentricity using the eccentricity slider. Note the maximum value allowed is not a real physical limitation, but one of practical consideration in the simulator.

- Animate the simulated planet. Select an appropriate animation rate.
- The planetary presets set the simulated planet's parameters to those like our solar system's planets (and one dwarf planet). Explore these options.

I.1 Where is the Sun located in the ellipse?

I.2 Can a planet move on a *circular* orbit? If yes, where would the Sun be with respect to that circle? If no, why not?

I.3 What is meant by the eccentricity of an ellipse? Give a description (in words, rather than using formulae).

I.4 What happens to an ellipse when the eccentricity becomes zero?

I.5 What happens to an ellipse when the eccentricity gets close to one?

I.6 Draw an orbit below with non-zero eccentricity and clearly indicate a point where r_1 and r_2 are equal in value.

I.7 On planet Blob, the *average global* temperature stays exactly constant throughout the planet's year. What can you infer about the eccentricity of Blob's orbit? Explain your reasoning.

I.8 On planet Blip, the *average global* temperature varies dramatically over the planet's year. What can you infer about the eccentricity of Blip's orbit? *(Note: This is very different than the cause of seasons on Earth but does happen on some other planets in our solar system.)* Explain your reasoning.

I.9 For an ellipse of eccentricity $e = 0.7$, calculate the ratio of aphelion (the point farthest from the Sun) over perihelion (the point closest to the Sun). Use the grid to read distances directly off the screen (you may need to estimate fractions of a box).

I.10 For $e = 0.1$?

I.11 Without using the simulation applet, come up with an estimate for what the ratio of aphelion over perihelion would be for $e = 0$? What about as e gets very close to 1?

The following questions pertain to our own Solar System. Use the built-in presets to explore the characteristics of the members of our system.

I.12 Which of the Sun's planets (or dwarf planets) has the largest eccentricity?

I.13 What is the ratio of aphelion to perihelion for this object?

I.14 Which of the Sun's planets (or dwarf planets) has the smallest eccentricity?

Part II. Kepler's Second Law

Kepler's Second Law states that as a planet moves around in its orbit, the area swept out in space by a line connecting the planet to the Sun is equal in equal intervals of time.

Click on the Kepler's 2nd Law tab.

- **Important**: Use the "clear optional features" button to remove the 1st Law options.
- Press the "start sweeping" button. Adjust the semi-major 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 as you move it around.
- 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.
- Set the eccentricity to something greater than e=0.4

II.1 What eccentricity in the simulator gives the greatest variation of sweep segment shape?

II.2 Where (or when) is the sweep segment the "skinniest"? Where is it the "fattest"?

II.3 For eccentricity $e = 0.7$, measure (in sec, using your stopwatch) the time the planet spends

(a) to the left of the minor axis: _______, to the right of the minor axis: _______

(b) Write down your chosen animation rate *(don't forget the units!)*: _______

(c) Using your selected animation rate, convert from simulator seconds to actual years: left of the minor axis: ________, right of the minor axis: _________

II.4 Do the same again for eccentricity $e = 0.2$.

(a) to the left: __________(sec) __________(yrs)

(b) to the right: __________(sec) __________(yrs)

II.5 Where does a planet spend more of its time: near perihelion or near aphelion?

II.6 Where is a planet moving the fastest: near perihelion or near aphelion?

Part III. Kepler's Third Law

Kepler's Third Law presents a relationship between the size of a planet's orbit (given by its semi-major axis, a) and the time required for that planet to complete one orbit around the Sun (its period, P). When the semi-major axis is measured in astronomical units (AU) and the period is measured in Earth years (yrs), this relationship is:

$$P^2 = a^3$$

Click on the Kepler's 3rd Law tab.

- The logarithmic graph has axes marks that are in increasing powers of ten. You will use this type of graph a little more in a future lab. For now, stay on linear.

III.1 Rearrange the equation for Kepler's 3rd Law to give an expression for the value of the semi-major axis, a, in terms of a given period, P (i.e. solve for a). If the period increases by a factor of two, how much does the semi-major axis change by?

III.2 Does changing the eccentricity in the simulator change the period of the planet? Why or why not?

III.3 Halley's comet has a semi-major axis of about 17.8 AU and an eccentricity of about 0.97. Compare (in a rough sense) this eccentricity to our Solar System's planets. What is the period of Halley's comet? (*Food for thought: The last time Halley's comet came by was 1986. How old will you be when it comes back?)*

III.4 How does Kepler's 2nd Law contribute to why we can only see the comet close to Earth for about 6 months during each of those periods?

5 - SURVIVOR CHALLENGE

Name 1: _____________Name 2: _____________ Name 3: _____________

Work in a group. Write down all names, but you only need to turn in one paper.

What's the Big Idea of this activity?

Real science – as opposed to "cookbook" classroom science -- involves using creativity and imagination to figure things out. You've learned how to determine your latitude, and how the sun moves across the sky at different times of the year. The goal of the activity is to determine – roughly – **where you are on the earth and what time of year it is**, by observing the sky and inventing a method. You have not been taught how to determine your longitude, but we hope you can figure that out, too! Another goal of the activity is to inspire creativity and a better understanding of how scientists actually work.

SYNOPSIS: You will be taken to a random location somewhere on the northern hemisphere of the Earth at a random time of the year. Your goal is to figure out where you are located and what month of the year it is using only basic observations of the sky and your ingenuity. You will be graded primarily on the quality of your plan, not your answers.

EQUIPMENT: This lab write-up, a pencil, and a white board and marker to share with your group for brainstorming. Globes, laser pointers, and red flashlights are available to share among the whole class.

TOOLS AT YOUR DISPOSAL: You will effectively be in control of the planetarium; here are some tools and superpowers you can utilize to help you figure out your time and location on Earth:

- You will have a chance to observe the Boulder sky on the mystery date for 24 hours before you are taken to a mystery location.
- You have an imaginary watch that is always set to Boulder time during this whole activity. At any time, you can ask the planetarium operator "What time is it in Boulder?"
- You may request information from the planetarium operators, for instance, "stop turning the sky at sunset and tell us the time when the sun sets." Or, "stop the sky at noon."
- Once you are in the mystery location, you can observe the sky for 24 hours (and stop the sky as you wish). You may also observe any day one month earlier and one month later than the mystery date.
- You DO NOT have superpowers to be able to see lines, grids, degrees, cardinal directions, or other projections on the sky. You must use what you've learned in class and your ingenuity to discover some of these things for yourself!

Observations we will make and what they can tell us:

For each item give your answer, what evidence you used *and* how accurate you think it is.

Our latitude is:

We know this because:

Our longitude is:

We know this because:

The date is:

We know this because:

Where do you think you are?

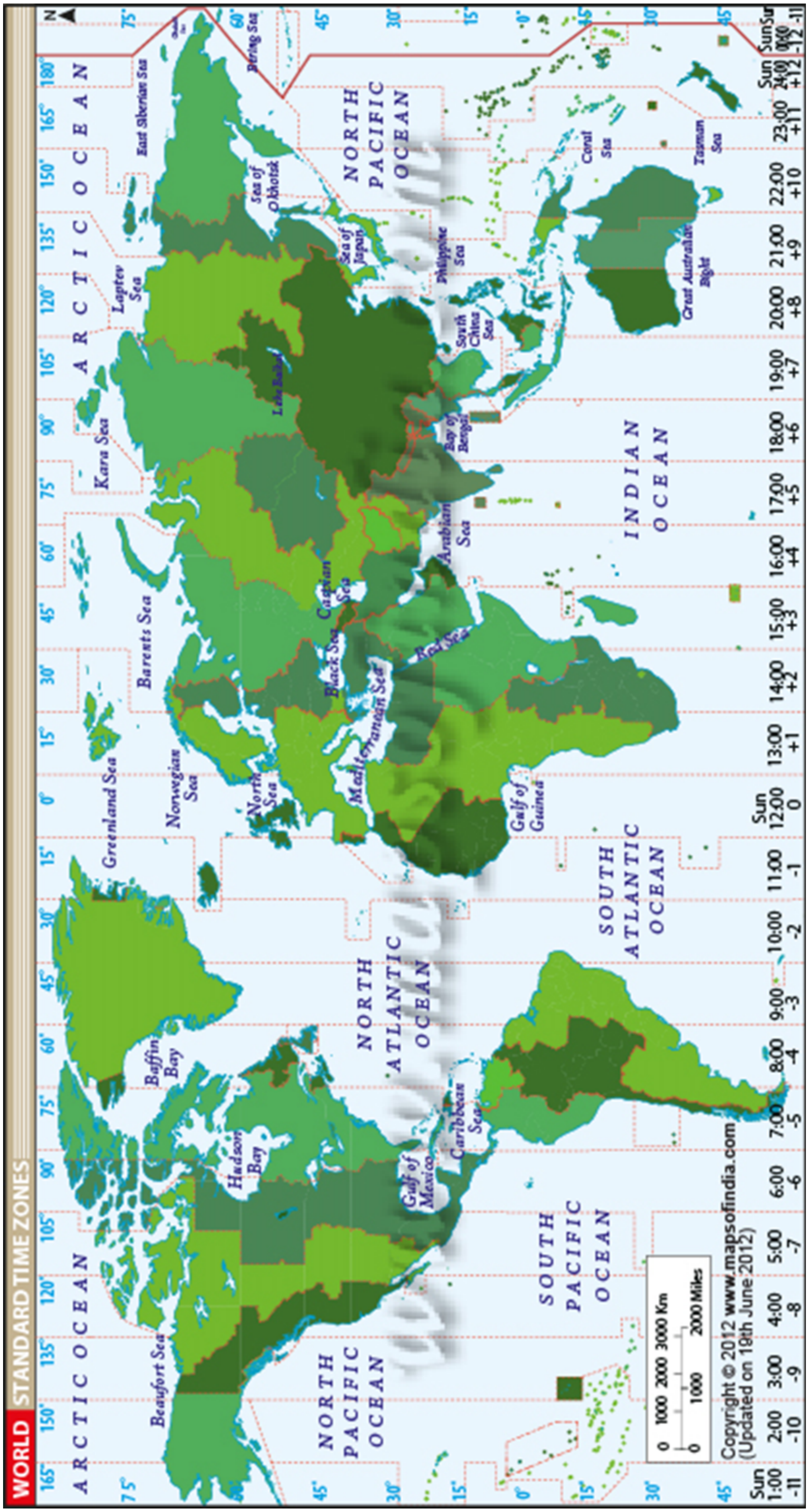


Image courtesy of www.mapsofindia.com

SPECTROSCOPY I – Light & Color

Learning Goals: The only way for astronomers to study distant objects is to examine the light we receive from them. What can we learn about astronomical objects from their light? Specifically, what does a planet's color tell us?

Equipment: Light bulb, set of 3 filters, spectroscope, colored marbles.

PRELAB QUESTIONS:
1) In general terms, explain how the spectroscope works. (You do not need to explain how the diffraction grating works, just what it does.)
2) Explain why the spectrum of white light looks the way it does.
3) • Explain why a blue shirt looks blue when viewed in white light.
   • What happens to all the other colors in the light?

A **spectrum** is the intensity of light at different wavelengths. Normally when we receive light from objects, the wavelengths are all mixed together and we can't tell how much of each wavelength is present. A **spectroscope** allows us to separate the different color components of light, allowing us to examine each wavelength separately. In this way, we can think of a **spectrum** as organized light -- organized according to wavelength.

Part I – White Light & RGB

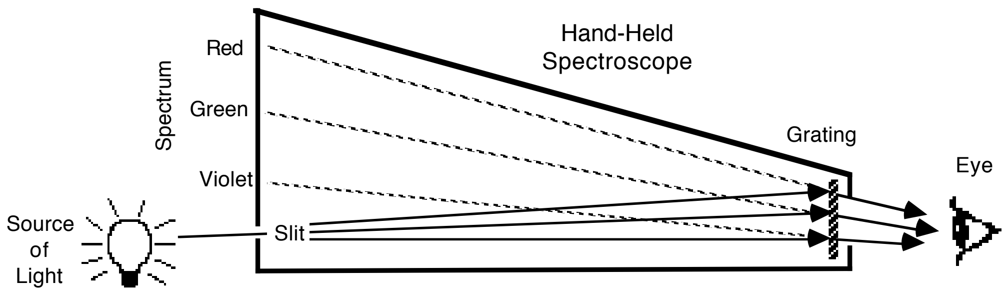
The goal of this section is to become familiar with how white light is a combination of colors. And to learn the "light verbs" that describe all the ways that light interacts with matter – emit, absorb, transmit, and reflect.

Turn on the light bulb.

1.1 List ALL the objects in the room that are ***emitting*** **visible light**.

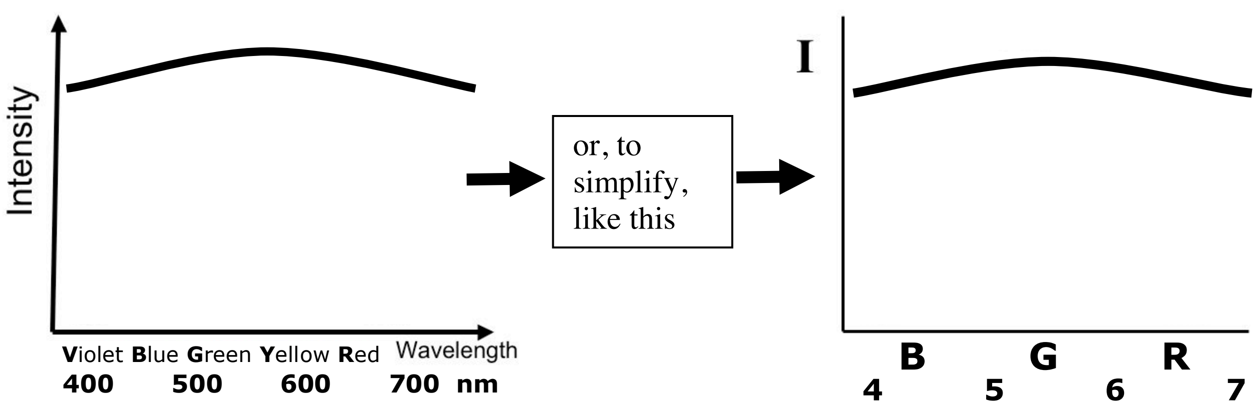
1.2 • Can you tell what colors are present within white light by simply looking at the bulb with the unaided eye? → Explain your answer.

A **spectroscope** is a device designed for viewing a spectrum. Light enters the spectroscope through a slit and strikes a diffraction grating made of a material that splits up each color in the light. The grating splits each color apart at a slightly different angle such that each color forms its own separate image of the light from the opening of the spectroscope. A slit is used that the opening to produce narrow images, so that adjacent colors do not overlap each other. The spectroscope has a numerical scale inside of it that measures the wavelength of the light in units of hundreds of nanometers.



1.3 Use the grating or spectroscope to look at the light bulb - What do you see?

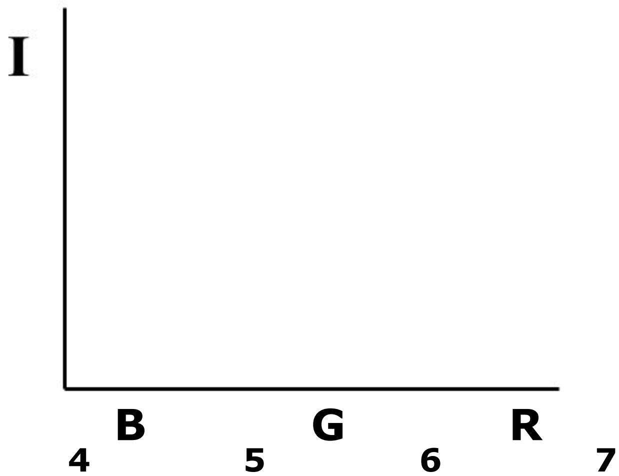
We can sketch the visible portion of a spectrum of white light like this:



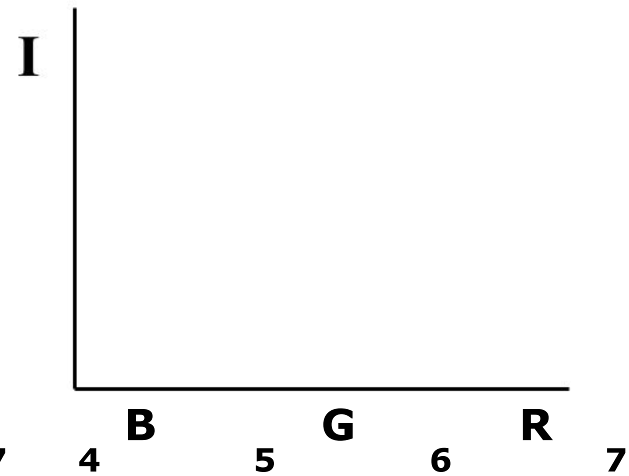
where all colors have a value for intensity because all colors are present in white light.

1.4 Using the spectroscope, look at the light through the various filters. Draw the spectra of the light being ***transmitted*** - “let through” - by the different filters. *Make sure the filter is covering the slit of your spectroscope.*

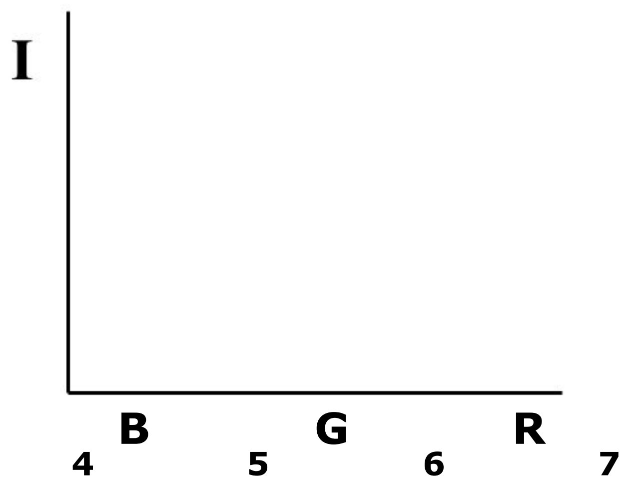
Filter:



Filter:

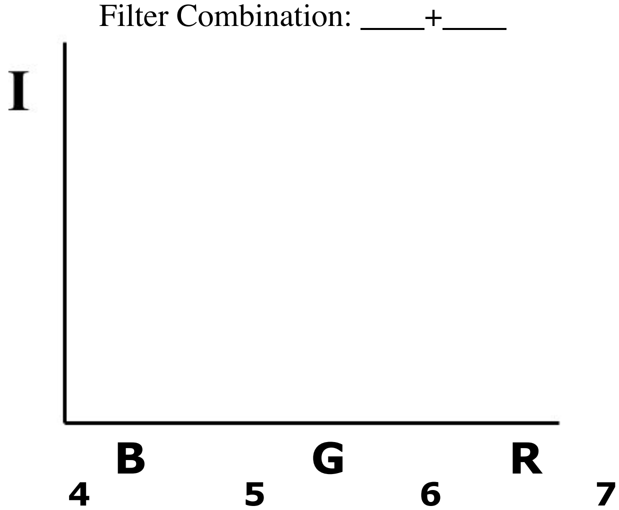


Filter: ________________

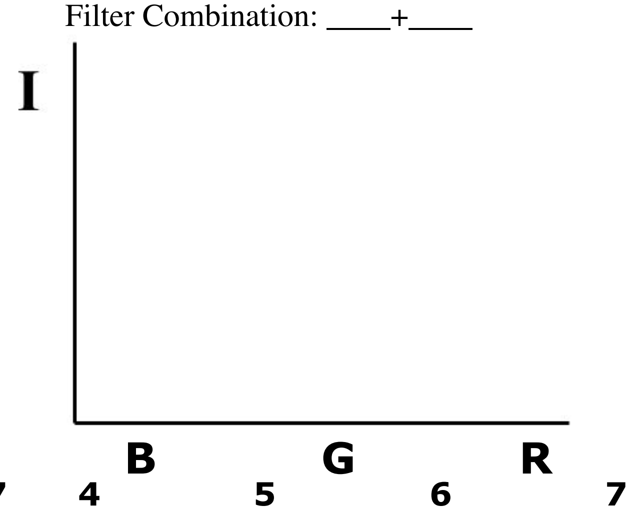


1.5 What happens when the light passes through 2 filters? **Before you try it…**on the graphs below, **predict** what the intensity curve would look like for 2 combinations of the filters - *choose 2 different combinations*.

Filter Combination: ____+____

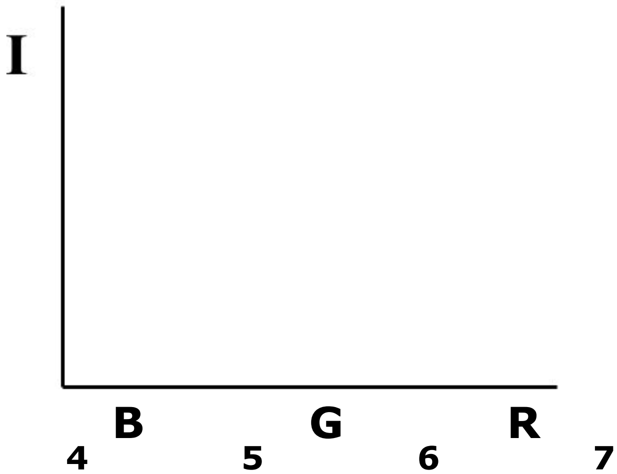


Filter Combination: ____+____

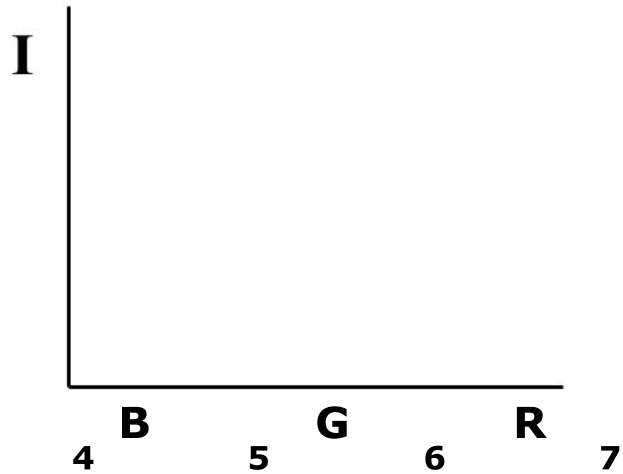


1.6 Now actually try out your 2 combinations from above and sketch your results below.

Filter Combination: ____+____



Filter Combination: ____+____



1.7 • Do your predictions from 1.5 match your findings from 1.6? → If not, explain why.
• Explain, in general, what using a filter does to the light coming into the spectroscope.

1.8 • Now think about the white light hitting your shirt/sweater.
• What color(s) is your shirt/sweater?

____

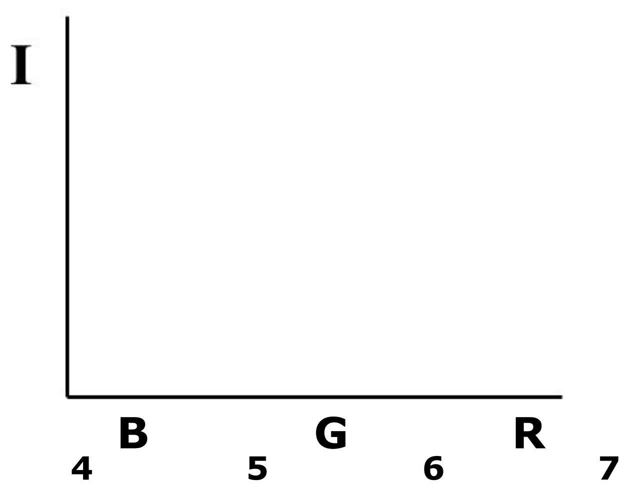
• What colors are ***reflected*** by your shirt/sweater?

____

• What colors are ***absorbed*** by your shirt/sweater?

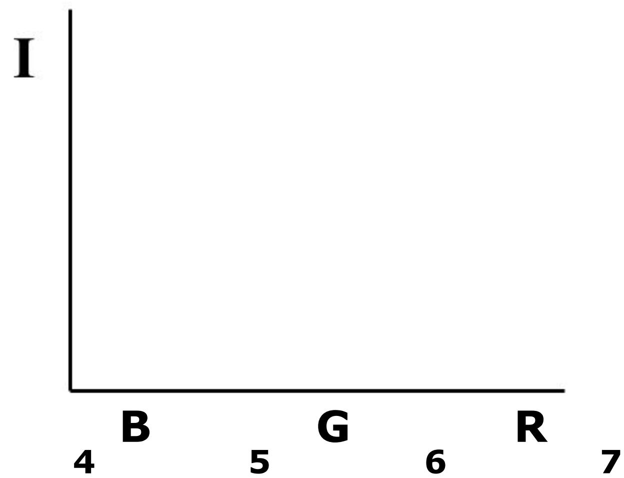
____

• On the graph to the right, draw what you think the spectrum of light **reflected** by your shirt/sweater is.



1.9 On the graph below draw **and label** what you think the reflected spectrum of the following 3 shirt colors would look like (you should have 3 different lines):

• Black •Gray •White



Part II – The RGB Room

The goal of this section is to explore the relationship between the color of an object, and how it is affected by the wavelengths of light available.

Up the first stairs you come to as you walk into the Observatory, on the left, there is a room with Red, Green and Blue spotlights. You can control the amount of each color light by sliding the 3 sliders on the white box.

2.1 In this section you will use marbles to study color.
• *Predict* what will happen if you look at a handful of colored marbles under a single colored light?

2.2 Try it. Take a small handful of marbles- make sure you have an assortment of colors. Now turn off all light except the red light and try to sort the marbles into piles according to color.
• Is it easy to sort out all the colors? → Explain why it is easy/hard to sort the marbles with only the red light on in terms of what is happening with light.

2.3 Once you've sorted the marbles under the red light, turn the white room light back on.
• Did you sort them all correctly?
• List a few colors you mistook for each other. → Explain why these colors were mistaken for each other.

2.4 Mix the marbles up again and now try to sort them using the green light only. Once they're sorted, turn on the white room light and check you work.
• Did you sort them all correctly?
• If not, did you mix up the same colors using the green light only as the red light only?

2.5 Keeping the same sorted piles you made in 2.4, turn off all the lights except the red light and green light.
• With both the red and green light on is it easier to tell which colors have been sorted incorrectly?
• Explain why it is/is not easier to sort with both the red and green lights on in terms of what is happening with light.

2.6 Now turn on all three colored lights.
• Are you able to clearly distinguish all the marble colors now? → Explain why or why not.

2.7 Now turn off all lights except the white room light and find the white sheet of paper with the red shape on it.
• **Predict -** will you be able to see the red shape on the paper under the red light only?

2.8 Now turn off the white room light and look at the sheet of paper under the red light only.
• Was your prediction from 2.7 correct? → Explain what is happening with light in this situation.

Before you leave, turn off all the colored lights and turn on the white room light.

Part III – The Yellow Room

Be sure to bring your spectroscope! **The goal of this section is to explore the relationship between the appearance of an object and how it is affected by the wavelengths of light available.**

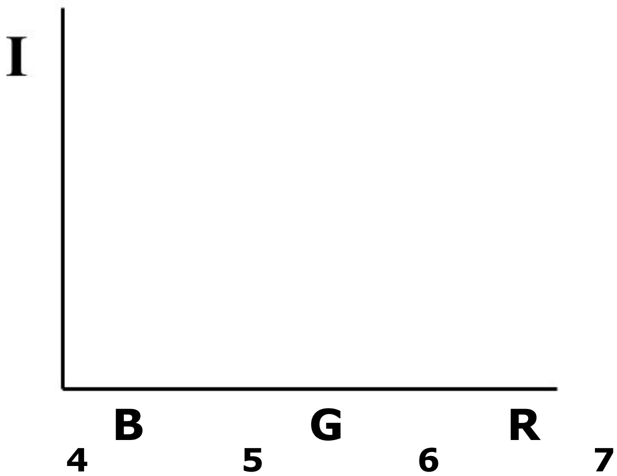
The yellow room is a room illuminated by different types of lights that all emit a very similar yellow color but do it very differently.

3.1 Look at the various objects in the room in each of the following two lights without the spectroscope – *be sure to turn off the room light and only open each light's door one at a time*.
• Describe how a few objects look under each light
Incandescent: Fluorescent:

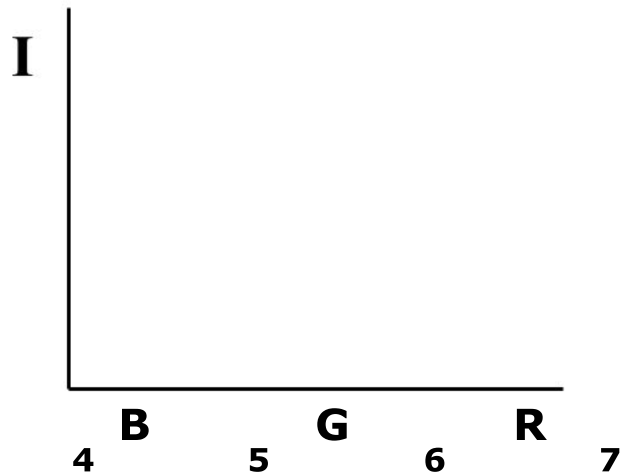
3.2 Based on your observations in 3.1, **predict** what each of the lights' spectra will look like **before** you look through the spectroscope

- Draw your prediction of the spectra for each bulb below. (You may also use words to clarify your prediction below.)

Incandescent:



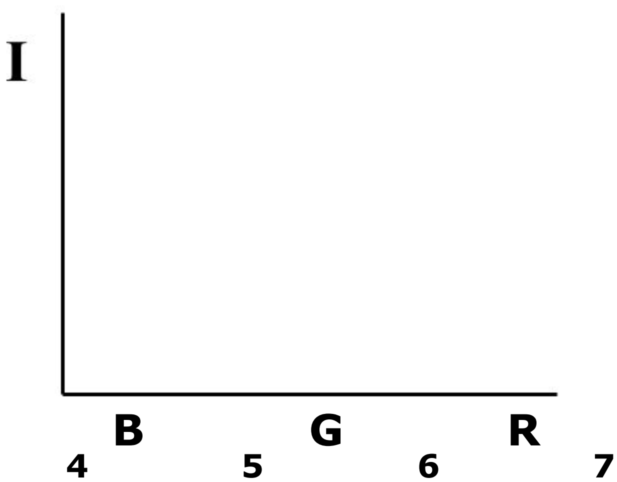
Fluorescent:



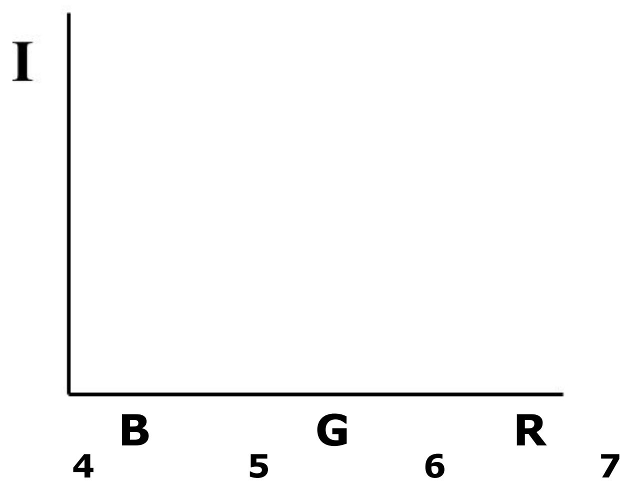
3.3 Now use your spectroscope, to examine the spectrum of each light.

- Were your predictions correct?
- If not, correct your descriptions below on the graphs.

Incandescent:



Fluorescent:



3.4 The next light you will examine is a sodium lamp. The sodium lamp emits yellow light at only <u>one</u> wavelength – this is known as "monochromatic light."

- **Before you look, predict** what the multi-colored sweater will look like under the sodium lamp.

3.5 Close all the light doors and make sure the room light is off. Now open the sodium light door.

- How do things look under the sodium light?
- How did the color of the multi-colored sweater change?

3.6 Check out some of the other colored items – guess what color they are. Then turn on the room light.

- Did you guess all the correct colors? → Explain why or why not.

3.7 Look at the sodium lamp through your spectroscope.

- Explain how the light emitted by the sodium lamp is changing the color you see on the multi-colored sweater and the colored objects in the room.
- Use what you observed through the spectroscope to aid your explanation.

3.8

- Choose one object in the room and explain why it looks the way it does in each of the 3 lights – be sure to say which object you chose in your answer.

Before you leave, make sure the sodium lamp is uncovered and all other lights are covered.
PLEASE DO NOT TURN OFF THE SODIUM LAMP.

Part IV – Colored Planets

The goal of this section is to apply your experience with white light and filters to study planetary objects. You will not need your spectroscope for this section.

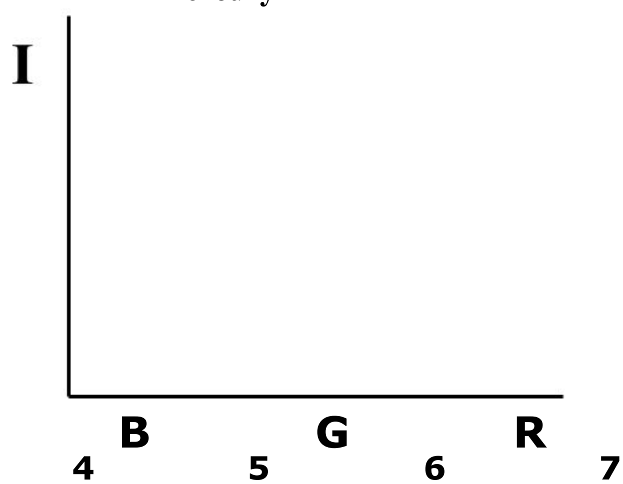
4.1 Examine the images provided of planetary objects. These planetary objects are reflecting visible light – that's why we can see them.

• Where is the reflected visible light from the planets originally coming from in our solar system?

4.2 • Sketch the spectra of reflected light from the different objects.

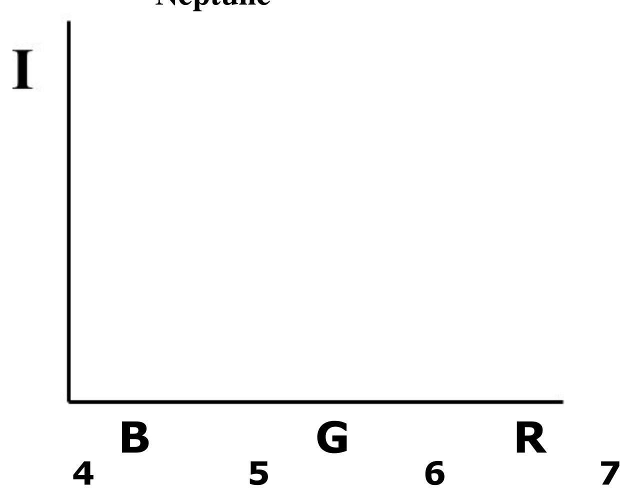
Io (Moon of Jupiter)

Mercury



Mars

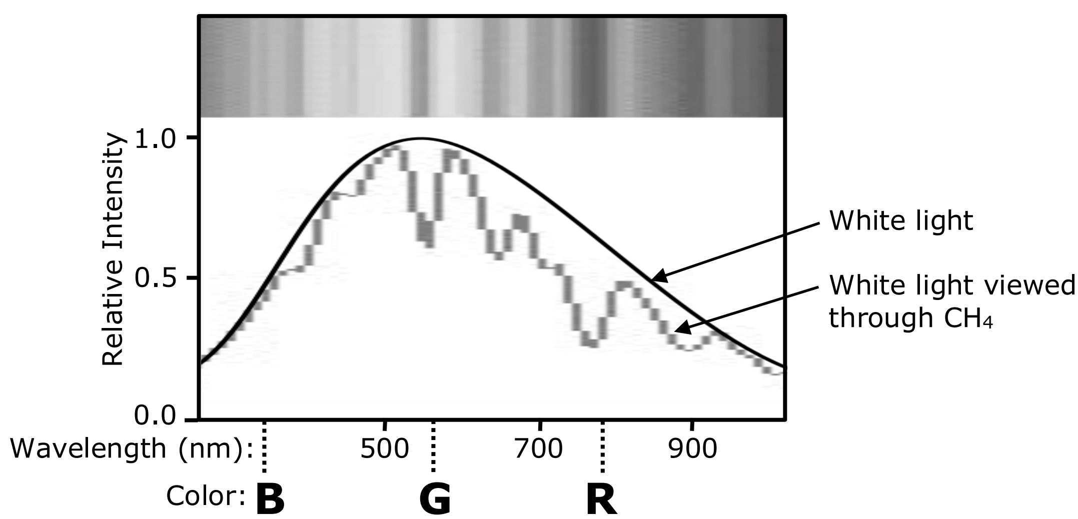
Neptune



4.3 Imagine you had access to a laboratory where you could examine the spectra of each element on the periodic table.

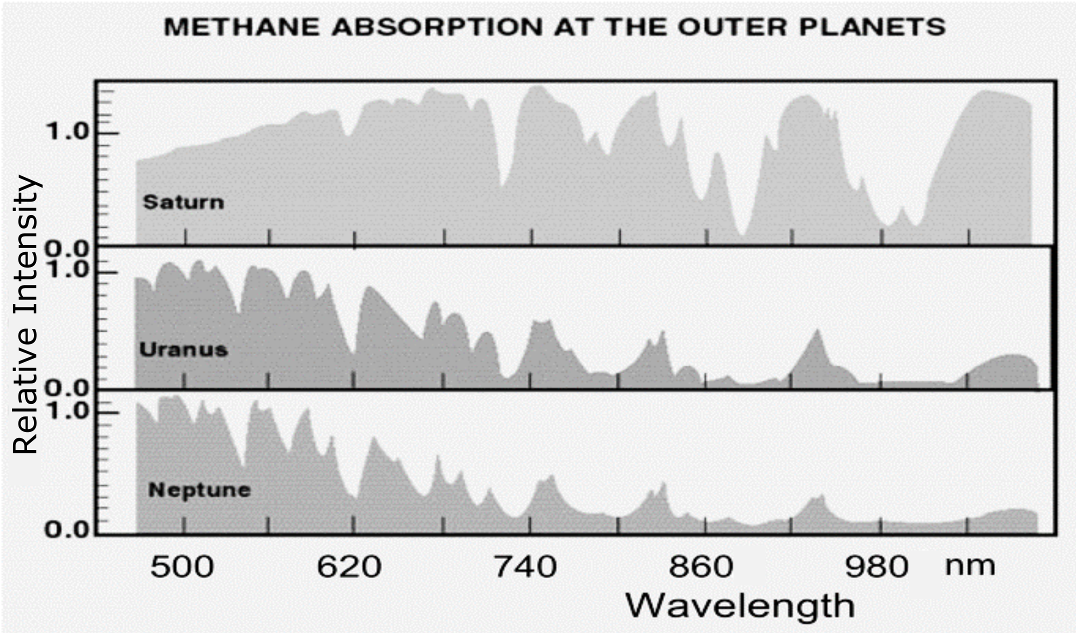
- How could you use the laboratory and the four sketches you made above to determine the elemental composition of the surfaces (or outer cloud layers) of the planetary objects above?

In the figure below there are two spectra: one of **white (aka visible)** light and one of **white** light that has **passed through methane gas** (CH_4).



4.4 We can observe how methane interacts with white like by looking at the **relative** difference between the *white light* spectrum and the *white light viewed through* CH_4 spectrum. By comparing the two spectra above, determine:

- What colors of the visible spectrum are **absorbed** by methane?
- What colors of the visible spectrum **transmitted** by methane? (To simplify, think about the BGR scale we used above).

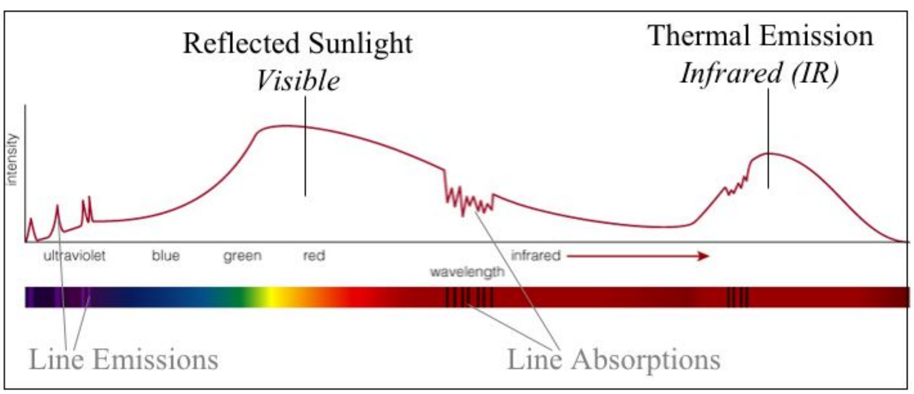


4.5 The 3 plots above are spectra of reflected light from Saturn, Uranus, and Neptune.
- Which planet(s) seem(s) to have significant methane in their atmosphere?

Part V – Planets and People at Infrared Wavelengths

Visible light is only one of several types of light that we can study. The goal of this section is to examine another type of light called infrared (IR) light. By using a camera designed to display IR light, you will discover how IR light contains information that otherwise cannot be seen with visible light alone.

In addition to **reflecting** visible light, planets also **emit** infrared, or IR light. The figure the right shows what the spectra of a planet looks like. In this section we'll explore some of the properties of IR light.



5.1 Do you think any of the objects in the room are emitting infrared light?
- Which one(s)?

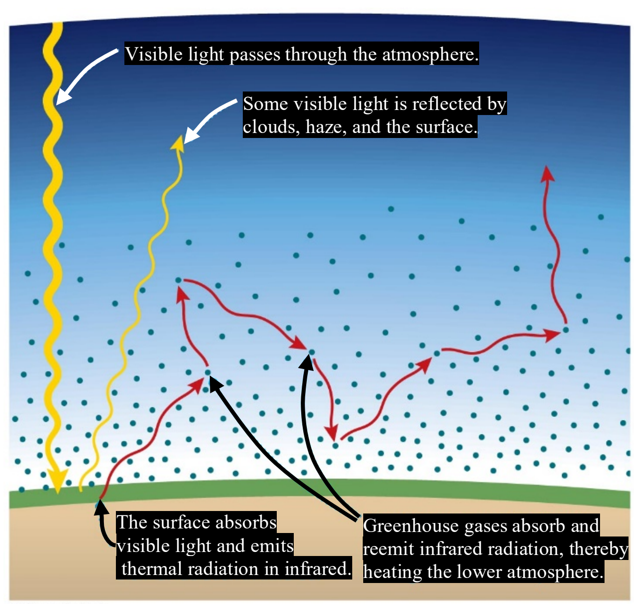
5.2 Check out the IR camera and TV monitor.
- Stand in front of the camera – What parts of the body look warm?
- What looks cold? (Note: the colors you see on the IR camera don't follow the temperature-color relationship aka Wein's Law)

5.3 Examine the black plastic garbage bags as well as the clear plastic square.
- Describe what you see. *Be sure to unfold the garbage bag entirely.*

5.4
- Does IR light interact with the black plastic garbage bag in the same way that visible light does? What about for the clear plastic square? → Explain why or why not for both objects in term of what is being **reflected** or **absorbed** and what is **transmitted.**

Garbage Bag: Plastic Square:

5.5 The phenomena you just examined above is related to the **greenhouse effect** that occurs in Earth's lower atmosphere. (Ask your TA/LA to explain this effect if you have not yet covered it in lecture.)
- Given what you know about the greenhouse effect, which material is the most similar to the Earth's lower atmosphere: the garbage bag or the plastic sheet? → Explain your answer.



7 - SPECTROSCOPY II – Spectral Barcodes

"I ask you to look both ways. For the road to a knowledge of the stars leads through the atom; and important knowledge of the atom has been reached through the stars." - A.S. Eddington

SYNOPSIS: Many objects in astronomy need to be studied from a distance by means of visible or invisible light (infrared; ultraviolet; etc.) What can we learn about astronomical objects from their light? What does light tell us about the chemical composition of the object that produced the light?

EQUIPMENT: Hand-held spectroscope, spectrum tube power supply, helium, neon, nitrogen, air, and "unknown" spectrum tubes, incandescent lamp, heliostat.

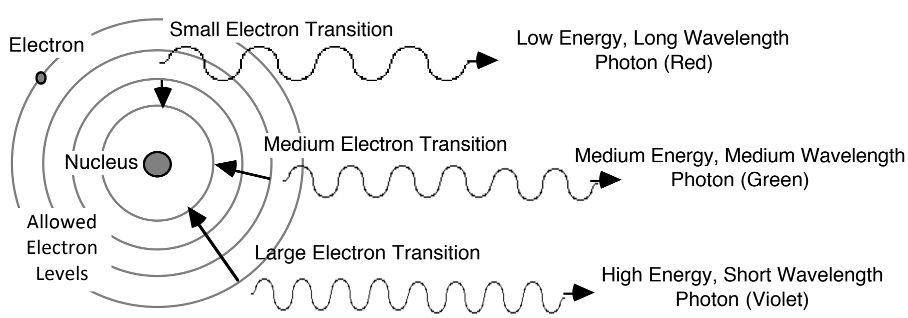
PRELAB QUESTIONS:

1) When electrons move down in energy levels, are they gaining or losing energy? If gaining, where did this energy come from? If losing, where does the energy go?
2) How does an incandescent light bulb differ from a fluorescent light bulb? Why would you expect their spectra to look different?
3) How can a spectrum be used to identify an unknown gas? Why are spectra often referred to as 'fingerprints' of a gas?

Reminder – What Is Spectroscopy?

Most of what astronomers know about stars, galaxies, nebulae, and planetary atmospheres comes from **spectroscopy**, the study of the colors of light emitted by such objects. Spectroscopy is used to identify compositions, temperatures, velocities, pressures, and magnetic fields.

An atom consists of a nucleus and surrounding electrons. An atom emits energy when an electron jumps from a high-energy state to a low-energy state. The energy appears as a **photon** of light having energy exactly equal to the *difference* in the energies of the two electron levels. Since each element has a different electron structure, and therefore different electron energy states, *each element emits a unique set of spectral lines.*



Part I – Electron Energy Transitions

I.1 (a) Using the model of electron transitions, explain how an atom can give off light.

(b) What can you infer about the transitions if atoms of a single element give off both red light and blue light?

I.2 **(a)** Using the model of electron transitions, explain how an atom can absorb light.

(b) What can you infer about the transitions if an atom absorbs both red light and blue light?

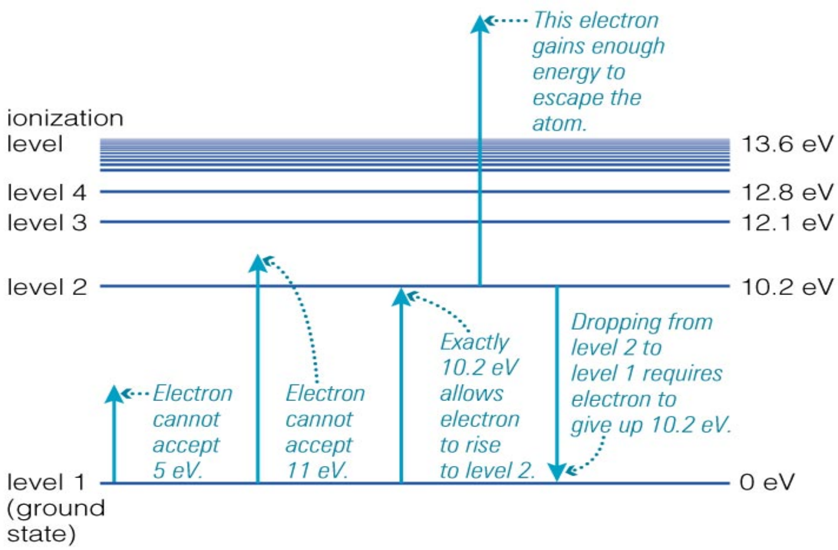
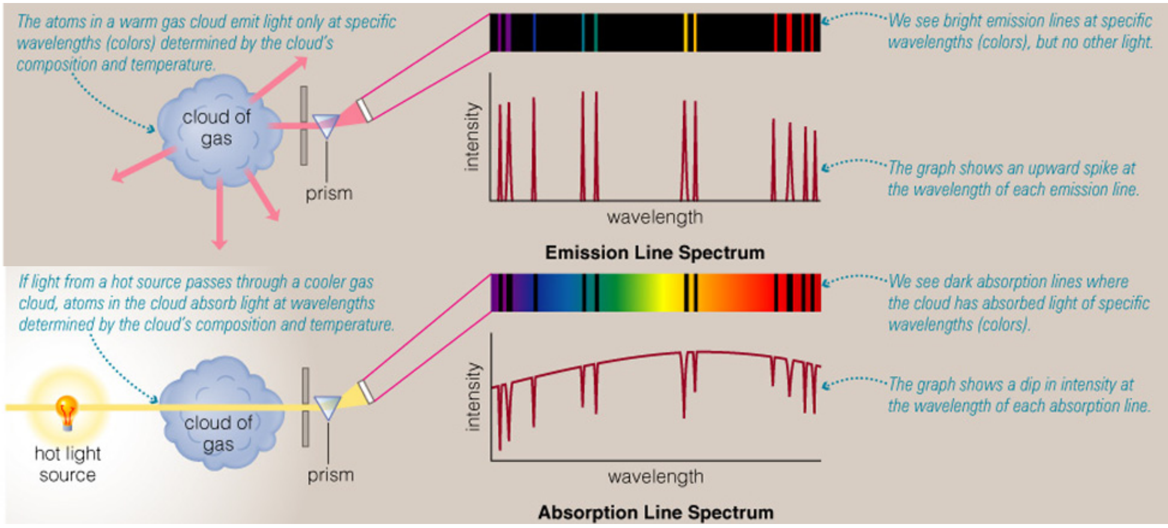
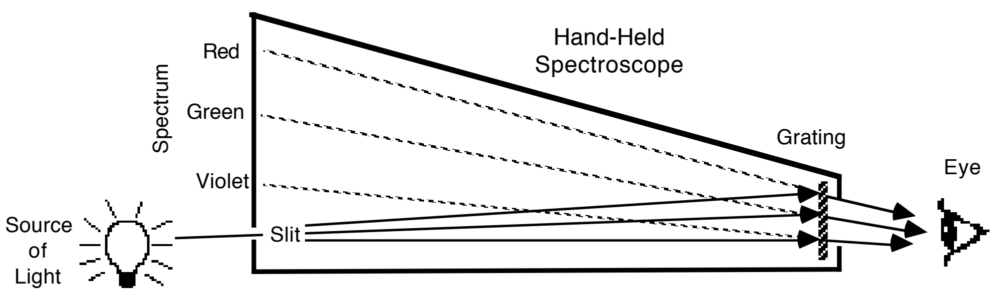


Figure 5.12 from the textbook showing the energy levels for an electron in a hydrogen atom.

I.3 Will an atom emit light if all of the atom's electrons are in the ground state? Explain your reasoning.



A **spectroscope** is a device that allows you to view a spectrum. Light enters the spectroscope through a slit and passes through a grating which disperses – or "splits up" - the light into its components (colors, wavelengths, energies).



Part II – Continuous and Emission Line Spectra

Look at an ordinary light bulb. Can you see all of the colors of the spectrum, spread out LEFT to RIGHT (Not up and down)? If the colors go up and down rotate your grating 90 degrees. Ask for TA/LA help if you don't see this.

You should see the familiar rainbow of colors you saw with the diffraction grating slide you used in the Spectroscopy 1 lab last week.

II.1 Look through the spectroscope at the *incandescent lamp* (regular light bulb) and sketch the spectrum:

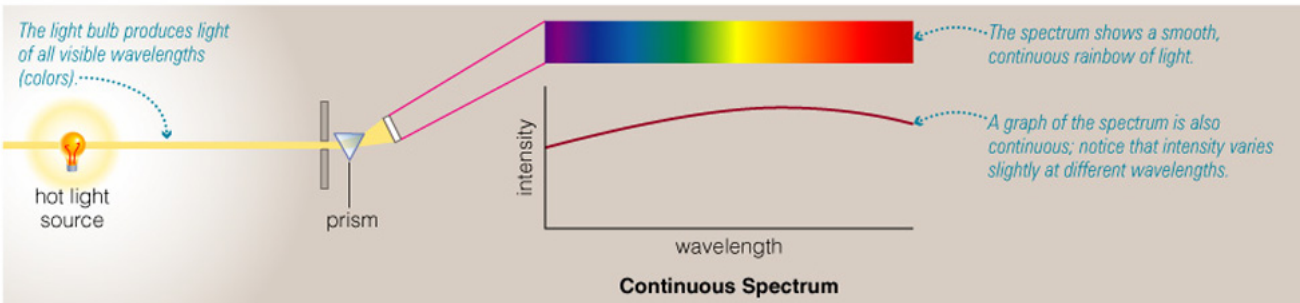
BLUE RED

(a) Describe (in very basic terms) what you see.

(b) Are there any distinct spectral lines?

(c) What is inside an incandescent light bulb that emits light: a solid or a gas?

A *solid* glowing object will not show a characteristic atomic spectrum, since the atoms are not free to act independently of each other. Instead, solid objects produce a **continuum spectrum** of light regardless of composition; that is, *all* wavelengths of light are emitted rather than certain specific colors.



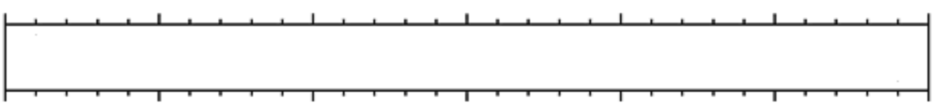
For each of these gases (Helium, Neon and Nitrogen):

- Install the element discharge tube in the power supply and turn it on
- Look through the spectroscope at the gas tube.
- Turn off the power supply before changing tubes.

CAUTION! The tubes are powered by 5000 volts! Do NOT touch the sockets when the power supply is on. The tubes also get very HOT! Let the tubes cool, use paper towels to handle them.

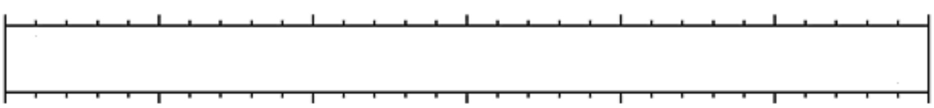
II.2 What colors do you see? Make a sketch - of the distinctly separate spectral lines (colors) of the light emitted by the element you are looking at on the frame below - use colored pencils or crayons if you wish.

Helium



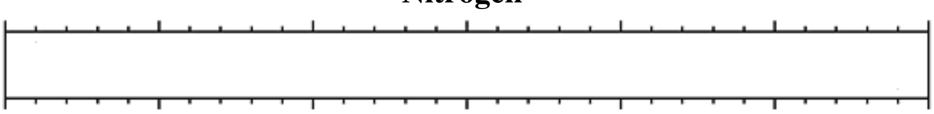
BLUE RED

Neon



BLUE RED

Nitrogen



BLUE RED

II.3 For each of these elements, how does the overall color of the glowing gas compare with the specific colors in its spectrum?

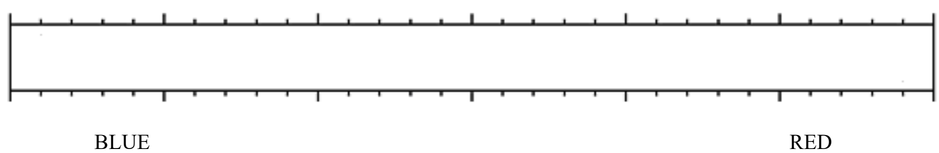
- Helium
- Neon
- Nitrogen

II.4 Judging from the number of visible energy-level transitions (lines) in the neon gas, which element would you conclude has the more complex atomic structure: helium or neon? Explain.

Fluorescent lamps operate by passing electric current through a gas in the tube, which glows with its characteristic spectrum. A portion of that light is then absorbed by the solid material lining the tube, causing the solid to glow, or **fluoresce,** in turn. You therefore get a combination of the spectrum of a solid and a gas.

II.5 *Predict*: Do you expect to see a continuous spectrum, a line spectrum, or a combination of both?

Point your spectroscope at the *fluorescent* lights, and sketch the spectrum.



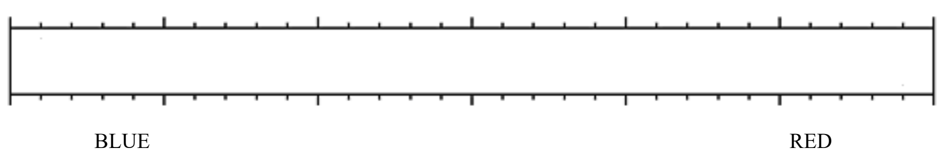
II.6 Which components of the spectrum originate from the gas?

II.7 Which components of the spectrum originate from the solid?

Part III - Identifying an Unknown Gas

Select one of the unmarked tubes of gas (it will be either hydrogen, mercury, or krypton). Install your "mystery gas" in the holder and inspect the spectrum.

III.1 What is the color of the glowing gas? Make a sketch of the spectrum and label the colors.



III.2 Identify the composition of the gas in the tube by comparing your spectrum to the spectra described in the tables on the next page. Explain which lines you used to make your identification.

Strongest lines are shown in **boldface** type. The numbers to the left of each color are the wavelengths of the spectral lines given in nanometers– that's 10^{-9} meters.

Hydrogen	
656	**Red**
486	**Blue-Green**
434	Violet
410	Deep Violet (dim)

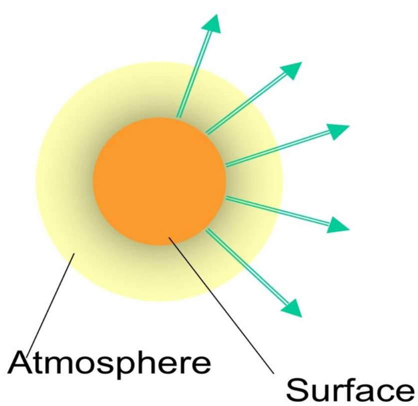
Mercury	
607	Orange
578	**Yellow**
546	**Green**
492	Blue-Green (dim)
436	**Violet**
405	Violet (dim)

Krypton	
646	**Red**
587	**Yellow-Orange**
557	**Green**
450	Violet (dim)
446	Violet (dim)
437	Violet (dim)
432	Violet (dim)
427	Violet (dim)

Part IV. Solar Spectrum – *Hopefully the Sun is shining!*

If the Sun is shining, the TA will use the Heliostat to bring up the solar spectrum. This involves using mirrors, lenses and a grating to pipe in sunlight from outside and to split the light by wavelength.

IV.1 What do you see? Describe the solar spectrum in terms of *continuous, emission* and/or *absorption* components.



IV.2 Based on the (extremely simplistic) model of the Sun above, which component of the spectrum comes from the Sun's surface? Which is due to the Sun's atmosphere?

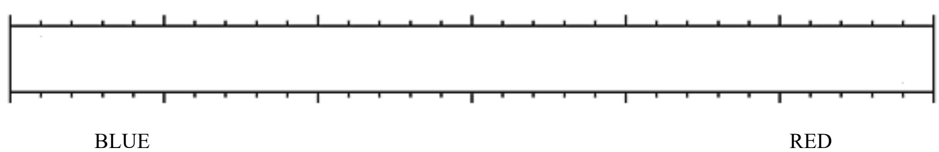
IV.3 Your TA will also put light from a couple of gas tubes through the same optics that will produce emission lines above/below the solar spectrum. Are these gases present in the solar spectrum? Explain.

IV.4 How many lines of hydrogen can you find in the solar spectrum? (List which ones.)

IV.5 Have your TA identify the sodium absorption lines. What color are they in? What color are sodium (emission) lamps? *(Hint: Think back to the last lab.)* Explain the reason for the similarity.

Part V – The Aurora – *What makes the Northern Lights?*

Install the tube of gas marked "*air*" and look at the spectrum. Compare it to the other spectra you have looked at.



V.1 What molecule(s) is/are responsible for the spectral lines you see in air?

The Physics of Auroral Light Formation

The high-energy electrons and protons traveling down Earth's magnetic field lines collide with the atmosphere (i.e., oxygen and nitrogen atoms and molecules). The collisions can excite the atmospheric atom or molecule or they can strip the atmospheric particle of its own electron, leaving a positively-charged ion. The result is that the atmospheric atoms and molecules are excited to higher energy states. They relinquish this energy in the form of light upon returning to their initial, lower energy state. The particular colors we see in an auroral display depend on the specific atmospheric gas struck by energetic particles, and the energy level to which it is excited. The two main atmospheric gases involved in the production of auroral lights are oxygen and nitrogen:

- **Oxygen** is responsible for two primary auroral colors: green-yellow wavelength of 557.7 nm is most common, while the deep red 630.0 nm light is seen less frequently.
- **Nitrogen** in an ionized state will produce blue light, while neutral nitrogen molecules create purplish-red auroral colors. For example, nitrogen is often responsible for the purplish-red lower borders and rippled edges of the aurora.

Auroras typically occur at altitudes of between 95 and 1,000 km above sea level. Auroras stay above 95 km because at that altitude the atmosphere is so dense (and the auroral particles collide so often) that they finally come to rest at this altitude. On the other hand, auroras typically do not reach higher than 500-1,000 km because at that altitude the atmosphere is too thin to cause a significant number of collisions with the incoming particles.

Sometimes you can see multiple colors (coming from different layers of the atmosphere) but more usually only one layer (and chemical constituent) is excited at a time, during a particular auroral storm.

Please do NOT mark on the photographs!

V.2 Look at the 4 auroral pictures provided on a separate sheet (2 taken from the ground, 2 from space). For each image say what gas is emitting the light and at what height: lower (<100 km), middle (100-200 km) or upper (>200 km) auroral regions of the atmosphere.

A

B

C

D

8 - COLLISIONS, SLEDGEHAMMERS, & IMPACT CRATERS

SYNOPSIS: The objectives of this lab are: (a) become familiar with the size distribution of particle fragments resulting from collisions; (b) compare that distribution with that of interplanetary debris found in the asteroid belt; and (c) relate the size distribution of craters on the Moon to the size distribution of fragments in the solar system.

EQUIPMENT: Sledgehammer, brick, denim cloth, sieves, plastic bags, buckets, scale, safety goggles, calculator, graph overlays.

PRELAB QUESTIONS:

1) Why does smashing the brick does not result in changing its density?
2) When you smash the brick, do you *expect* more large pieces or small pieces?
3) Why should counting a small patch of craters on the moon show the same distribution as asteroids in the solar system?
4) Complete parts I.1-I.3 of the lab *before* coming to lab. You may be required to show this completed to your TA to get full credit on your prelab.

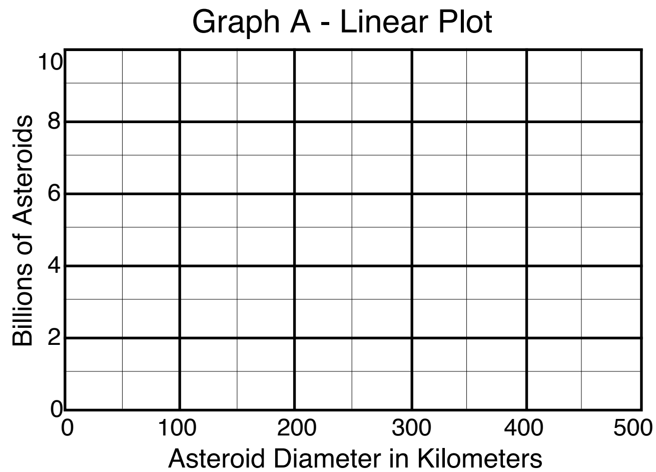
Part I. Power Law Distributions

Numbers and sizes of asteroids in the asteroid belt are not random, but rather exhibit a fairly well behaved and predictable pattern. For example, smaller asteroids are much more numerous than larger ones. Only three asteroids in the belt have diameters exceeding 500 km, yet twelve have diameters greater than 250 km, and approximately 150 asteroids are greater than 100 km across. Thousands of asteroids tens of kilometers in size have been catalogued. There are also uncountable numbers of smaller ones going all the way down to grain-sizes. The term given to this relationship between number and size in such a system is the **size distribution**.

Size Distribution of Asteroids

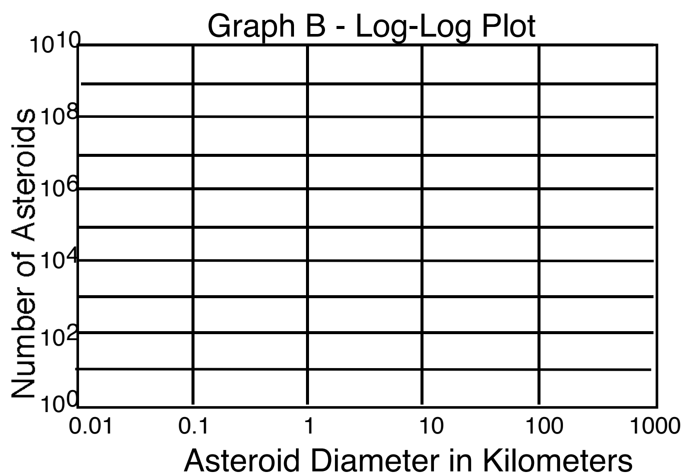
Diameter	*Number*
500 km	Three (3×10^{0})
250 km	Ten (1×10^{1})
100 km	130 (1.3×10^{2})
10 km	5,000 (5×10^{3})
1 km	1,000,000 One Million (10^{6})
0.05 km	10,000,000,000 Ten Billion (10^{10})

I.1 Using Graph A (a **linear plot**), try to graph the size distribution of all of the asteroids in the list above.



You will probably find that plotting these data on this simplistic scale is extremely difficult (or impossible). The range of the numbers involved is simply far too large to conveniently be displayed in any meaningful manner on a linear plot.

I.2 Now, plot the same numbers again, but this time using the scale provided with Graph B (a **log-log plot**).



Graph B is a **logarithmic** plot, in which both the x- and y-axes are in increasing powers of 10. Commonly, the use of logarithmic scales enables you to accommodate the full range of the numbers involved, and also can show you if there are any interesting distribution trends among those numbers.

I.3 In Graph B, how many orders of magnitude (powers of 10) are there on: (i) the x-axis? (ii) the y-axis?

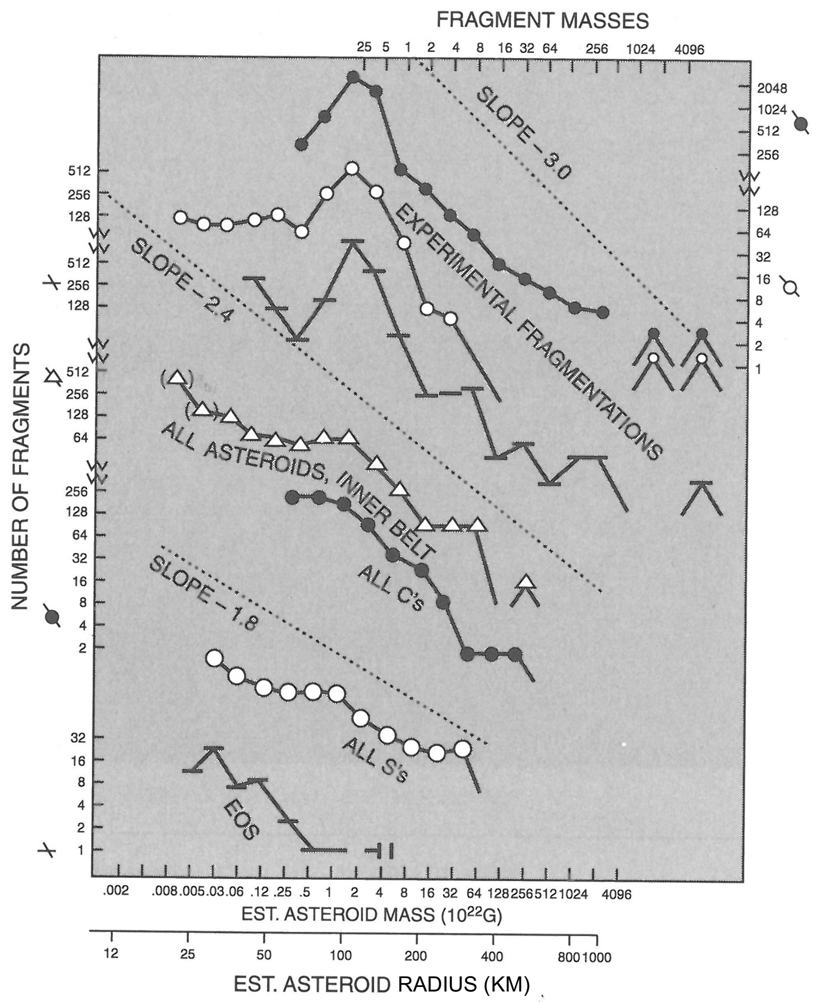
The trend of asteroid sizes approximates a **power law** of the form:

$$N = A\ R^b$$

Here N is the number in a given radius (R) interval on the logarithmic scale, and A is a constant of proportionality. (By switching from diameters to radii, we've simply hidden a factor of ½ into the constant A.) When plotted on a log-log plot, the distribution of objects that follow a power law behavior yield a *straight line*, the *slope* of which is equal to the power law exponent *b* (which is always a negative value). For objects in the asteroid belt, *b* has a value of approximately –2. This power law distribution of relative abundance persists over many orders of magnitude (many powers of ten).

In the simplest terms, this mathematical relationship means that there are many more small fragments than large fragments resulting from disruptive collisions in the asteroid belt. The surprise is that such a general trend should be so precise that it holds true over objects differing in size by 100 million!

The figure below shows both the results of experimental fragmentation, and the actual distribution of asteroids. The lines connecting the data points for the asteroids correspond approximately to b = –2.

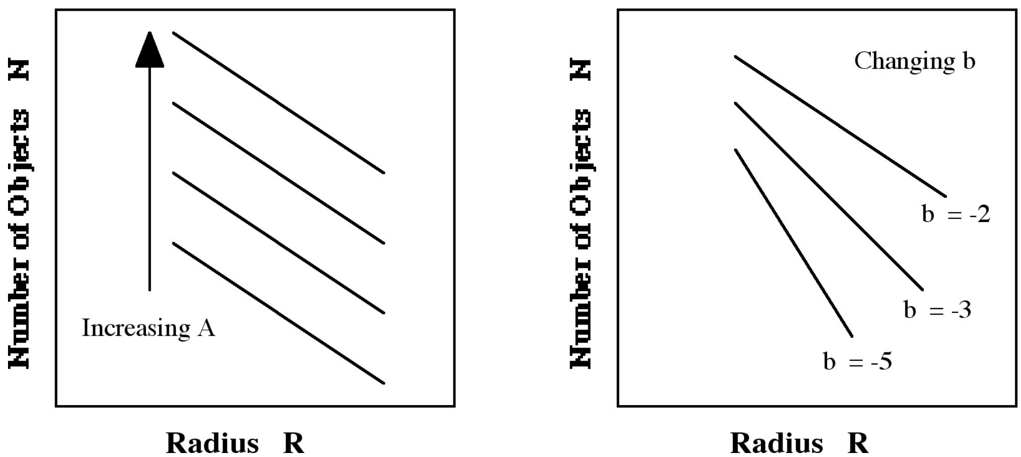


Size distributions of impact-shattered rock fragments and asteroids: The top three curves are fragment distributions of artificial targets of rock with masses on upper scale. The bottom four curves show actual asteroids, with masses on the lower scale, including members of the Eos Hirayama family—which may be fragments of a single asteroid collision event.

(From *Moons and Planets*, W. Hartmann, 4th Ed. 1999)

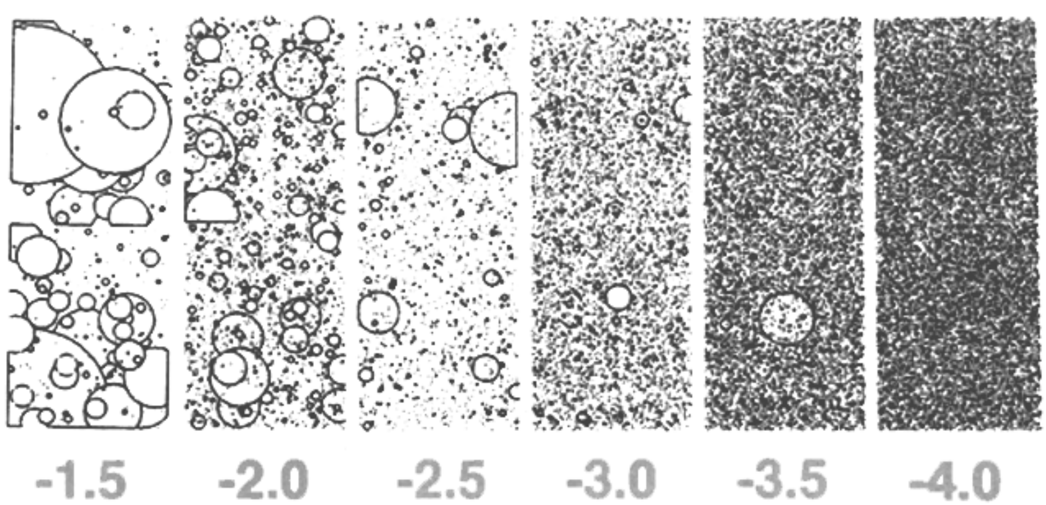
The power law distribution of the sizes of asteroids therefore suggests a **collisional fragmentation process**, the consequences of which are fascinating. The sizes continue getting smaller and smaller and the numbers continue to become greater and greater.

The equation $N = AR^b$ describes a relationship between the number of objects, *N*, and their radius, *R*. But what are the effects of changing the values of the parameters *A* and *b*? The left figure below shows the effect of increasing *A*. The line representing the power-law distribution simply shifts up or down as *A* becomes bigger or smaller (meaning that there are more or fewer of the objects counted in the study). However, the relative distribution of the object sizes remains unchanged. The right figure below shows the effect of changing the exponent *b*. The slope of the line changes, as does the fundamental relationship in the distribution between large and small objects. Specifically, if b = –1 then there will be 10 times more objects that are 1/10 the size. If b = –2, there will be 100 times more objects; and if b = –3, a thousand times more objects than the number of objects 10 times bigger.



I.4 If the value of *b* becomes "more" negative (e.g., as *b* goes from –2 to –3), does the slope get more or less steep?

Below is a diagram made using a computer simulation of different size distributions for a range in the values from b = –1.5 to –4.0.



I.5 Which value of b creates more big particles and fewer small particles? Which creates more small particles and fewer large particles?

Part II. Destructive Learning

You will test the hypothesis that asteroid size distributions are the result of collisional processes by simulating such collisions for yourself, using a brick as a rocky asteroid and a sledgehammer to provide the impact(s).

It is anticipated, however, that you will be producing far too many small "asteroids" to count one at a time. To overcome this limitation, it is possible estimate their number, N, by calculation, using the **density** of your original "asteroid" as a guide.

Density is a measure of the amount of mass in a given volume, and it is measured in units of mass (grams or g) per volume (cubic centimeters or cm^3). Water, for comparison, has a density of exactly 1 g/cm^3. Thus, one cubic centimeter of water would weigh one gram if placed on a metric scale. Moreover, if we had a container of water that weighed 100 grams, we would know that we had a volume of 100 cubic centimeters of water.

II.1 Use the metric scale to measure the mass (in grams) of your brick "asteroid":_______

II.2 Measure the sides of the soft-brick and calculate its volume (in cm^3):

Length (cm) =

Width (cm) =

Height (cm) =

Volume = L x W x H =

II.3 Calculate the density of the soft-brick using the equation: **Density = Mass / Volume**

Now take your sledgehammer, brick "asteroid," goggles and denim cloth, and find a safe place outside for a smashing good time!

Step 1 Wrap the brick in one sheet of cloth, and then wrap that in the second cloth. (*Note:* The cloths containing the brick may not last for more than a few hits before it rips; their purpose is to hold the pieces together as well as possible so that you won't lose any.)

Step 2 Now, the fun part: smash your brick! You will most likely have to hit the brick about 4 to 6 times (representing 4 to 6 "collisions" with other asteroids) to ensure that you end up with enough small pieces for your analysis. (*Note:* The largest pieces you will be interested in are only one inch across.) ***Please do the smashing in the gravel/dirt area outside SBO to avoid breaking the sidewalk! Each member of your group should hit the brick at least one time. The person hitting the brick MUST be wearing the goggles!***

Step 3 Being careful not to lose any of the pieces, fold up the cloth sheet and bring your sample fragments to the sieves.

Part III. Sorting and Counting Your Fragments

Be sure to read and follow EACH step carefully. There are a total of five sieves of differing sizes: 2.54 centimeter diameter sieve, 1.27 cm, 0.64 cm, 0.32 cm, and 0.16 cm. The idea is to separate your material—by following the steps below—according to these sizes. You will begin by putting all the material into the *largest* sieve, thereby separating out the biggest pieces. Pieces larger than 2.54 centimeters in diameter will stay in he sieve while everything else will fall through. You will then use the *second* largest sieve, and sto on down to the smallest.

III.1 Place the pan below the 2.54 cm sieve. Slowly pour the material into the sieve, gently agitating the sieve as you go. You may need to do a little at a time if there is too much material for the sieve. (*Note:* Do not be too rough with the sieves. By excessively shaking the sieve you may inadvertently cause unwanted further grinding.)

III.2 Separate your largest pieces—these will not be used in the analysis.

III.3 With the remaining material, use the next-sized sieve to separate out the next-largest pieces and place these in a baggie. These fragments are the largest you will consider in your analysis. Keep track of this material by placing a small piece of paper in the baggie that records the sieve size.

III.4 Repeat the process for each sieve in descending size order. Discard all material that falls through the smallest sieve.

III. 5 Weigh the material in each baggie with your balance scale. Record the results in column 6 of the table on page 97. (*Note:* You do not need to empty the material onto the scale. Instead, simply put the baggie on the scale. The small mass contribution from the baggie is negligible.)

The next step is to create a plot of the number of objects versus sieve size. Of course, one way to do this would be to count each fragment within each baggie. However, because we know the densities of our brick "asteroid" fragments, there is a much simpler way to estimate these numbers.

You have measured the *total* mass of all the objects in a certain size range (column 6 of the table). If you divide this number by the mass of a *single* object of that size, the result will be an estimate of the total number of fragments within that range (and within your baggie).

Assuming that each particle is approximately spherical in shape, and also that the average size of the particles in a baggie is halfway between the two sieve sizes that yielded the sample (the mean particle size from column 5 above). Then the mass of a single object can be calculated from

$$\mathbf{M_1 = Volume \times Density = [(4/3)\,\pi\, R^3] \times Density}$$

where M_1 is the mass of one particle of radius R. The density is the value you previously calculated. (While the brick is now in fragments, this has not changed the density of its pieces.)

III.6 Calculate the mass of one object having a size equal to the average size of a particle collected in each sieve using the equation given on the previous page. In column 7 of the table, enter the mass of a single representative particle in each of your four bags. (*Hint:* You should NOT need to actually weigh a single particle.) Show one example calculation below.

III.7 You now have enough information to estimate the total number of particles in each bag. Enter the estimated total number of particles in each size range in column 8.

Smashing Brick Data Table

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Bag #	*Former Sieve Size (cm)*	*Current Sieve Size (cm)*	*Mean Particle Diameter (cm)*	*Mean Particle Radius R (cm)*	*Mass of Bits(+Bag) (grams)*	*Mass of One Particle M_1 (grams)*	*Number of Particles N*
1	2.54	1.27	1.91	0.95			
2	1.27	0.64	0.96	0.48			
3	0.64	0.32	0.48	0.24			
4	0.32	0.16	0.24	0.12			

III.8 To check the validity of your approach, actually *count* the number of fragments in one (or more) of the baggies. (You might choose the baggie containing the fewest and largest fragments, but that choice is up to you). Record your answer below and compare it with your estimate from column 8.

Part IV. Plotting and Analyzing Your Results

IV. 1 Using the log-log plot of the graph on page 99, plot your results showing the number of particles N versus the mean particle radius. (*Hint:* You will need to use your own data to come up with labels for the Y-axis. Remember this is a log-log plot!)

Does your data form *roughly* a straight line? If not, can you think of any reason why not?

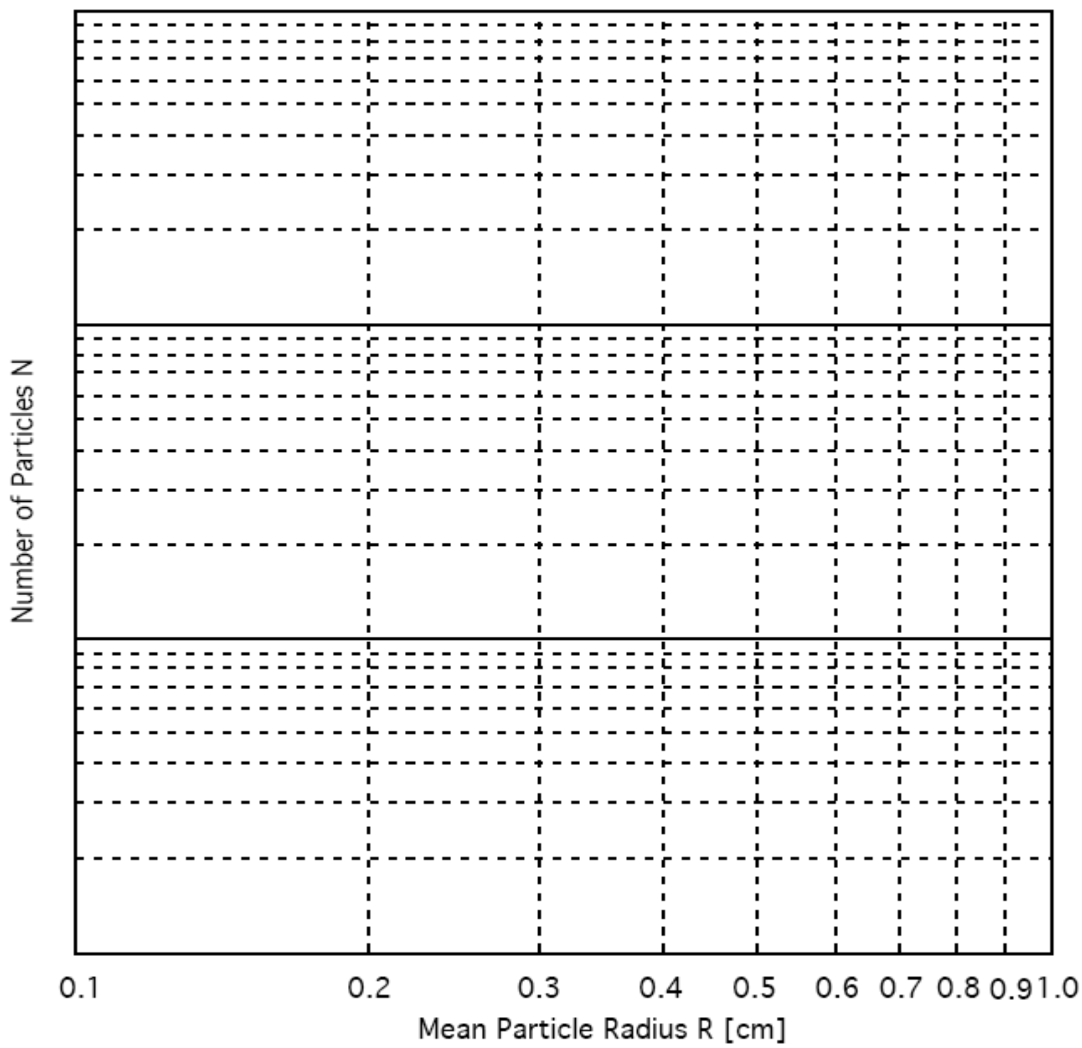
IV.2 Using the transparencies for different exponents (values of *b*) and overlaying them on your plot, find the one which best matches your plot (Make sure you keep the X and Y axes of the overlay parallel to the X and Y axes of your graph. Then judge by eye which line seems closest to your data points.) What is your estimate of *b* for your brick fragments?

IV.3 How does this compare with the value of *b* for the asteroid power law distributions (b=-2)? Does your power-law distribution from smashing particles tend to match those of asteroids? If your power-law distribution differs from that of the asteroids, explain whether your smashing experiment yielded too many large-sized, or too many small-sized particles. (*Hint*: See question I.5.)

IV.4 What do your results imply about the conditions that existed at the time asteroids were being formed?

IV.5 How do you think your plot would have changed if you had smashed the brick several more times? Would the slope change? Would the line shift up or down? Explain your reasoning.

Smashing Bricks: the Asteroid Collision Simulation



Part V. Asteroid Impacts on the Earth

Because both the Moon and the Earth occupy the same general region of the solar system, it is reasonable to assume that both have been bombarded by similar numbers and sizes of space debris. The only difference is that impacts on the Earth have been moderated somewhat by the atmosphere, and most of Earth's craters have been obliterated by geological activity (erosion, volcanism, and tectonics).

The surface geology of the Moon, on the other hand, has remained fairly undisturbed (except for impacts) since the last maria-building lava flows, which ended roughly 3.5 billion (3.5×10^9) years ago. Based on crater counts, approximately 30 objects 1 km in diameter have hit each 100,000 km^2 of the lunar surface in the last 3.5 billion years.

(Want to participate in helping astronomers identify craters on the Moon? Check out http://www.moonzoo.org!)

We can, therefore, use the lunar crater record to estimate the numbers and sizes of impacts that have occurred in the past on the Earth. The radius of the Earth is 6368 km. The total surface area of the Earth can be computed from the formula for the area of a sphere of radius R:

$$\textbf{Surface Area of a Sphere} = 4 \pi R^2$$

V.1 What is the surface area (in km^2) of the Earth?

V.2 How many times bigger is the Earth's surface area than the crater-counting standard area of 100,000 km^2 on the Moon?

V.3 So, in the same corresponding period of time that craters have accumulated on the Moon, about how many 1-kilometer diameter impactors (asteroids or comets) have hit the Earth?

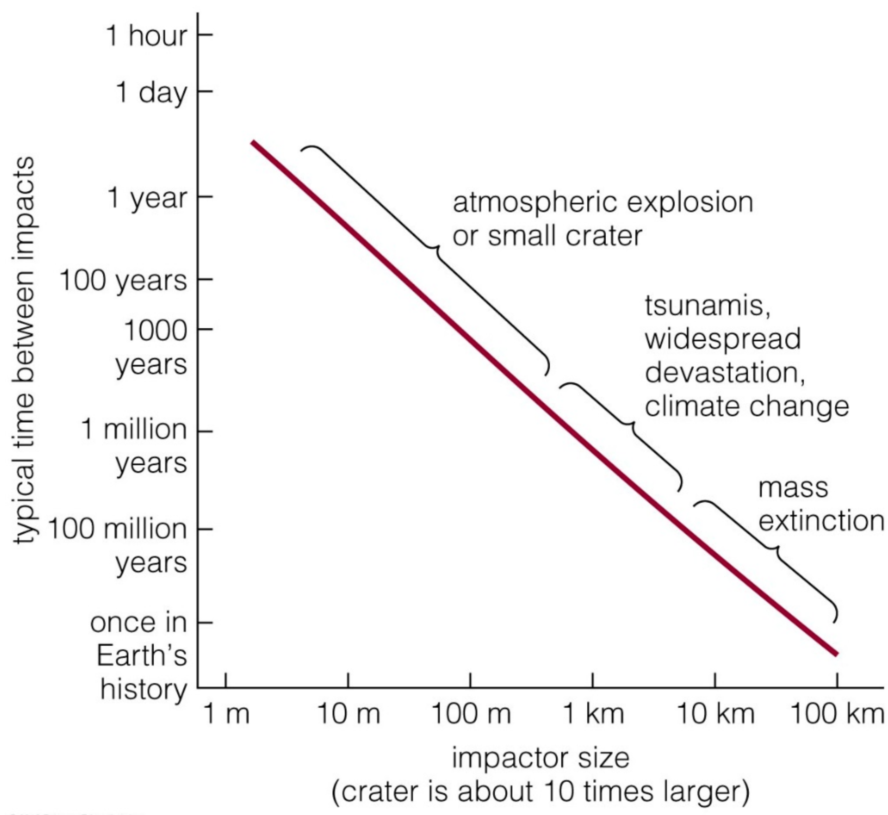
V.4 What is the typical frequency that we can expect for Earth to be hit by a 1 km diameter impactor in a one-year time period? (*Hint*: In question V.3 you calculated the total number of impacts over the last 3.5 billion years.) Is this number larger or smaller than 1? What does that mean?

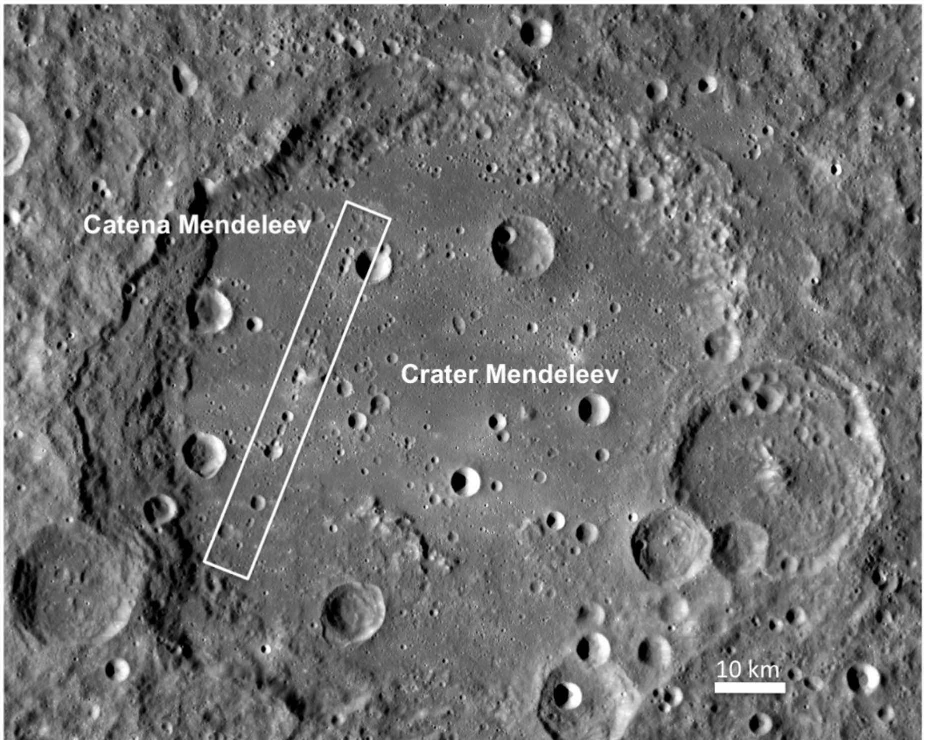
V.5 On average, about how frequently do such impacts of this size occur on the Earth? (*Hint:* Question V.4 asked you to calculate impacts per year, this question is asking for years per impact.)

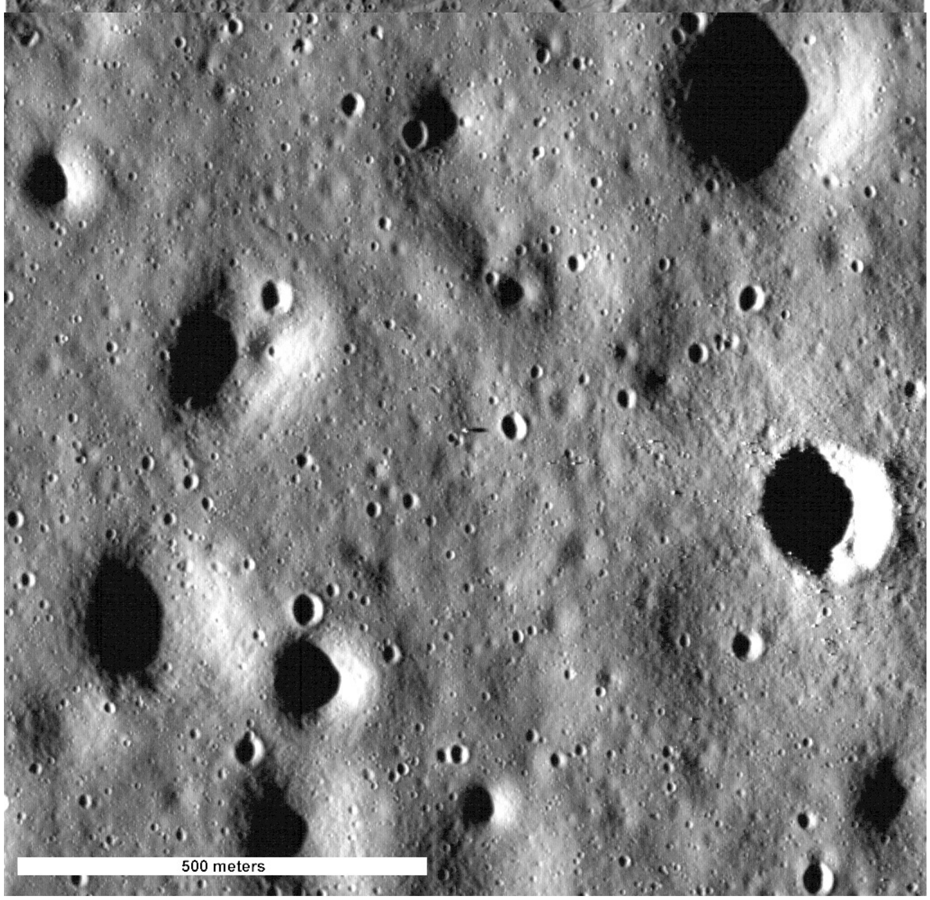
V.6 Based on your calculations, what are the approximate odds that a 1 km diameter object will strike the Earth in your *lifetime*? (Such an impact, incidentally, would bring about continent-wide devastation, global atmospheric disruption, and likely an end to human civilization!) (*Hint*: You calculated the annual probability – that's the chance of a hit in a year – the odds increase if you wait a whole lifetime.) *THINK! Does your answer make sense?* If not, you may have made an error along the way… go back and check!

V.7 Compare your assessment of typical collision frequency with the estimates shown in the graph below. Based on your answer, do 1 km impactors hit the Earth more or less frequently than the graph suggests?

When you are finished, please clean up you lab station. Replace all lab materials so the lab station appears as it did when you began. Have your TA check out your station before you leave.







Both images from the Lunar Reconnaissance Orbiter (launched in 2009) currently orbiting the Moon. That little dot in the middle of the bottom picture (casting a shadow) is the Apollo 11 Lunar Module!

9 - THE SEASONS

SYNOPSIS: This exercise involves making measurements of the Sun every week throughout the semester, and then analyzing your results at the semester's end. You will learn first-hand what factors are important in producing the seasonal changes in temperature, and which are not.

EQUIPMENT: Gnomon, sunlight meter, heliostat, tape measure, calculator, and a scale.

PRELAB QUESTIONS:
1) What do you think causes the seasons? How could you test your hypothesis?
2) How is local apparent solar time different than the time shown on your watch?
3) Can the Sun ever be measured at 90° altitude from here in Boulder? If so, on what date? If not, why not?

SUGGESTED REVIEW: Unit conversions (page 8) and angles and trigonometry (page 17).

Most people know that it is colder in December than in July, but why? Is it because of a change in the number of daylight hours? The height of the Sun above the horizon? The "intensity" of the sunlight? Or are we simply closer to the Sun in summer than in winter?

Each of these factors can be measured relatively easily, but seasonal changes occur rather slowly. Therefore, we will need to monitor the Sun over a long period of time before the important factors become apparent. We will also need to collect a considerable amount of data from all of the other lab sections, in order to gather information at different times of the day, and to make up for missing data on cloudy days.

Today you will learn how to take the solar measurements. Then, every week during the semester, you or your classmates will collect additional observations. At the semester's end, you will return to this exercise and analyze your findings to determine just what factors are responsible for the Earth's heating and cooling.

Part I. <u>Start</u> of the Semester: Learning to Make Solar Measurements

TIME OF DAY

As the Sun moves daily across the sky, the direction of the shadows cast by the Sun move as well. By noting the direction of the shadow cast by a vertical object (called a **gnomon**), we can determine the time-of-day as defined by the position of the Sun. This is the premise behind a **sundial**.

I.1 Note the time shown by the sundial on the deck of the Observatory. This is known as "local apparent solar time," but we will just refer to it as "sundial time." Determine the time indicated by the shadow to the nearest quarter-hour:

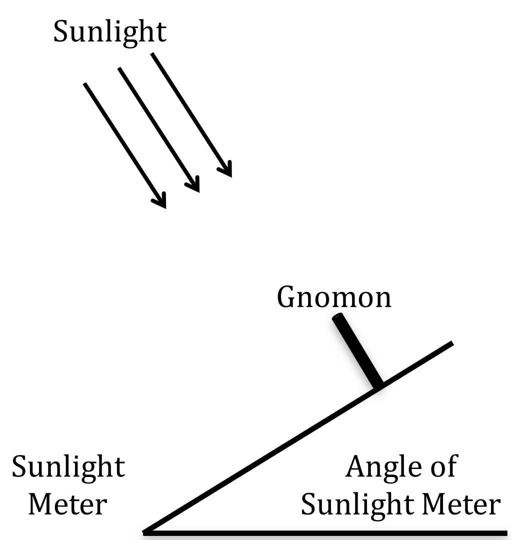
Sundial Time = __________.

I.2 Why do we use a sundial instead of a clock or watch?

THE SUNLIGHT METER

The "sunlight meter" is a device that enables you to deduce the relative intensity of the sunlight striking the flat ground here at the latitude of Boulder, compared to some *other* place on the Earth's surface where the Sun is, at this moment, directly overhead at the **zenith**.

I.3 On the observing deck, aim the sunlight meter by rotating the base and tilting the upper plate until its gnomon (the perpendicular stick) casts no shadow. When properly aligned, the upper surface of the apparatus will directly face the Sun.



The opening in the upper plate is a square 10 cm x 10 cm on a side, so that a total area of 100 cm^2 of sunlight passes through it. The beam passing through the opening and striking the horizontal base covers a larger, rectangular area. This is the area on the ground here at Boulder that receives solar energy from 100 cm^2 worth of sunlight.

I.4 Place a piece of white paper on the horizontal base, and draw an outline of the patch of sunlight that falls onto it.

I.5 Measure the width of the rectangular region; is it still 10 cm? _______

Measure the length (______), and compute the area of the patch of sunlight (width x length):

Area = ___________

I.6 Now calculate the relative solar intensity, which is the fraction of sunlight we are receiving here in Boulder compared to how much we would receive if the Sun were directly overhead:

$$\text{Relative Solar Instensity} = \frac{100cm^2}{Area} = \frac{100cm^2}{\_\_\_\_\_} = \_\_\_\_\_\_\_\_\_\_$$

Since you have aligned the sunlight meter to point directly at the Sun, you can use the angle of the meter to calculate the altitude of the Sun (i.e. the angle between the Sun and the horizon).

I.7 Using the protractor, measure the angle between the sunlight meter and the horizon. (Your TA/LA may need to show you how to obtain an accurate measurement.)

Sunlight meter angle = ___________.

I.8 The angle you have measured is not actually the altitude of the Sun. (*Hint:* If the Sun was on the horizon (i.e. altitude = 0°) what angle would the protractor read?) To get the altitude of the Sun, you'll need to subtract the sunlight meter angle, from 90°.

Solar Altitude = 90° – Sunlight meter angle = ___________.

THE RELATIVE SIZE OF THE SUN AS SEEN FROM EARTH

In the lab room, your instructor will have an image of the Sun projected onto the wall using the Observatory's **heliostat**, or solar telescope. As you know, objects appear bigger when they are close, and they appear smaller at a distance. By measuring the projected size of the Sun using the heliostat throughout the semester, you will be able to determine whether or not the distance to the Sun is changing. If so, you will be able to determine whether the Earth is getting closer to the Sun or farther away, and by how much.

I.9 Use a meter stick to measure the diameter (to the nearest millimeter) of the solar image that is projected onto the wall. (Note: because the wall is not perfectly perpendicular to the beam of light, a horizontal measurement will be slightly distorted; so *always measure vertically*, between the top and bottom of the image).

Apparent Solar Diameter = _________

PLOTTING YOUR RESULTS

You will use three *weekly group charts* to record your measurements, which will always be posted on the bulletin board at the front of the lab room: the Solar Altitude Chart, the Solar Intensity Chart, and the Solar Diameter Chart. This first week, your instructor will take a representative average of everyone's measurements and show you how to plot a data point on each graph. After this week, it will be the responsibility of assigned individuals to measure and plot new data each class period. *You will be called upon at least once during the semester to perform these measurements*, so it's important for you to understand the procedure.

I.10 On the weekly **Solar Altitude Chart**, carefully plot a symbol showing the altitude (I.8) of the Sun in the vertical direction, and the sundial time (I.1) along the horizontal direction, showing when the measurement was made. Use a pencil (to make it easy to correct a mistake), and use the symbol appropriate for your day-of-the-week (M-F) as indicated on the chart. Other classes will have added, or will be adding, their own measurements to the chart as well.

I.11 On the weekly **Solar Intensity Chart**, carefully plot a point that shows the relative solar intensity (I.6) that was measured at the corresponding sundial time (I.1). Again, use the appropriate symbol.

I.12 On the weekly **Solar Diameter Chart**, plot your measurement of the diameter in mm (I.12) vertically for the current date (horizontal axis). (There may be as many as three points plotted in a single day from three different lab sections.)

I.13 Make predictions as to which of the above measured factors should affect the seasons, and describe how each of the data should change over the semester in order to support those predictions. (You will find out by the end of the semester if your predictions were correct. If not, do not change your predictions here! Making incorrect predictions is part of science. You will not be marked down for incorrect predictions.)

Part II. <u>During</u> the Semester: Graphing the Behavior of the Sun

At the end of each week, the Observatory staff will construct a best-fit curve through the set of data points, extrapolating to earlier and later times of the day so that the entire motion of the Sun, from sunrise to sunset, will be represented. Although the data represent readings over a 5-day period, the curve will represent the best fit for the mid-point of the week. These summaries of everyone's measurements will be available for analysis the following week and throughout the remainder of the semester.

Every week take a few moments to analyze the previous week's graphs, and record in the table on the next page:

II.1 (a) The date of the mid-point of the week (Wednesday).

(b) The *greatest* altitude above the horizon that the Sun reached that week.

(c) The number of hours the Sun was above the horizon, to the nearest quarter-hour.

(d) The *maximum* value of the intensity of sunlight received here in Boulder, relative to (on a scale of 0 to 1) the intensity of the Sun if it had been directly overhead.

(e) The average value of the apparent diameter of the Sun as measured using the heliostat.

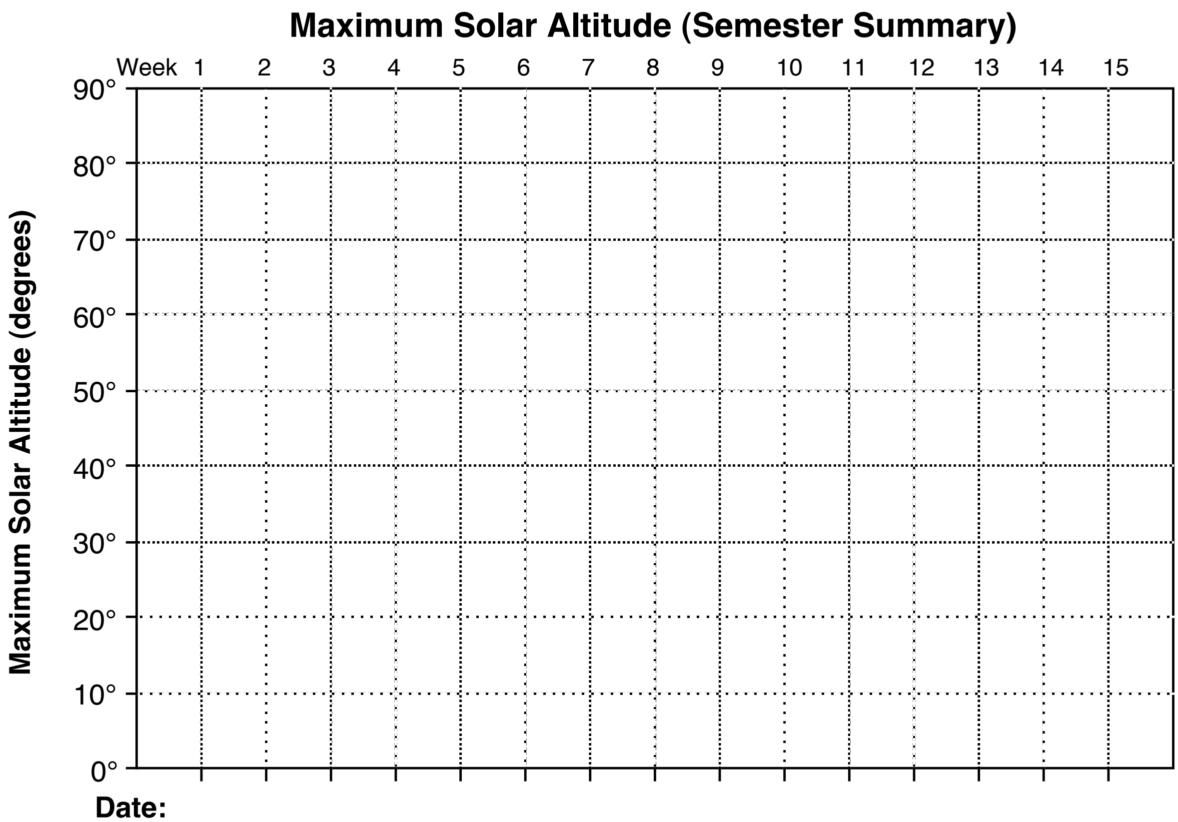
Solar Data

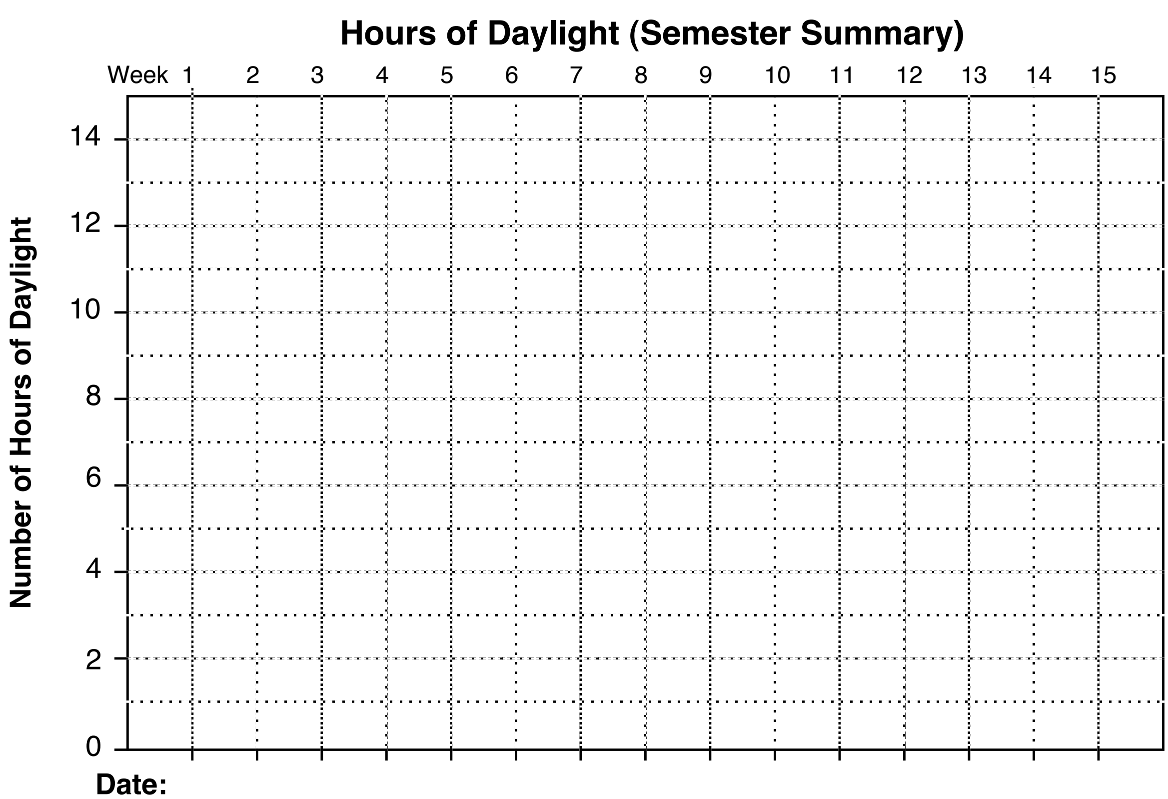
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Week #	**Date**	**Maximum Solar Altitude (deg)**	**Number of Daylight Hours**	**Maximum Solar Intensity**	**Solar Diam. (mm)**	**Area of Sunlight (# of boxes)**	**Solar-Const. Hours**	**KWH/ Meter^2 per Day**
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

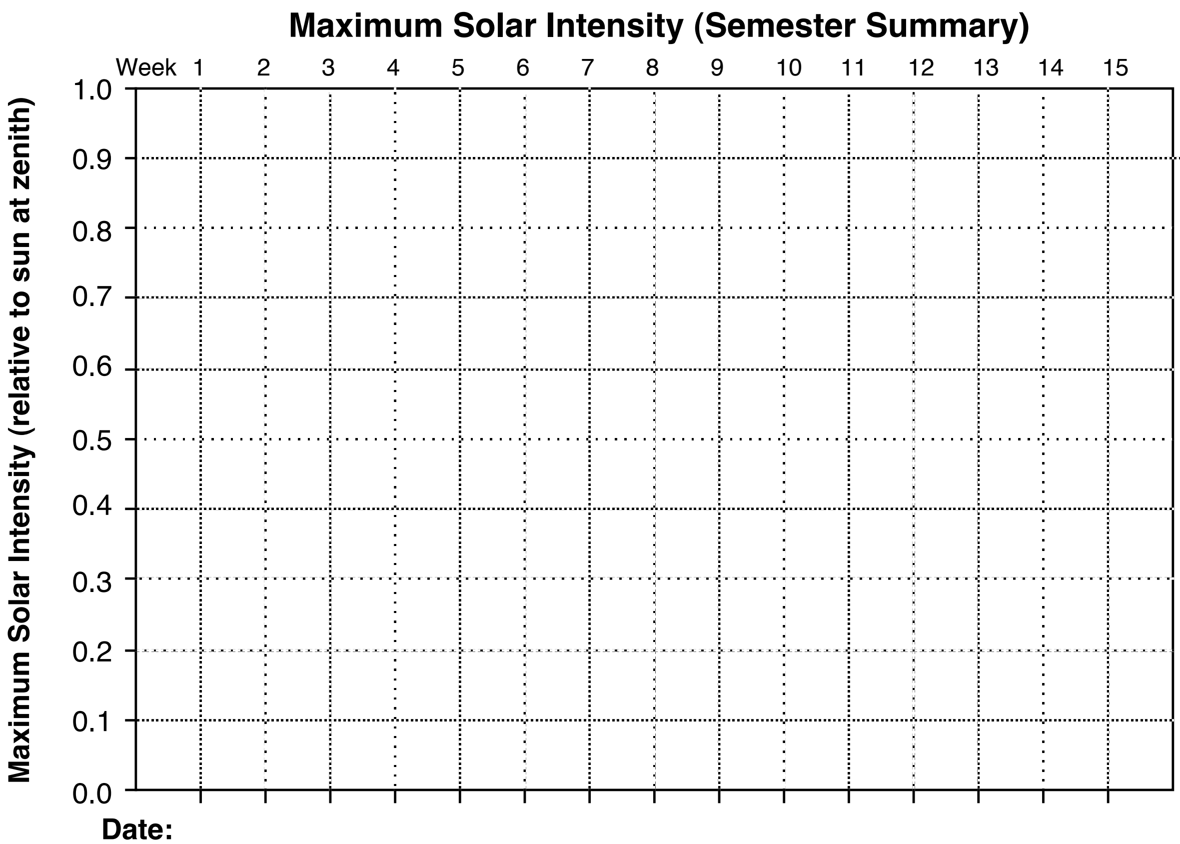
II.2 Also each week, transfer your new data from columns (a) through (e) in the table above to your own personal *semester summary graphs* on the next two pages: Maximum Solar Altitude, Hours of Daylight, Maximum Solar Intensity, and Solar Diameter. Be sure to include the appropriate date at the bottom of each chart. (Don't connect the dots!)

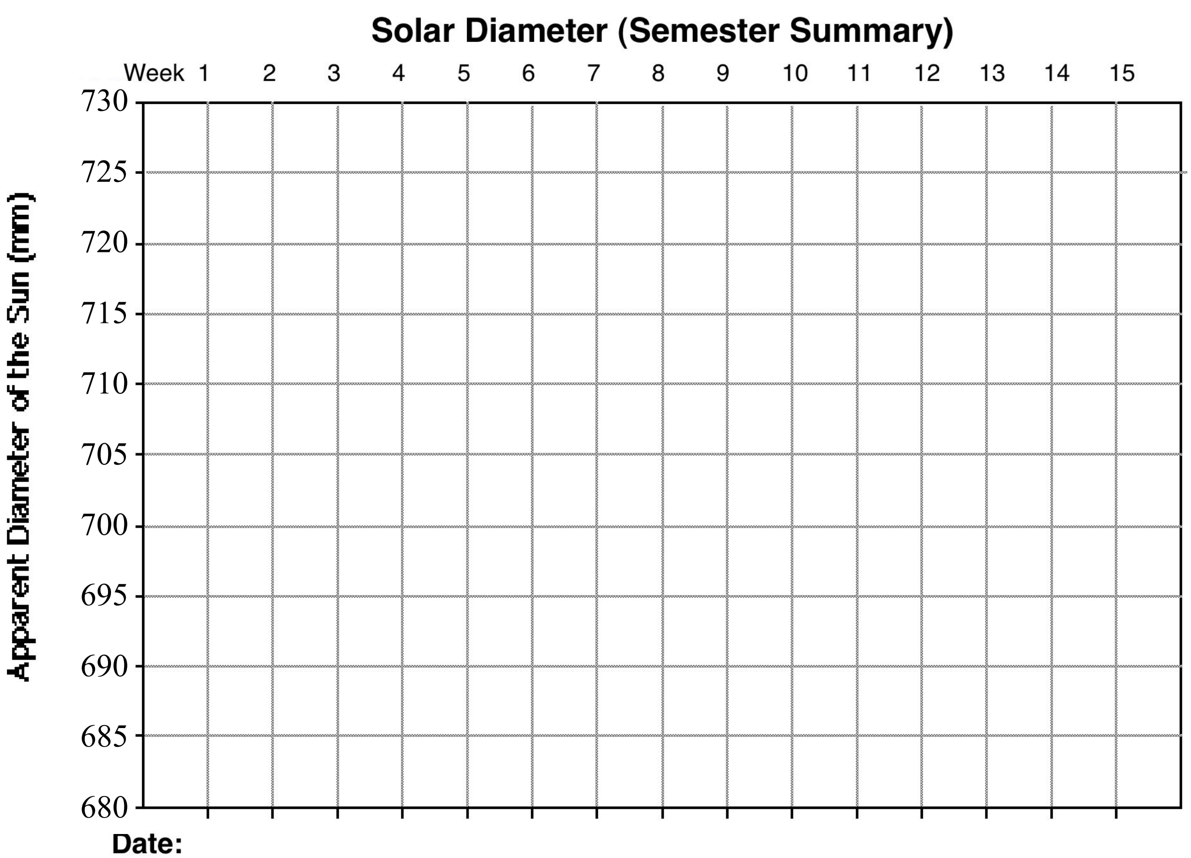
II.3 You have been elected as the head of your *Survivor* tribe. You must determine, and prove, on which day of the year the Summer Solstice occurs (but you have no written calendar). How would you do this?

Students using a gnomon sundial.


Maximum Solar Altitude (Semester Summary)
Week 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
90° 80° 70° 60° 50° 40° 30° 20° 10° 0°
Maximum Solar Altitude (degrees)
Date:


Hours of Daylight (Semester Summary)
Week 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
14 12 10 8 6 4 2 0
Number of Hours of Daylight
Date:


Maximum Solar Intensity (Semester Summary)
Week 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Maximum Solar Intensity (relative to sun at zenith)
Date:


Solar Diameter (Semester Summary)
Week 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
730
725
720
715
710
705
700
695
690
685
680
Apparent Diameter of the Sun (mm)
Date:

Part III. End of the Semester: Analyzing Your Results

By now, at the end of the semester, your collected data is expected to provide ample evidence for the cause of the seasonal change in temperatures.

III.1 Draw best-fit curves through your graphed data points on the previous two pages. The lines should reflect the actual trend of the data, but should smooth out the effects of random errors or bad measurements.

Do you expect these downward or upward trends to continue indefinitely, or might they eventually flatten out and then reverse direction? Explain your reasoning.

Now, use your graphs to review the trends you've observed:

III.2 Measured at noon, did the Sun's altitude become higher or lower in the sky during the course of the semester? On average, how many degrees per week did the Sun's altitude change?

III.3 Did the number of daylight hours become greater or fewer? On average, by how many minutes did daylight increase or decrease each week?

III.4 What was the maximum altitude of the Sun on the date of the **equinox** this semester? On that date, how many hours of daylight did we have?

III.5 Did the "sunlight meter" indicate that we, in Boulder, received more or less solar intensity at noon as the semester progressed?

III.6 Did the Sun's apparent size grow bigger or smaller? Does this mean that we are now closer to, or farther from, the Sun as compared to the beginning of the semester?

III.7 Has the weather, in general, become warmer or colder as the semester progressed? Which factor or factors that you have been plotting (solar altitude, solar intensity, number of daylight hours, distance from the Sun) appear to be *correlated* with the change in temperature? Which factor or factors seems to be *contrary* (or anti-correlated) to an explanation of the seasonal change in temperature?

If you receive a bill from the power company, you are probably aware that each kilowatt-hour of electricity that you use costs money. One kilowatt-hour (kWH) is the amount of electricity used by a 1000-watt appliance (1 kilowatt) in operation for one hour. For example, four 100-watt light bulbs left lit for 5 hours will consume 2.0 kWH, and will cost you about 15 cents (at a rate of $0.075/kWH).

Every day, the Sun delivers energy to the ground, free of charge, and the amount (and value) of that energy can be measured in the same units that power companies use. The amount of energy received by 1 m^2 on the Earth directly facing the Sun is a quantity known as the **solar constant**, which has a carefully measured value of 1.388 kW/m^2. That is, a perfectly-efficient, 1 m^2 solar panel, if aimed constantly towards the Sun, will collect and convert to electricity 1.388 kWH of energy every hour (worth slightly more than a dime).

Each weekly Solar Intensity Chart contains all the information you need to find out how much energy was delivered by the Sun, in kWH, on a typical day that week. Note that one "solar-constant hour" is equivalent to the rectangular *area* on the chart 1.0 intensity units high (the full height of the graph, corresponding to a solar panel that always directly faces the Sun) and one hour wide. The actual number of "solar-constant hours" delivered in a day to flat ground in Boulder is likewise the total *area under the plotted intensity curve*, from sunrise to sunset.

III.8 Each Solar Intensity Chart is printed on graph paper. How many boxes are in *one* solar-constant hour? __________

III.9 As a class group exercise, determine the number of kWH delivered on a sunny day to every m^2 of ground in Boulder, for each week that you have collected data.

To do this, count the number of boxes contained under the curve of one of the Solar Intensity Charts. (For box counting, we can be quite rough. Count boxes that are more than 50% included as one box and anything less than 50% counts as zero.) Then convert to solar-constant hours using your conversion measured above. Finally, multiply that number by 1.388 kWH to obtain the total energy contribution of the Sun to each m^2 of ground during the course of a day. Your TA will collect the values from the various groups.

In your data table from Part II, record the weights in column (f), the calculated solar-constant hours in column (g), and the equivalent kilowatt-hours in column (h).

III.10 From column (h), what is the percentage of the amount of energy received at the end of the semester compared to that at the beginning of the semester? (For the moment, we will ignore any effect due to a change in the distance to the Sun.)

$$\frac{\text{Final Week's kWH}}{\text{First Week's kWH}} = \_\_\_\_\_\_ \times 100\% = \%\text{ of Initial Solar Energy}$$

A percentage greater than 100% implies than an increase in energy was received over the semester; a ratio less than 100% implies that less solar energy was delivered as the semester progressed.

Now we can find out just how important was the change in distance from the Sun:

III.11 What is the ratio of the apparent diameter of the Sun between the end and the start of the semester?

$$Diameter\ ratio = \frac{Final\ Week's\ Diameter}{First\ Week's\ Diameter} = \frac{\qquad}{\qquad} =$$

The energy delivered to the Earth by the Sun varies inversely as the *square* of its distance from us. The diameter ratio calculated above is already an inverse relationship (that is, if the diameter appears *bigger*, the Sun's distance is *smaller*), so we just have to square that ratio to determine the change in energy from the Sun caused by its changing distance from us. For example, if the ratio is 1.10 (10% closer), the Sun will deliver 21% *more* energy ($1.10^2 = 1.21$). If the ratio is 0.90 (Sun 10% further away), it will deliver $0.90^2 = 0.81$ = 81% as much energy (equivalent to 19% *less* energy).

III.12 How much *more* or *less* energy (expressed as a percent change) does the Sun deliver to us now, compared to the start of the semester, solely as a result of its changed distance?

If only the *distance* from the Sun caused the seasonal changes in temperature, would we be warmer or colder in the wintertime? Explain your reasoning.

III.13 Compare the relative importance of the sunlight intensity-duration effect (III.10) with the solar-distance effect (III.12). Which of the two factors is clearly the most important in causing seasonal changes? Explain clearly how you arrived at your conclusion.

III.14 Which of the quantities you measured in this lab would be different if we were at a higher latitude in the northern hemisphere (and *how* would they be different)? If we were at a lower latitude in the northern hemisphere? If we were at the same latitude as Boulder, but in the southern hemisphere (on the same date)?

10 - DETECTING EXTRASOLAR PLANETS

Name: ___________________________

LEARNING GOALS: Detecting planets around other stars is a very challenging task. What is the transiting planet method of detection? What can we learn about extrasolar planets using this method?

EQUIPMENT: Lamp, ruler, Lego™ orrery (with a variety of detachable planets), light sensor, laptop (or other) computer with LoggerLite™ software, modeling clay (available from your lab instructor for the optional section at the end), calipers

In March 6, 2009, the NASA *Kepler* spacecraft successfully launched and began monitoring the brightness of more than 100,000 stars. The Kepler mission is NASA's first mission with the precision capable of finding Earth-size and smaller planets around other stars. In this lab, you will discover how Kepler's instruments work and what we can learn about extrasolar planets.

In this lab, you will occasionally be asked to predict (as a real scientist would) the outcome of an experiment before you try it. Make these predictions BEFORE moving on to the experiment itself. You will not be marked down if your predictions are wrong.

Unfortunately, the Lego orrery does not simulate a true solar system since it does not exactly follow Kepler's 3rd Law ($P^2=a^3$). Keep this in mind.

Part I. Setting up your Kepler Simulation

The transit detection method is an *indirect* detection method in that it is not directly detecting the planet itself but rather the planet's interactions with its central star. By detecting a repeating dimming of the star's brightness, scientists can infer that a planet is orbiting around the star and occasionally blocking some of the star's light from the telescope.

In this lab, the light sensor will simulate both the *Kepler* telescope and its light detecting hardware. The lamp will simulate the star and the Lego orrery will be configured to simulate various planets moving around that star.

The first thing you'll need to do is place the star in the middle of the orrery. Adjust the lamp so the bulb is over the middle shaft of the orrery. Be sure the base of the lamp is not blocking the path to the light sensor.

Next you'll need to align the light sensor so it is pointing directly at the center of the light source. (Make sure none of the planets are between the star and the light sensor during alignment.)

I.1 Using your ruler, measure the height of the star and adjust your light sensor to the same height. Record the height of your star and light sensor: _________________

I.2 Next you'll need to make sure your light sensor is pointed directly at the center of the light source. You could do this by eye (and probably should, in order to get a rough alignment) but can do so much more accurately using the LoggerLite software (if the software is not already running, ask your TA or LA to help start the program). This will also give you a chance to play with the light sensor to see how it works. Explain how you can use the LoggerLite software to align your sensor.

I.3 Record the value for the peak brightness of your lamp: _________ *(The light bulb itself might show some small variability. As long as it's not periodic, this will not effect your measurements. Most real stars actually show some variability.)*

Part II. Measuring the Effect of Planet Size

II.1 Affix a medium-sized planet to the middle arm of the orrery. Try to get the height of the planet to be the same height as the center of your star and your light sensor. Turn on the orrery motor and start the LoggerLite data collection. Describe the results.

II.2 (a) Suppose that your planet was ½ the diameter of your star. What percent of the star's light would you *predict* that planet would block?

(b) As seen from a distance, planets and stars look like circles. Draw a planet and a star on top of each other below with the planet having a diameter that is ½ that of the star (use circles, don't do a 3-dimensional drawing). To help make the point even clearer, temporarily pretend the star and planet are squares, with the smaller one ½ the width of the larger (start the square "planet" in the corner of the square "star"). Draw accurately!

Star & Planet

Star & Planet (drawn as a squares)

(c) Based on your drawing, how does the *area* of the star compare to the area of the planet? (You should be able to give actual numbers here, not just bigger or smaller).

II.3 (a) Using the clamps provided, measure your star (in the orrery) and record its size here (be careful not to break your bulb!): ____________

(b) Now measure your planet and record its size here:_______________

(c) What is the ratio of the diameters?________________

(d) What is the ratio of the areas?________________

II.4 What percent of the star's light do you predict the planet will block? Did you use (c) or (d) above? Explain your choice.

II.5 (a) Use the experimental setup to measure the percentage of the light that is actually blocked. *Show your work.* (You can use the "Examine" button in LoggerLite to get the exact y-value at any point on your graph. Be sure to run your orrery for *at least* two complete orbits of the planet.)

(b) How well does your result agree with your predictions?

(c) What might be the cause(s) of any differences? Show your prediction and result to your TA or LA before you proceed.

II.6 Replace the medium planet with a different sized planet, run the orrery, and describe the results. Compare your results to those you found in the previous question.

Part III. Measuring the Effect of Planet Distance

III.1 Other than brightness, predict the effect of changing the orbital distance of the planet and record your prediction. Be as specific as possible. (*Hint: The spacecraft is called the* *Kepler* *spacecraft…)*

III.2 Move the planet to a different position, run the orrery for at least two orbits, and describe your results.

III.3 How well do your results agree with your prediction? If they disagree, what might be the cause(s) of any differences?

(*The reason we ignore brightness variations is that this is a result of not being able to put the star system extremely far away from our detector, as is the case in real astronomy.)*

Part IV. Measuring a Complex Planetary System

Split your lab group into two teams. Each team will take one turn acting as the extrasolar system creators and one turn acting as the *Kepler* Science Team. Fill in the appropriate sections when it is your turn to act as that team.

Extrasolar System Creators: Place the cardboard divider between your teams so the *Kepler* Science Team cannot see the orrery. Using the various planet choices, create a solar system consisting of up to three planets. You don't *have* to use all three but try to make it challenging!

IV.1 Record the sizes for the three planets you chose in the table below.

Planet	Size
1st Planet (closest to star)	
2nd Planet	
3rd Planet	

IV.2 In the space below, draw your *prediction* for what the Kepler light curve will look like. Explain, in words, your prediction.

When you are ready, turn on the orrery and tell the *Kepler* Science Team to begin their analysis.

***Kepler* Science Team:** Your job will be to act as the scientists analyzing Kepler's data here on Earth. Without seeing the orrery, you will need to determine what kind of solar system the Kepler satellite has discovered.

IV.3 In the space below, make a sketch of the detected light curve. You might need a few minutes of data to recognize the full pattern. (If you want, you can print out your light curve and attach it to your lab write-up.)

IV.4 Based on the detected light curve, what are the sizes and distances of the planets around the system you've detected? Be as specific as possible (i.e. can you guess exact sizes?) Explain your reasoning.

IV.5 Once you've completed your analysis, check with the other team to see what actual planets were used. Was your analysis correct? If not, why not?

Now switch roles with the others; create a new solar system, and let the others analyze it. If you were the *Kepler* astronomers, you are now the creators, and should go back and fill in IV.1 and IV.2.

Part V. Summary

V.1 What are the difficulties that might be associated with detecting planets using the transit method? There are several answers to this question; you should list at least two for full credit.

V.2 For each of the following pairs, which type of extrasolar planets would the transit method work best? Large planets or small planets? Planets close to their host star or far from their host star? Highly eccentric orbits or circular orbits? Stars close to Earth or far away? Explain your reasoning.

V.3 If you had a spectrograph instead of a light sensor, how could this method be used to tell if a transiting planet had an atmosphere?

Part VI. Detecting Earth-size Planets

VI.1 Earth's radius is 6,400 km and the Sun's radius is 700,000 km. Using the reasoning you came up with in II.5, calculate the percentage of the Sun's light that Earth would block during a transit.

VI.2 The *Kepler* spacecraft is able to measure individual brightness changes of as little as 0.002%, and by averaging together many measurements can sometime reach a measurement precision of 0.0002% (two parts per million)! What do you estimate to be the smallest brightness change you could reliably detect with your light sensor and model?

If you wish to explore the concepts a little further, your TA has modeling clay available. Create your own planets and predict what the light curve will look like. Some outcomes may surprise you! Please clean up your lab station before you leave and leave it setup for the next lab group.

For more information on the Kepler Mission, see http://www.nasa.gov/kepler (or follow the Kepler mission on twitter at http://twitter.com/NASAKepler).

LAB 10B: Doppler Detection and Computer Modeling of Extra Solar Planets

Team members: ____

Big  Ideas

1. The first detections of planets orbiting other stars ("extra-solar planets") were made by measuring the very tiny Doppler shifts of the star.
2. Computer simulations help us understand the possible structure of other solar systems.

Learning Goals

1. Understand how the presence of one or more planets causes a star to move.
2. Try building several possible solar systems.

IMPORTANT NOTE: Many labs are like cookbooks –they tell you exactly what to do. That is not the way real science works. *Real science* (as opposed to boring classroom science) is all about using your imagination and creativity.

Procedure

Part I. Go to the website of the CU-developed PHeT, phet.colorado.edu. Select "Physics Simulations" (at upper left), then "My Solar System," and run the applet. (http://phet.colorado.edu/en/simulation/legacy/my-solar-system)
The default is to have a "Star" of mass 200 and a planet of mass 10, or a mass ratio of 20 to 1. Make the mass ratio 2 to 1 (give body #2 a mass or 100), which would be more like a double star system than a star and a large planet.

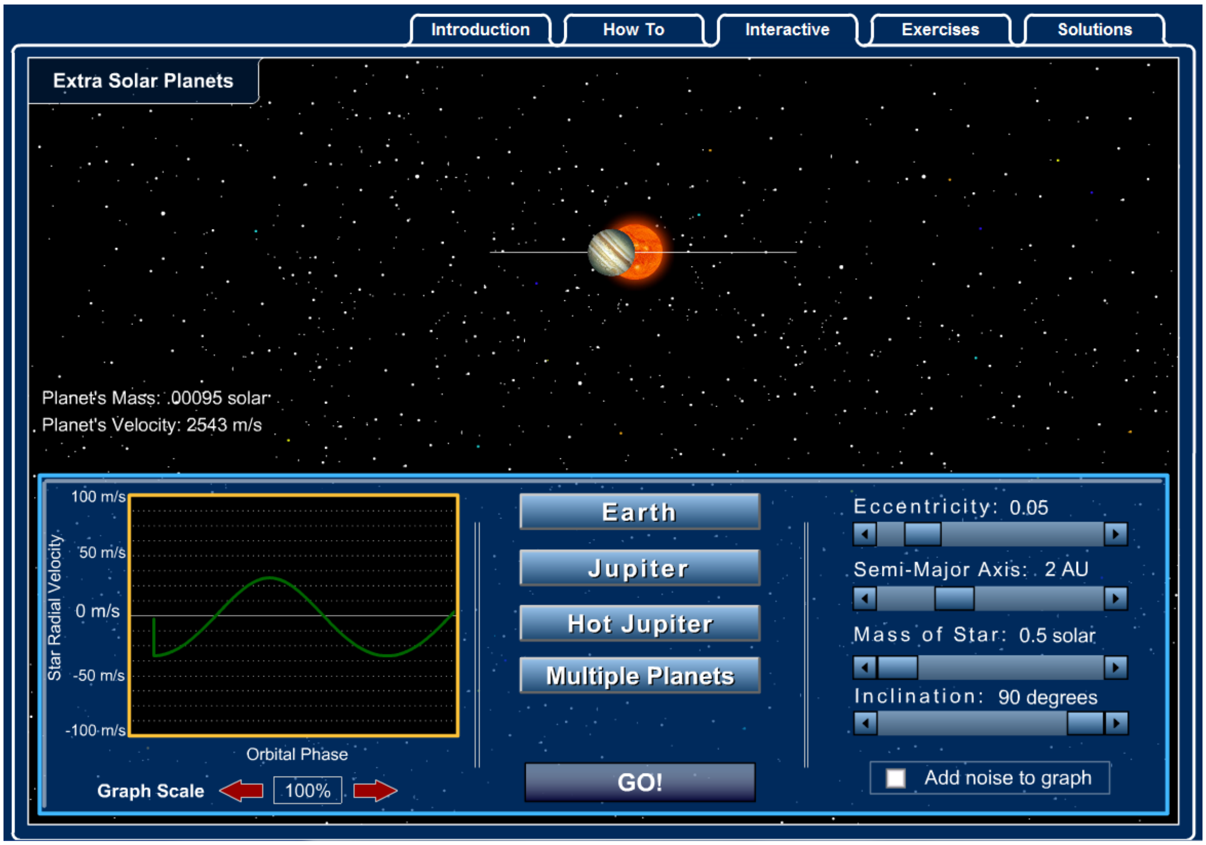
1. Do both bodies move? ______ What is the ratio of their distances from the center of mass (the center of motions)? __________ What is the ratio of their speeds?

2. Now change the mass of body #2 back to 10. When the planet moves, does the star move? What is the ratio of their distances from the center of mass? What is the ratio of their speeds?

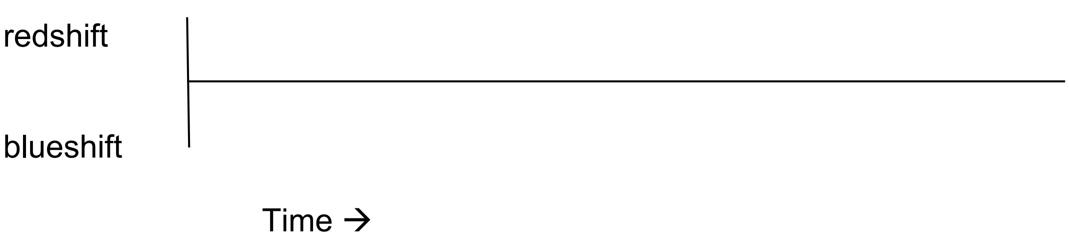
3. The actual ratio of the masses of the sun and Jupiter are about 1,000 to one. What is the ratio of the speed Jupiter causes the sun to move, compared to Jupiter's orbital speed?

Jupiter causes the sun to move at about 13 m/s. What common motion in your daily life is approximately that speed? This tiny Doppler shift of the star is what astronomers measure to detect extra-solar planets.

Part 2. Now go to the website: http://spiff.rit.edu/classes/phys230/lectures/planets/ExtraSolar_Nav.swf It looks like this:



Set the eccentricity to 0 (a circle), the semi-major axis to 2 AU (2x earth's distance from the sun), the mass of the star to 0.5 solar mass, and inclination to 90 degrees (edge on). Predict (sketch) how you think the Doppler Shift (also called "radial velocity") will change as time passes.



Hit "Go" and see how it actually changes. Change your sketch if it is different than expected but please **do not** erase your prediction.

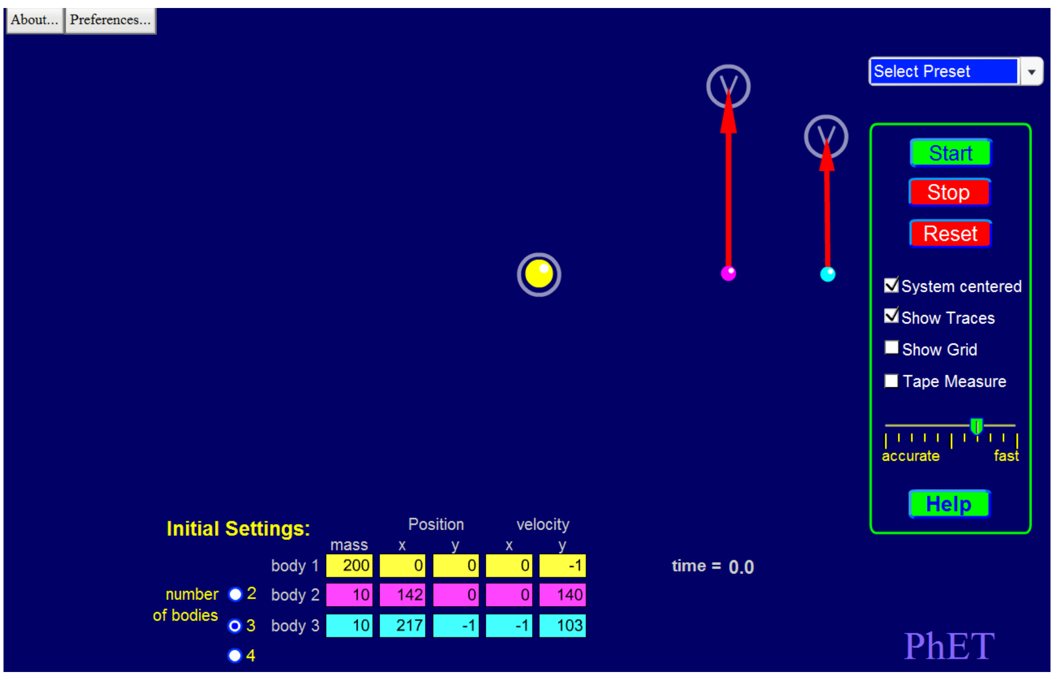
Change the inclination to 0 degrees (top view) and watch the orbit. What does the Doppler Shift look like now? Why?

Can the Doppler Shift method find planets around any star, or only orbits with certain orientation towards earth?

Set the inclination to 90 degrees and choose multiple planets. Do you understand why the Doppler Shift changes the way that it does? Explain:

Part 3.

Go back to the "My Solar System" PHeT and choose 2 planets, each of mass 10, arranged like the photo:



Is your "solar system" stable? Why or why not?

Can you make it stable? How? (Show your LA or TA if you can).

Can you add a 3rd planet, also of mass 10, and make a stable solar system? Try it. Show your LA or TA what happens….

LAB 11A: THE SUN, SEEN FROM SPACE AND FROM THE EARTH

Name(s) ____________________________ ____________________________

Goals:

1. (Clear skies permitting) Sketch a sunspot using the Sommers Bausch solar telescope.
2. Use time-lapse video of the sun taken in visible light to follow the movement of sunspots and determine the rotation period of the Sun.
3. Examine time-lapse videos of the sun taken from space in visible, ultraviolet, and X-ray light and sent back to earth.
4. Appreciate that observations from space allow us to learn far more about the sun than observations from the ground made only in visible light.

Definition: Time-lapse means speeding up time so that hours or days go by in a few minutes.

Some Background Information about the Sun and Sunspots:

- Different layers of the sun's atmosphere have different temperatures. Surprisingly, the further out in the atmosphere you go the *hotter* it is. The outmost layer (corona) is hotter than the middle layer, the chromosphere, and the chromosphere is hotter than the lower photosphere, the layer you see with just your eyes and a dark filter.
- Sunspots are seen in the photosphere. They are areas of strong magnetic activity.
- Sunspots appear dark because they are not as hot or bright as the area surrounding them.
- They can grow or die out as they move across the surface of the Sun.

What layer of the sun have YOU seen? _________________________________

Equipment: The Sommers Bausch Observatory solar telescope, images from a website of the *Solar Dynamics Observatory,* a NASA satellite that observes the sun in many wavelengths. Meter stick or other ruler.

WARNING: The intense solar light from the heliostat can cause eye damage! Do NOT look up the beam of sunlight!

Mapping Sunspots

Mapping and counting sunspots was the original way astronomers studied solar activity. It is how the 11-year sunspot cycle was discovered, and now we know that all forms of solar activity including the solar flares that affect the earth are more intense every 11 years at "solar maximum."

Your TA, LA, or Instructor will use the solar telescope (heliostat) to focus an image of the Sun. If you can find a sunspot, sketch it on this recitation paper. ***Do not write on the wall or the solar telescope screen!*** **Sketch on paper ↘**

Measure the size of the entire solar image and write the value here: ____________________

The earth is approximately 1/100 the size of the sun. How large would the earth appear if it was as far away as the sun and seen with the solar telescope? __________________________

Measure the size of your sunspot: _____________________ How does the size of your sunspot compare to the size of the earth?

If it is cloudy, you can do the above using a satellite image! See below.

Using Satellite Images

The Solar Dynamics Observatory (SDO) is a NASA mission designed to help understand the causes of solar variability and its impacts on Earth by studying the solar atmosphere in many wavelengths simultaneously. Initials such as "AIA" or "HMI" refer to instruments carried on the satellite. Numbers (171, 304, etc.) tell the wavelengths of light each instrument detects. The units are angstroms; or 10^{-7} mm. Visible light ranges from about 4000-7000 angstroms. Numbers such as 304 or 1600 are ultraviolet light. What kind of energy do you think a number of 94 is?

____

(Note: the boundary between ultraviolet and X-rays is not exact. The shortest ultraviolet wavelengths are called "Extreme ultraviolet" and the longest wavelength X-rays are "Soft X-rays.")
You can see a description of the images taken by SDO here:
http://www.nasa.gov/content/goddard/nasas-sdo-shows-the-suns-rainbow-of-wavelengths

First you will use visible light images to measure the rotation of the sun using sunspots. The visible light images are similar to the drawing you made (if it was clear), but there's data for many months.

Using a web browser go to http://sdo.gsfc.nasa.gov/data/aiahmi/
In the box that says "Telescope" select HMI Intensitygram (Orange)**.** These are images taken with visible light.

Select a date range to give you about 30-40 days' worth of data. You have to click 3 times to select a date and time, so be patient. **Scroll down to select 10 in the n-th box so that only every 10th image will be loaded.** (This is important as there is a download limit, and otherwise it will take forever.)
At the end of this exercise is a plot of sunspot numbers. Since the sun's activity follows an 11 year cycle, and the SDO satellite has been taking data for many years, **a wise choice of which 30 or 40 days you select will give you more sunspots!**

When you **click on Submit**, at the bottom of the page**,** a time-lapse video showing the Sun's image for the past month will be played. As you watch sunspots move across the surface of the Sun, you can determine the time that it takes them to move by stopping the movie and recording the date and time from the image. Unfortunately the Orange movies you just saw don't display the date and time. But the AIA1700 movies do, and they also show the photosphere. So use them. The format of the date and time information shown under the pictures is: yyyymmdd_hhmmss. Now you are going to determine the rotation period of the sun.

1. List the beginning and end times for the motion of 3 sunspots as they move completely across the Sun. You will need to change hours into fractions of days for the Difference column.

Sunspot	**Beginning Date & Time**	**Ending Date & Time**	**Difference (days)**
1			
2			
3			

Do your 3 values differ from each other? If they do, why do you think that is?

2. What is your value for the rotation period of the Sun (in days) based on the sunspot motion you measured? _________________

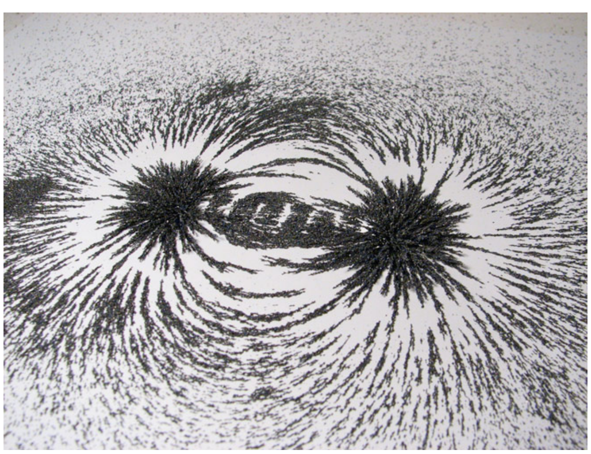
Now you will use videos taken in extreme ultraviolet and X-ray light.

The 3 main layers of the sun's atmosphere are the photosphere (the lowest visible layer), which you see with your eyes and the solar telescope, the chromosphere, and the corona (the outermost or highest layer). The photosphere is the coolest layer and the corona the hottest.

3. Choosing between visible, ultraviolet, and X-ray light, which is best to view the photosphere?
______________________. Which is best to view the chromosphere? ____________________
Which is best to view the corona? __________________________________

Go back to the SDO web page and change the "Telescope" box to AIA 304. Choose "Submit" and watch the time-lapse ultraviolet video of the sun.

Magnetic fields are important in the sun but you can't see magnetic fields…or can you? Did you ever "see" the magnetic field of a bar magnet?



The figure at left shows small pieces of iron sprinkled on a piece of paper.

4. Do you think there is a bar magnet below the paper? How can you tell? _______________

____

Change the "Telescope" box to AIA 171 and hit "Submit." This will download a video taken in extreme ultraviolet light.

5. Watch the video carefully. Do you see evidence of magnetic fields on the sun? If so, what is your evidence?

If you download video "HMI Magnetogram," you will see where astronomers measure magnetic fields, with black and white representing the different magnetic polarity (N and S).

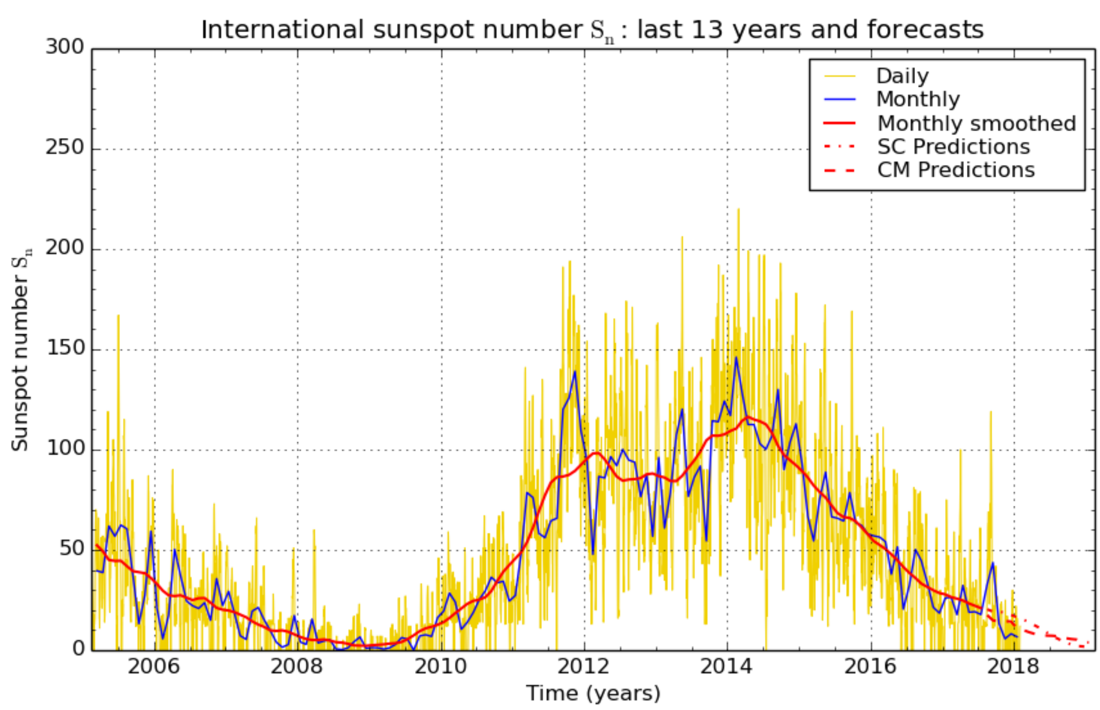
Which polarity leads (is ahead in the direction of rotation)? ________________________
Is your answer the same for both hemispheres of the sun? ___________________

If you download video "Composite AIA 171, HMI Magnetogram," you can see a **beautiful video** that overlays the extreme ultraviolet video and the magnetic field video. Can you see the patterns of magnetic field? Do the areas of strong magnetic field and loops of hot gas coincide?

____

Some of the very hot gas of the sun's corona escapes into space and forms the "solar wind." Some of these electrons and protons hit the earth. Because of *Earth's* magnetic field the path of the particles is bent and they come down near the north and south poles, making the aurora: the northern and southern lights.

Here is an awesome video of solar activity: [in the future link to a shorter url?]
https://www.youtube.com/watch?v=HFT7ATLQQx8



SILSO graphics (http://sidc.be/silso) Royal Observatory of Belgium 2018 February 1

LAB 11B: THE CU STONEHENGE CHALLENGE

Challenge: Where will the Sun set on Monday October 28, 2019?

OK - so we can't really have you build with stones on campus (hmmm... some year), but you can predict sunset. Here's what you are supposed to do.

Divide into teams of 3-4 students...We will place a pole on the slight rise where Dr. Duncan is standing in the photo below. This is west of the Colorado Scale Model Solar System (west of the main doors of Fiske Planetarium). Your challenge is to decide where the sun will set, and place your team's stake on the side of the path near Mercury and Venus on so that the post's shadow will point towards it as the sun sets over the Flatirons on October 28. **YOUR STAKE MUST BE IN PLACE BY FRIDAY OCTOBR 25.**

Rules

- A box of stakes is available in the Summers Bausch classroom. Mark it - artistically! - in a way you can identify.
- Take a picture of your stake in place, in case someone should move it!
- There are no restrictions on resources or tools used to make a prediction EXCEPT that you MAY NOT use electronic devices such as GPS or cell phones. You may ask for equipment during lab. We have protractors, compasses, etc. YOU have a nice planetarium program, Voyager, which comes with your Textbook. **(Turn over)**

PRIZES! All ASTR1010 students are invited to the judging party that will be when the sun sets over the Flatirons on Oct. 28. I estimate this will be roughly 5 pm. (On line you can find the time of sunset listed as about 6pm – but they don't take the Flatirons into consideration! The "Voyager" planetarium program that came with your book can be useful, but it doesn't know about Boulder's mountains either.) Don't be late if you attend! Each student who attends will be given a free ticket to a Fiske Laser Show. Members of the team whose stake is closest to the shadow, who are present, will receive an edible prize. If it is cloudy or rainy, the judging will be postponed until the first clear sunset!

Grades - As a team, compose a short paragraph or two describing **how** you decided where to place your stake. **We will grade each team according to how sensible and thoughtful your method is.** You DO NOT have to be the winning team to get full credit! Some teams may suggest more than one idea...if so, describe the plusses and minuses of each. The better your ideas the better your grade! -Dr. Duncan.

Names: ____

How we plan to place our stake:

THE MASS OF SATURN

Introduction & Motivation

Newton's Version of Kepler's 3rd Law (NVK3L) has three variables: the semi-major axis of the orbit (**a**), orbital period (**p**), and the mass of whatever is being orbited around (**M**). If you know any two of these quantities, you can find the third.

$$p^2 = \frac{4\pi^2}{GM}a^3 \qquad\qquad M = \frac{4\pi^2}{G}\frac{a^3}{p^2}$$

Most usefully, this is how we can use the motion of an object due to gravity to determine mass.

This is the third part of a three-part observational lab. The first two parts composed the night lab **Saturn Observations**. In that lab, students (including you?) observed Saturn with the telescopes at SBO both visually (through the eyepiece) and using the camera to record a detailed digital image. Next, they measured four quantities in the image and uploaded them to the class data archive.

In this lab, you will use the entire data archive collected by the Fall 2019 ASTR 1010 and 1030 classes (including the data point you contributed!) as well as data points possibly contributed by a few other sources to determine the mass and density of the planet Saturn.

Part 1 - Expectations

Kepler's first law tells us that orbits are elliptical. The moons of planets are no exception to this rule. The rings of Saturn are composed of trillions of chunks of ice so they too can be thought of as tiny moons, all orbiting Saturn on elliptical orbits. In the case of Titan and the ring particles, the orbits are almost perfect circles. Furthermore, the rings and most of the large moons (including Titan) orbit in the equatorial plane of Saturn.

Q1.1: In the space below, draw a sketch of what Saturn (the planet), the rings, and the orbit of Titan would look like **as viewed from directly above Saturn's north pole**. Titan orbits about ten times farther from the planet than the rings do. Recall the observed pattern in our solar system about what direction objects tend to orbit and rotate. Indicate where the north pole is and which direction Titan and the rings are rotating.

However, we are viewing Saturn from within the Ecliptic plane not above the north pole. Saturn, like Earth, has a rotation axis which is tilted with respect to the Ecliptic. Saturn's **axial tilt is 27°** and, in 2019, is experiencing summer in the northern hemisphere (Saturn's north pole is tilted toward the Sun (and the Earth) by 27 degrees). Since a Saturnian year is almost 30 Earth years, northern summer will last for a long time!

Q1.2: Sketch what Saturn, the rings, and Titan's orbit should look like **as viewed from Earth**. Indicate where the north pole is and which direction Titan and the rings are rotating. [hint, think of what Saturn looks like through a telescope on Earth, as shown at the end of this lab.]

Q1.3: In part 2 of the night lab, students measured four quantities: radius of Saturn, radius of the rings, distance to Titan, and Titan's position angle (the compass direction from Saturn to Titan). Which quantities do you expect to vary as Titan orbits Saturn?

Q1.4: Look at the sketch you made for Q1.2. How will the apparent **distance** between Titan and Saturn change with **time**? Sketch a plot of what you expect.

Part 2 - Observational Data

We will take your images and measurements from the Night Lab and compile them into a table of the Saturn-Titan data (Table 1, provided at end of lab). Groups with single letters (e.g. A, B) are data from astronomy student images in the first half of the Fall 2019 semester. Groups with double letters (e.g., AA, BB) are "guest" observations by other groups which *may* have been included if not enough student observations were made. Measured distances are in **Saturn radii**. Please refer to the data table to answer the questions in this section.

Q2.1: The radius of Saturn and its rings shouldn't change (much) over the course of our observations. How do you explain the variations in measured quantities between groups?

Since observations were taken over two months, different groups observed Titan at different points in its orbit. By plotting out these points, we can determine the semi-major axis of Titan's orbit. By looking at how long it takes to complete one orbit, we can find Titan's orbital period. Since we are interested in plotting how Titan's distance and position angle vary with time, we have converted observation date into "Day of Semester" (i.e., how many days since August 26^{th}, the first day of the Fall 2019 semester). This will make plotting quantities versus time a great deal easier than calendar date.

Q2.2: Use the graph paper below to plot the Saturn-Titan distance on each observation date. Time should go on the horizontal axis (x-axis); 2 days per box is a convenient unit. The vertical axis (y-axis) will be D_{Titan}. Pick a value for the tick marks that make the plot use a good range of the y-axis. Be sure to label your axes.

If we had observations every night, it would be easier to see the orbit in distance versus time plot you created above and your plot might look like your expected behavior (Q1.4). Perhaps you can see a pattern in the data, but maybe not. The data are **sparsely-sampled** (there are long gaps between observations). However, Titan's position is **periodic**; it should appear at the same location every orbit. This allows us to analyze the data in a different way.

Q2.3: Plot **distance** versus **position angle** on Figure 2. To visualize Titan's orbit, it is much more convenient to use a polar plot (radius, angle) on the next page rather than a traditional cartesian (x,y) plot. On a polar plot, data is plotted as a distance from the center (radius) and a specific angle from 0 (angle). In order to fit the data onto one graph, let each circle in radius represent a unit of 2 Saturn radii.

1 Mark the cardinal directions at the outside of the circle. North should be at 0°, East at 90°, etc.

2 Sketch the "ball" of Saturn by drawing a circle with the appropriate diameter (remember that each ring on the graph represents an increase of 2 Saturn radii.)

3 Sketch the **rings** of Saturn as you did the planet. Draw an ellipse with the appropriate diameter in the east-west direction. The north-south dimension should be the same as the ball.

4 Now start plotting the Titan distances from the data table. Plot <u>all</u> the data points. Find the appropriate angle and mark at the appropriate distance from the center. Label each point carefully with the group ID or date so you can relate your sketch to the data in the data table.

5 Compare your sketched points to your expectations from Q1.2. Can you draw an elliptical orbit through the data points which looks like your expectation?

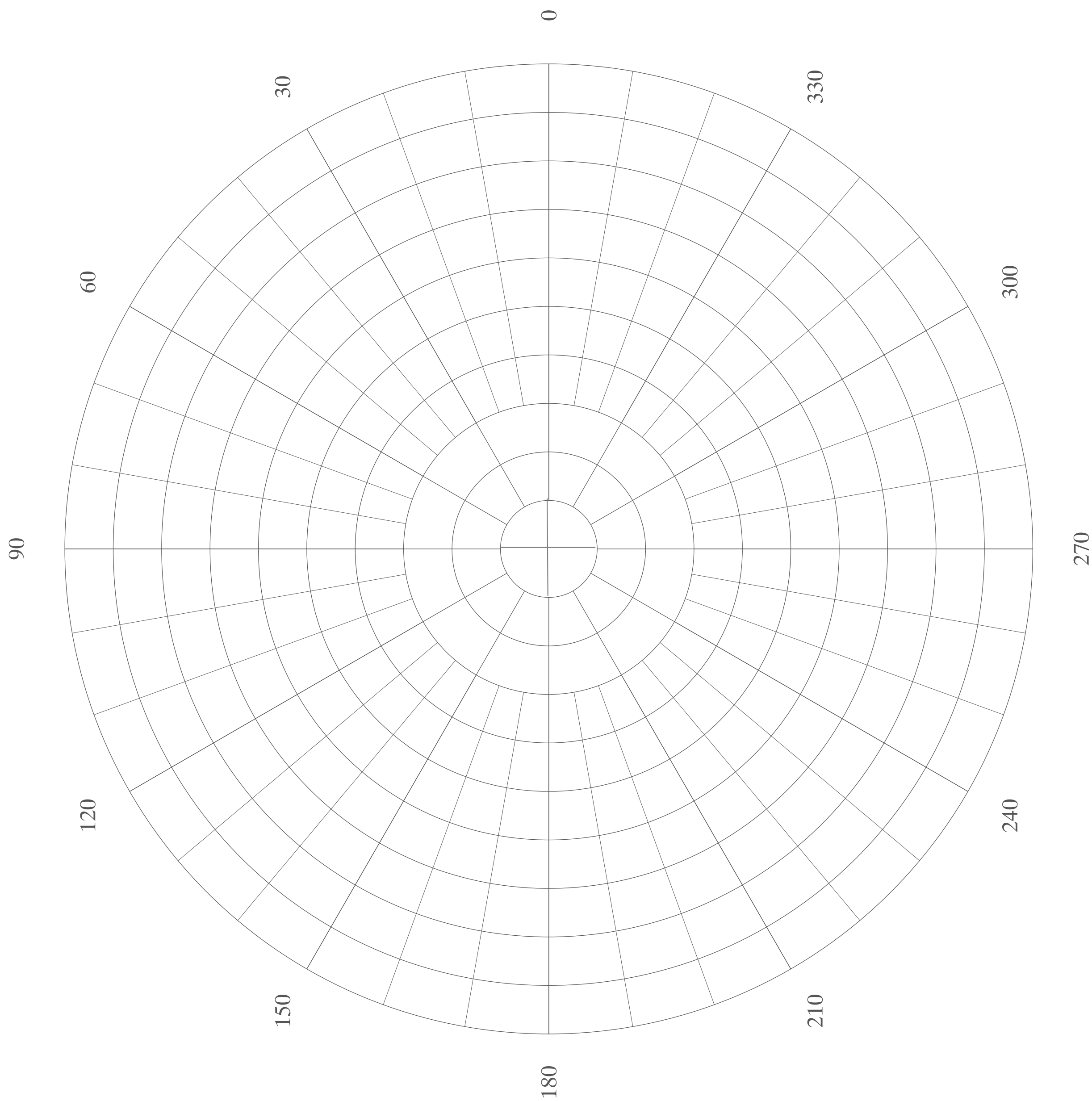
Q2.4: In plotting the data, did any of the data points seem suspicious? Two teams' data have been manipulated to include mistakes in recording their data. Which observations are mistaken? What do you think the mistakes might have been?

Q2.5: From Fig. 2, what is the **semi-major axis** of Titan's orbit (and what is the unit)? Explain how you got your result?

Q2.6: Also, from Fig. 2, what is the **period** of Titan's orbit?

<u>Before continuing, check your previous two answers with your TA or LA.</u>

Figure 2:



Part 3 - Determining the Mass of Saturn

Use the plots you made in part 2 to determine the two quantities you need to solve for Saturn's mass.

Q3.1: To use NVK3L, we will need physical units (km) not Saturn radii. Convert your semi-major axis value from Q2.5. Use the fact that **Saturn's average radius is 58,232 km**.

a = ______________________ Saturn radii

a = ____________________ km

Q3.2: What is the period of Titan's orbit? **p =** _______________________ days

$$M = \frac{4\pi^2}{G}\frac{a^3}{p^2}$$

Q3.3: Now solve for the Mass of Saturn using NVK3L. In the units of km and days, $G=4.98 \times 10^{-10}$ km^3/(kg • day^2).

M = ___________________________ **kg**

Q3.4: To put your number in context, compare the mass of Saturn to that of Earth ($M_{Earth} = 6 \times 10^{24}$ kg).

How many times Earth's mass is Saturn? ________________________

Q3.5: Finally, we can calculate the planet's density. Use the radius from Q3.1.

Volume$_{\textbf{Saturn}}$ = $4/3\ \pi\ R^3$ = __________________ km^3

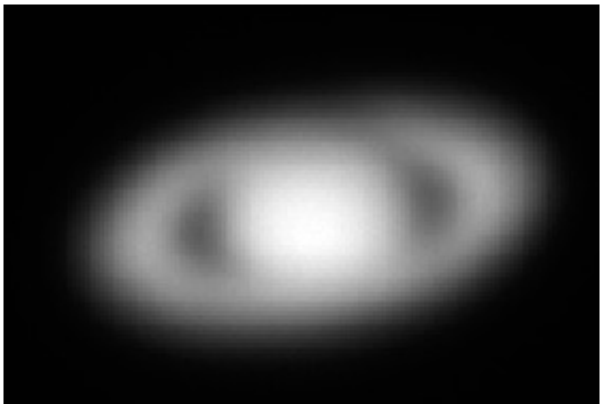
Density$_{\textbf{Saturn}}$ = Mass / Volume = ______________________ kg/km^3

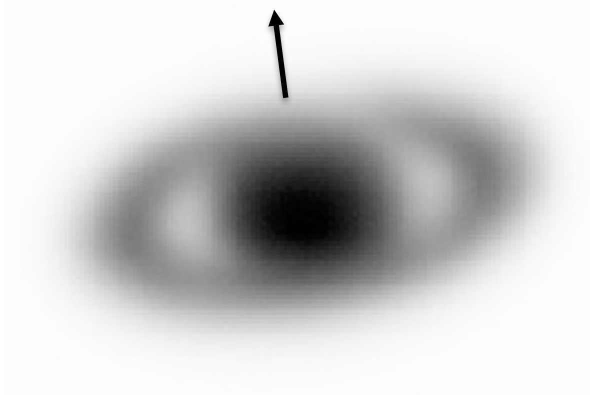
To convert kg/km^3 to the more conventional g/cm^3, use the following relationships:
1 kg = 10^3 g and 1 km^3 = 10^{15} cm^3
[therefore, if you calculate a density in kg/km^3, multiply the result by 10^{-12} for g/cm^3]

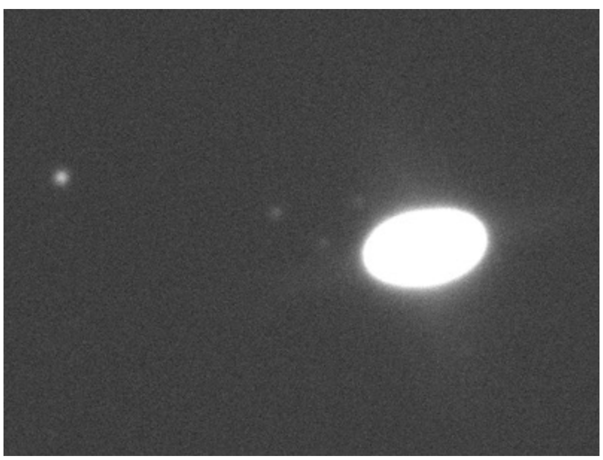
Density$_{\textbf{Saturn}}$ = Mass / Volume = ______________________ g/cm^3
**Hint* You should get a density for Saturn that is LESS dense than water (1 g/cm^3)!!*

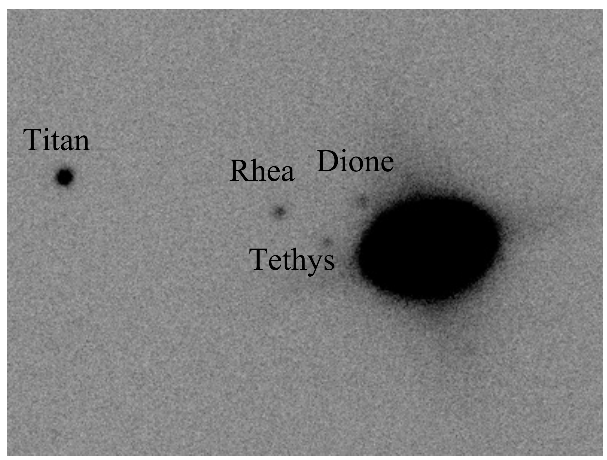
Table 1: Saturn Observational Data

Group ID	Observation Date	DoS *(day)*	R_{Saturn} *(pixels)*	R_{Rings} *(Saturn radii)*	D_{Titan} *(Saturn radii)*	Pos. Angle *(degrees)*
A						
B						
C						
D						
E						
F						
G						
H						
I						
J						
K						
L						
M						
N						
O						
P						
Q						
R						
S						
T						
U						

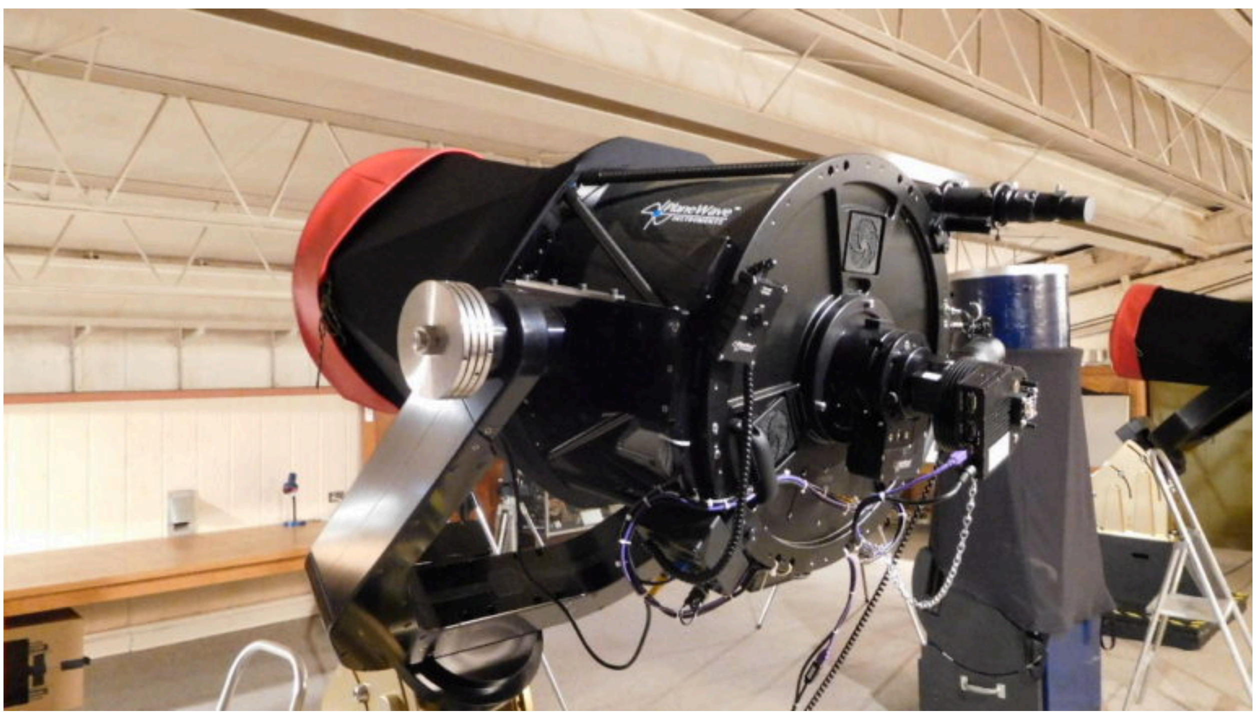



North

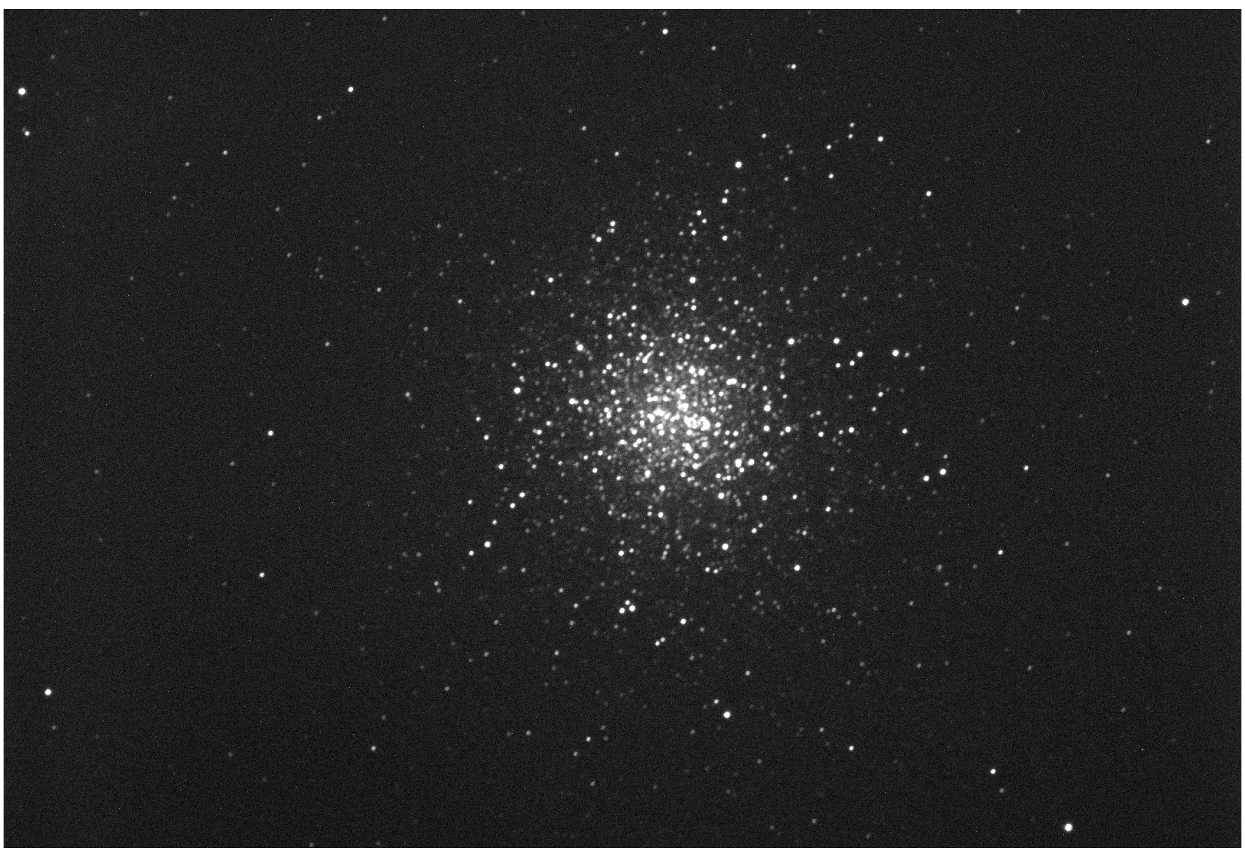



Titan
Rhea
Dione
Tethys

NIGHTTIME OBSERVING PROJECTS



Artemis and Apollo are the new, twin, state-of-the-art 20-inch optical telescopes at Sommers-Bausch Observatory deck. (Photo by Gary Garzone, BASS)



Messier 13, a bright Globular Star Cluster in Hercules imaged with the CCD camera on Apollo, the western SBO 20” telescope.

EFFECTS OF LIGHT POLLUTION

Note: unlike the other labs in this book, this exercise is to be completed on your own time over the course of the semester. It is due to your lab TA by your last lab meeting of the semester or before.

In this observing lab you will observe the night sky from **two locations**: one dark site and one more suburban/urban to assess the effects of light pollution on what we see in the sky. You will estimate the amount of human-caused light pollution and document the effects on the stars you can see in one or more constellations. You will submit your observational data to the Globe at Night citizen-science program to help monitor light pollution worldwide.

Since the moon can be quite bright, YOU MUST OBSERVE DURING ONE OF THESE TIME PERIODS in order to avoid moonlight. Do not put this off until the last minute!

Date Range	Constellation
September 1-10	Cygnus
October 1-10	Pegasus
October 30 – November 8	Perseus
November 29 - December 8	Perseus

1) Prepare for your observing sessions

Visit the website for the Globe at Night project: **http://www.globeatnight.org/**

This program monitors the brightness of the night sky and light pollution by charting how many stars you can see in a particular constellation. They ask you to estimate the "magnitude" of the faintest stars you can see and log this, along with the date/time and your longitude and latitude. This is combined with others' observations worldwide to create a year-by-year record of light pollution around the globe. The project is sponsored by the National Science Foundation, the Association of Universities for Research in Astronomy, and the National Optical Astronomical Observatories.

Read about the project from their Call to Action under the Learn (about light pollution) tab.

Verify which constellation(s) you will be looking for. Familiarize yourself with the "magnitude charts" for the constellation. Enter your latitude (40^{o}N) to make sure the constellation is oriented properly for an evening observation.

The term "**magnitude**" dates back to Hipparcos in ancient Greek times, who gauged the brightness of stars from 0 (very bright) to 7 (the faintest he could see). Note that, counter-intuitively, smaller magnitude numbers denote brighter stars! Modern astronomers still use this system and have extended it to very bright objects (Venus is about magnitude -4) and extremely faint objects (the Hubble Space Telescope has recorded stars as faint as magnitude 30). The mathematical definition of a magnitude is that 1 magnitude difference in brightness corresponds to a factor of 2.5 in apparent brightness (i.e. a star of magnitude=4 is 2.5 times brighter than a star of magnitude=5).

For your observations, you will use magnitude charts from the website to estimate the brightness of the faintest stars you can see in a constellation from two different locations. In the middle of a city, the faintest stars you can see may only be magnitude=1 or 2. From a dark site, it may be magnitude=5 or higher.

Preview the "Report" page to see what data you'll need to enter (an example is shown below). Make a note of these before you observe so you can fill out the page later. You should be able to locate your position to ~1 city block (1/10 of a mile). Click on the map window to see how this works. Note that you can use your cell phone to access the website and enter your data: your current time and location will be automatically recorded. **Test this before you go out at night.** Be sure to choose "night mode" if you're using your phone while observing at night--your phone will turn red which doesn't hurt your dark-adapted vision.

2) Choose your observing locations.

A **bright skies** site should be something in a city or suburb (on campus is fine but avoid campus lights!) Find something as dark as possible (i.e., don't stand right under a streetlight). If you're on campus, the middle of Norlin Quad or Farrand Field might be a good choice.

Your **dark skies** site should be **as far from city lights as possible**. Ideally, you'd be out in the middle of the desert or mountains. However, this has practicality issues. *Anywhere* on campus or even most places inside the city of Boulder do **NOT** count as dark skies sites. If you're in Boulder, here are a few very good locations:

- West on Baseline Road up over the top of Flagstaff Mountain. Find the pull-off for the Meyers Gulch or Walker Ranch open spaces (about 12 miles by road from Boulder).
- Peak to Peak Highway. Drive west up Boulder Canyon to Nederland. At Nederland go either north or south several miles on Peak-to-Peak Highway (State #72). Find a pull-off where you can see lots of sky.
- North of Boulder. The area near Boulder Reservoir ("the Res") and other farm land in the rural areas between Boulder, Lyons, and Longmont are pretty dark. Be sure you are not trespassing.

Another possibility is to make a high-impact observation for the Globe at Night project. At the bottom of their home page they show a map showing previous observations for the year. You can get a feel for where the bright (yellow) and darker (orange to red) sites are and choose one for either your bright or dark sites. If you can, choose a site that will "fill in" the map. (Note that a report of a "dark" site within the city of Boulder is probably an error).

OR

An independent blogger at http://lossofthenight.blogspot.com/2015/03/the-globe-at-night-revisit-project-2015.html has compiled a list of sites that have a previous observation but then nothing for the past few years. Check the map to see where these high-priority "revisit" sites are. There are quite a few in Boulder County and nearby- can you visit one of these for either your bright or dark site and help with the long-term monitoring program? You don't need to get to the exact coordinates- they say within 100 meters would be excellent (and it would be OK to be off by more than that).

There is no need to do your bright- and dark-sky observations on the same night or even during the same observing 'window'. However, be sure you observe during the dates of the observing campaign (listed at the top of this activity), not during a time when the moon is up.

3) Make your observations

Travel to your observing location between the hours of about 8-11pm. **Please be careful** - for your safety and that of others- always bring a friend or two (it's a lot more fun that way, too!) Be especially careful if walking along roadways and bring a small flashlight for navigation.

For your bright site: try to situate yourself in a place that is not directly under or near a bright light source. Find your constellation and compare it with the magnitude charts from the Globe at Night website. Choose which one corresponds best to the stars that you can see. Fill in the information they require for time/date, location, magnitude chart, sky conditions, and any comments you'd like to add. [Ignore the SQM query unless you want to look into what this means and see if their phone app works- reports are mixed]. Submit your data and log your data on the sheet at the end of this activity.

For your dark site: find the darkest location you can, away from any obvious local lighting. Sit quietly for about 10 minutes to let your eyes adapt (you can close your eyes if you like). If you have a phone, flashlight or other light source with you, either turn it off (!!!) or use "night mode" to turn the display red to help keep your pupils from closing up. Do the same observations for Globe at Night. Can you see the Milky Way?

4) Document your observations

Find the web form to report your observations (example on the next page). Fill in the data for both your bright and dark sites. Either print your report page when you submit it or copy the information on the sheet at the end of this activity.

Next, please answer the questions below:

4a) What is the difference in the faintest magnitude stars you can see between your bright and dark skies? Between your bright skies and the darkest skies (~mag 7)? Converting magnitude to brightness use the scale that each magnitude difference is a factor of 2.5. E.g.,

1 magnitude difference = 2.5 times fainter

2 magnitudes = 2.5 x 2.5 = 6.25 times fainter

3 magnitudes= 2.5 x 2.5 x 2.5 = 15.6 times fainter

4 magnitudes = 39 times fainter

5 magnitudes = 100 times fainter

How much fainter (in absolute terms, not magnitudes) are the faintest stars you can see in your dark sky, versus the faintest in your bright sky?

4b) Did one part of the sky seem brighter than another? What might cause this?

4c) Did you see the Milky Way from your dark site?

4d) Visit the International Darksky Association website at http://darksky.org/

4e) Write a 1-2 paragraph commentary on a topic discussed on the website pertaining to dark skies or light pollution (i.e., Dark sky parks, problems with LED lighting, nighttime lighting and crime, etc.) Does light pollution affect just professional astronomers or is it a larger, societal issue?

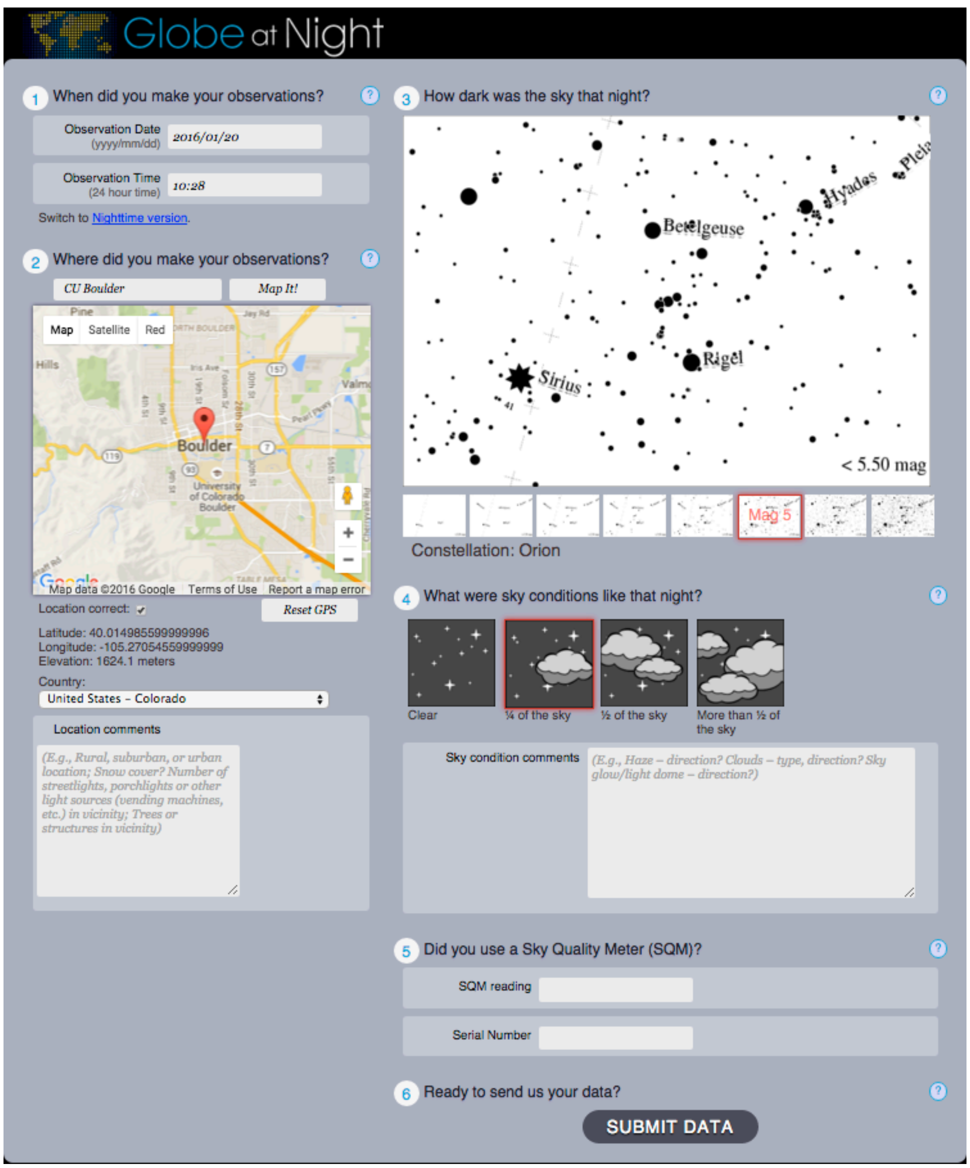
Summary

To hand in for your activity: Three pages total.

1) Two (or more!) log sheets printed from the GlobeatNight website (see example below); one for your bright sky location and one for your dark sky location. Use the "location comments" box to describe your location. On each one, please write down anyone (whether in our class or not) who you were with at the time.

2) One (typed) page answering the questions in part 4. If you'd like to share your reactions to this exercise or anything interesting you observed, feel free to do so.

HAVE FUN WITH THIS AND BE SAFE!



OBSERVING SATURN AND ITS MOONS

MOTIVATION and SYNOPSIS:
This is a new, three-part observational lab in which you will learn various aspects of observational astronomy, basic data analysis, and apply your results in a realistic way to determine some real aspects of planetary science.

In **Part 1**, you and a group of 2-3 other students will observe Saturn through the telescopes at the Sommers-Bausch Observatory (SBO) on campus both visually (through the eyepiece) and using a camera to record a detailed digital image.

In **Part 2**, each student will use software to perform some basic analysis of the image(s) you took at the telescope. You will measure four different quantities from your image and record them on a class data repository for future use. Part 2 is to be completed after your observing session (part 1). Your TA will give you a due date for Part 2.

Part 3 of this lab will be completed during one of your regular day-time lab sessions in late-October/early-November. You will use the data collected by the entire class (including your data points) to determine the orbit of Titan around Saturn to calculate the mass of the Saturnian system.

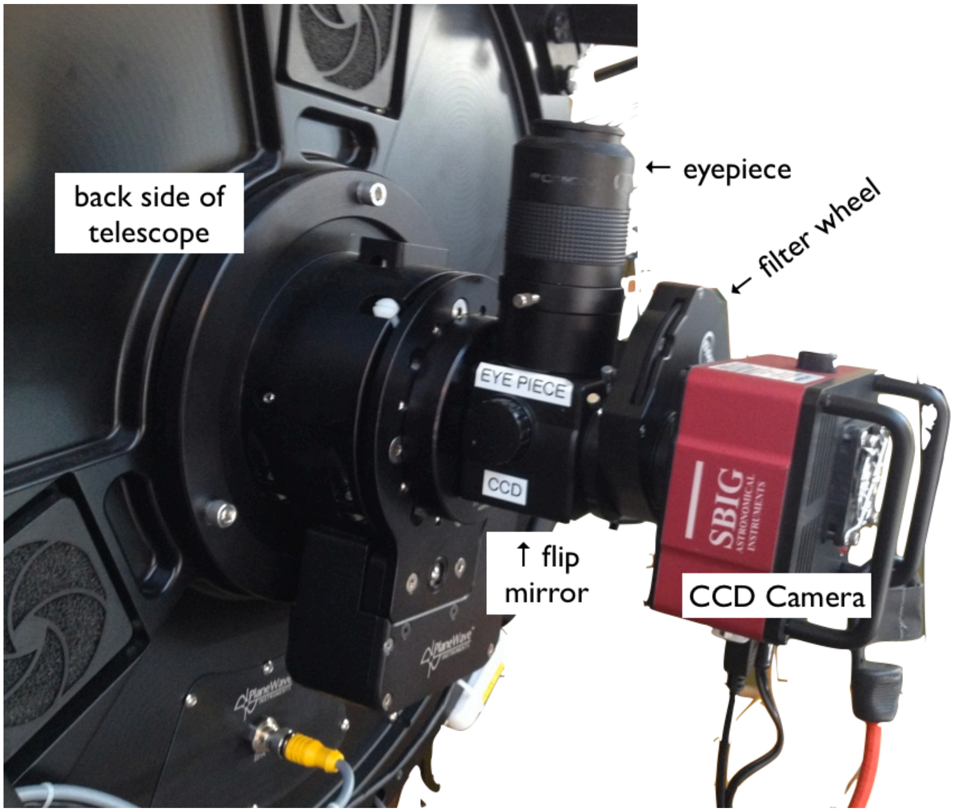
OBSERVING SCHEDULE:
Saturn is only visible in the evening sky for the first half of the Fall 2019 semester. ASTR1010 has several observing nights scheduled during this period. To complete parts 1 and 2 of this lab, you MUST attend at least one of these observing nights. **Do not put this off until the last minute!** Periods of bad weather and telescope scheduling can make your first-choice evening unavailable. Your grade on this lab is based on completing parts 1 and 2. Part 3 is counted as a regular day-time lab and can be completed even if you don't get to the telescope.

PRELAB:
Read through Part 1 of the lab to familiarize yourself with the procedure and what you will need to do. Time at the telescopes is limited, so knowing what to do is crucial to smooth operation. TAs/LAs will be there to assist, but you should expect to do much of the work with the telescope and computer yourself.

PART 1 - Observing Saturn

1.1 - Point telescope to Saturn

1) At the computer terminal on the observing deck, locate the window for TheSkyX software. Find the vertical Telescope tab on left edge of the window.
3) In search box on left side, enter Object Name (Saturn) and click Find. (You can also find Saturn on the map and click on it. A red target symbol should appear on the sky map.
4) Check that the area around the telescope is clear and announce that you are slewing. When the area is clear, click Slew. Telescope should start to move and yellow target symbol should move over to cover the red symbol.



The back side of the 20-inch telescopes with the important parts labeled. The flip mirror allows light from the telescope to enter either the eyepiece or the camera. The filter wheel allows you to block different colors of light from the camera.

1.2 Visual observations

- A knob below the eyepiece controls a flip mirror that sends light to either the camera or the eyepiece. Make sure the knob is rotated counter-clockwise as far as it will easily move.
- Look through the eyepiece (use the step ladder if necessary).
- Do you see Saturn? Is it in focus? If not, ask a TA/LA to focus the system for you.
- If Saturn is in the best focus, you should be able to see the *Cassini Division*, a gap between the inner (B) ring and outer (A) ring. You should also be able to see some of Saturn's larger moons. There may be up to five visible. *Titan* is the brightest of these, but you may also see *Rhea, Dione, Tethys, Enceladus,* and *Iapetus*.

Record your visual observations below: Make a sketch of what you see through the eyepiece.

1.3 Camera observations:

1) Turn the flip mirror knob to send light to the camera (rotate the knob clockwise)
2) Click the Filter Wheel tab on left edge of the screen (near the Telescope tab).
3) Use the pull down in the Filter Wheel window to select the red (r) filter (it may already be there) and click Move Now to rotate the filter wheel to move the filter in place. This filter blocks most of the light from the telescope so the camera electronics are not overwhelmed (Saturn is bright!).
4) Click the Camera tab on left edge of screen.
5) Set Exposure Time to **0.1 second**.
6) Click Take Photo. An image should appear in another window in a few seconds.
7) In the image window, click the Histogram icon in the upper left. Move the brightness control sliders on the image to look for the same details you saw with your eye. Is the image in-focus? Is the image saturated? The brightest part of Saturn should be around 20,000 counts (but definitely BELOW 30,000 counts!) Seek help from your TA to check. Note, atmospheric turbulence blurs images and may wash out features. Take another image and see if it is better or worse than the first one.
8) Take a few images (at least 3) until you get one that is as clear and sharp as possible.

1.4 Save your data:

When you have gotten the sharpest image you can, save it to the disk (Please save ONLY your best image). In the FITS Viewer window (where the image is), click the Photo pull-down menu select Save As.

Save in the class Google Drive directory using a file name that identifies your team and the date (e.g., "Smith_Brown_Jones_sept14.FIT").

1.5 Reset the telescope for the next team:

Close your image window.

Move the telescope. In the Telescope control panel, Find "Vega", and click Slew.

Flip the mirror back to eyepiece mode (turn counter-clockwise) and make sure a bright star appears in the center of the field.

You're done for the night. Congratulations!

Part 2: Image Analysis

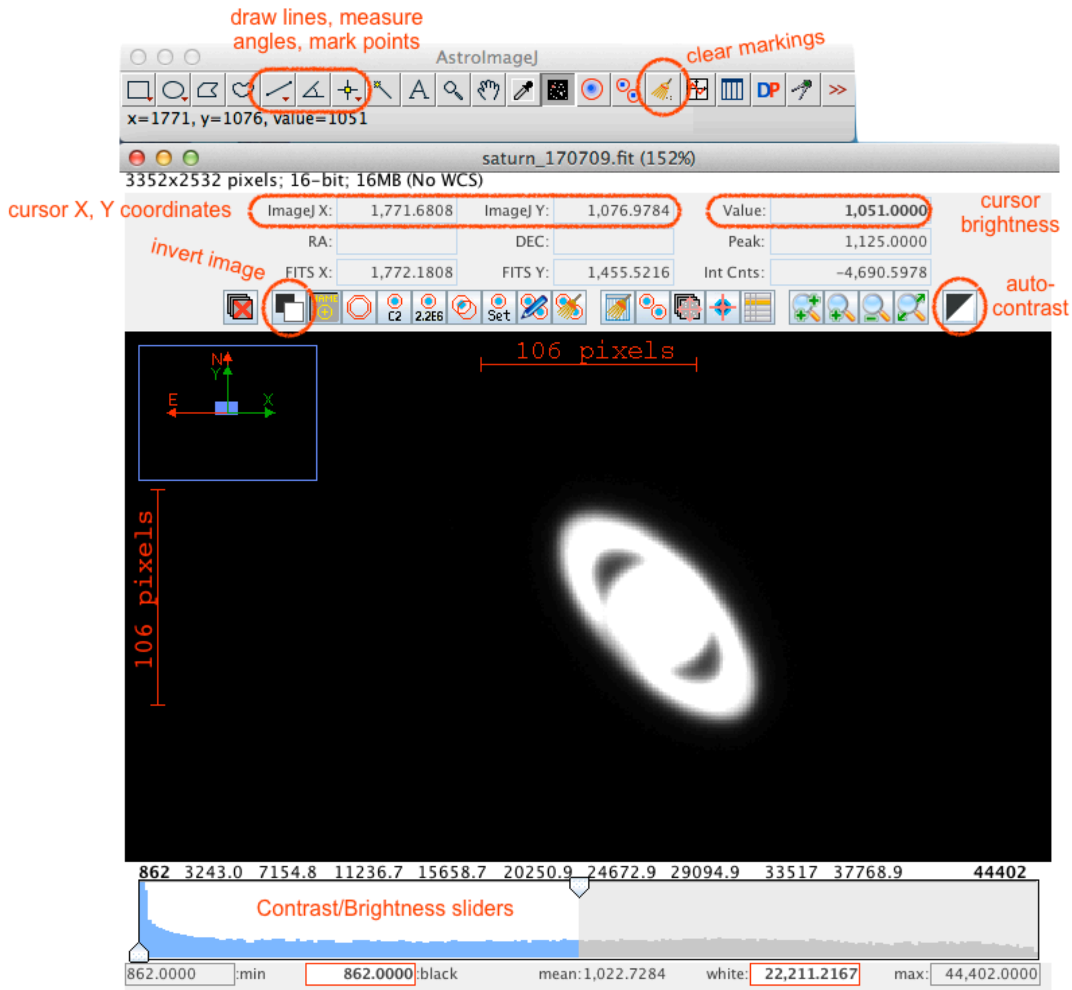
After your observing session, you'll need to do some analysis on your Saturn image. In this class, we will use the *AstroImageJ* software package distributed for free from the University of Louisville. It is a powerful-yet-intuitive code which will run on most computers.

2.1 Download *AstroImageJ*

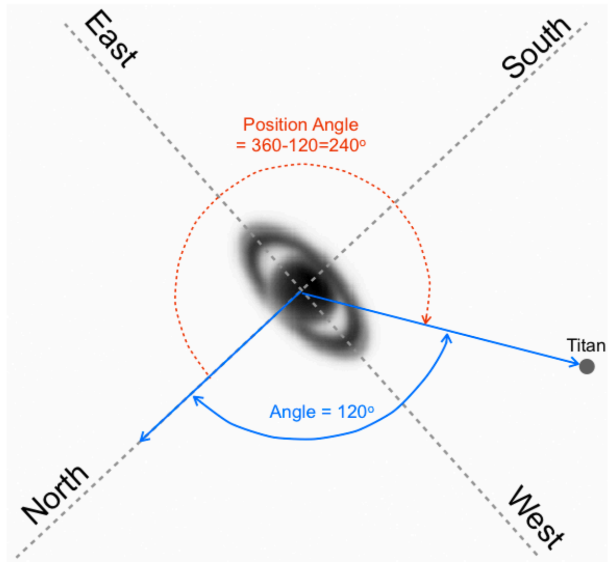
Download whichever version of the software is appropriate from
http://www.astro.louisville.edu/software/astroimagej/

2.2 Copy your observations

Copy the *.fits* file from the class data directory to your local computer.
Open your image using *AstroImageJ* (File > Open)



Take a few minutes to familiarize yourself with the software. Try **zooming** in and out. Notice the X and Y coordinate boxes at the top of the image window and/or in the toolbar window. Try sliding the bars around on the **contrast sliders**. Try inverting the image (switching black and white with the invert button). Do you see more of less detail on the planet? What setting allows you to see the moons best? Can you see both moons and ring details at the same time?



2.3 Identify coordinates in your image:
Adjust the image so you can clearly see as many details of the planet and rings as possible. It is currently northern summer at Saturn, so the planet is tilted with its northern hemisphere toward us. North corresponds to a line perpendicular to the ring semi-major axis. (In the example above, north points down and to the left.) East is 90 degrees clockwise from the north line. In this example, Saturn would be in the SW quadrant.

2.4 Diameter of Saturn and Rings
Use the line tool in the toolbar to measure the diameter of Saturn in pixels. The line tool will give you a length in pixels, but you can also record the X and Y positions of any two points and use the Pythagorean theorem to compute a length between points 1 and 2:

$$dist^2=(x_1-x_2)^2+(y_1-y_2)^2.$$

Divide this number by two so you have a measurement of Saturn's radius *in pixels*. You will use this number to convert the rest of your measurements into units of Saturn radii.

Saturn diameter: __________ pixels
Saturn radius: __________ pixels

Now measure the diameter of the rings (east-west distance) and convert to Saturn radii using the number of pixels you just calculated for Saturn's radius.

Ring diameter: __________ pixels = __________ Saturn radii

2.5 Titan
Zoom out and adjust the contrast until you can easily see Saturn and its moon(s).

Identify which moon is Titan (it will be the brightest and probably the farthest from the planet as well). The website https://www.wwu.edu/skywise/saturn.html can help. Note that UT time is 6 hours ahead of Mountain Daylight Time. *(If you cross 24h be sure to add one day to the UT date!)*

Which quadrant does Titan lie in with respect to Saturn? (NE, SW, etc.) ___________

Use the same technique you used above to measure distance from the center of Saturn to Titan.

Titan distance: __________ pixels = __________ Saturn radii

Next, measure the "position angle" from Saturn to Titan. This is defined as the direction from the center of Saturn to Titan and measured in degrees east of north. Use the angle tool in *AstroImageJ* to measure the angle. Click Titan, then click the center of Saturn, then another point along the north axis of the planet. Remember that position angle is degrees east of north; if Titan is in the SW or NW quadrant, you'll need to subtract your angle measurement from 360 degrees.

Titan PA = ______________ degrees east of north

It's easy to get the sense of this number wrong, so check which quadrant Titan lies in and compare to the example figure and table. In the example, north lies in the lower left direction, so Titan is in the SW quadrant. The angle measurement from *AstroImageJ* is 120°. However, we must go from north through east, so PA=360°-120°=240°.

Quadrant	PA range
NE	0-90
SE	90-180
SW	180-270
NW	270-360

2.6 Upload your data
In one of the in-class labs, you will be combining your measurements with those of the rest of the class to determine some important parameters about Saturn. As part of this, you will upload your measurements to a form. See the class web page for instructions.

Include your **name** and that of others on your team (this information will be anonymized before presented to the whole class). Enter the Mountain Daylight Time **date** and **time** of your observations. Note **weather**, **equipment**, and any other information you think might be relevant.

Next, record the four quantities you calculated in sections 2.4 and 2.5:
- **radius** of Saturn (pixels)
- **diameter** of ring system (Saturn radii)
- Saturn-Titan **distance** (Saturn radii)
- Saturn-Titan **position angle** (degrees E of N)

2.7 Above and beyond (optional):
Can you identify any other moons in your image? If so, note them down in the comments section of the web form. The website https://www.wwu.edu/skywise/saturn.html will give you the positions of the five bright moons. Note that UT time is 6 hours ahead of Mountain Daylight Time. *(If you cross 24h be sure to add one day to the UT date!)*

CONSTELLATION AND BRIGHT STAR IDENTIFICATION

SYNOPSIS: In this self-paced lab, you will teach yourself to recognize and identify a number of constellations, bright stars, planets, and other celestial objects in the current evening sky.

EQUIPMENT: A planisphere (rotating star wheel) or other star chart. A small pocket flashlight may be useful to help you read the chart.

Part I: Preparation, Practice, and Procedures

Part II contains a list of 30 or more celestial objects that are visible to the naked eye each semester. You are expected to learn to recognize these objects through independent study, and to demonstrate your knowledge of the night sky by identifying them.

Depending upon the method chosen by the course instructor, you may have the opportunity to identify these objects one-on-one with your lab instructor during one of your scheduled evening observing sessions. Alternatively, there may be the opportunity to take an examination over these objects in Fiske Planetarium near the end of the semester. In addition, there may be the opportunity to do both, in which case the better of your two scores would be counted.

If you are given the option, and if you wait until the end of the semester to take the verbal quiz and then are clouded out, you have no recourse but to take the Planetarium exam. *Do not expect your TA to schedule additional time for you. If you have not taken the oral test and are unable to attend the special exam session at Fiske (or it is not offered), you will not receive credit for this lab!* "*Poor planning on your part does not constitute an emergency on our part.*"

You can learn the objects by any method you desire:

③ Independent stargazing by yourself or with a friend.

③ Attending the nighttime observing sessions at the Observatory, and receiving assistance from the teaching assistant(s) or classmates.

③ Attending Fiske Planetarium sessions.

③ All of the above.

Observing and study tips:

③ It is generally be to your advantage to take the nighttime verbal quiz if it is an option, since *you* control the method and order of the objects to be identified. In addition, it is easier to orient yourself and recognize objects under the real sky rather than the synthetic sky of the planetarium, since that is the way that you learned to recognize the objects in the first place.

- Your textbook may come with access to planetarium software, or you can download free software from http://stellarium.org/. These tools can be a great way to explore the night sky even during the daytime and/or from the comfort of your desk. Then you can go outside to see how the real thing compares with the simulation.

- But if you like a hands-on aid, we recommend using the large, 10" diameter Miller planisphere available from Fiske Planetarium: it is plastic coated for durability, is easiest to read, and includes sidereal times. The smaller Miller planisphere is more difficult to use but is handier to carry. Other planispheres are available from the bookstore or area astronomy stores.

- To set the correct sky view on your planisphere, rotate the top disk until the current time lines up with the current date at the edge of the wheel. Planispheres indicate local "standard" time, not local "daylight savings" time. If daylight savings time is in effect, *subtract* one hour from the time before you set the wheel. (For example, if you are observing on April 15th at 11 p.m. Mountain Daylight Time, line up 10 p.m. with the April 15th marker).

- The planisphere shows the current appearance of the entire sky down to the horizon. It is correctly oriented when held overhead so that you can read the chart, with North on the chart pointing in the north direction. The center of the window corresponds to the zenith (the point directly overhead). When you face a particular direction, orient the chart so that the corresponding horizon appears at the bottom. As with all flat sky maps, there will be some distortion in appearance, particularly near the horizons.

- Be aware that faint stars are difficult to see on a hazy evening from Boulder, or if there is a bright moon in the sky. On the other hand, a dark moonless night in the mountains can show so many stars that it may be difficult to pick out the constellation patterns. In either case, experience and practice are needed to help you become comfortable with the objects on the celestial sphere.

- Learn relationships between patterns in the sky. For example, on a bright night it may be virtually impossible to see the faint stars in the constellation of Pisces; however, you can still point it out as "that empty patch of sky below Andromeda and Pegasus". You can envision Deneb, Vega, and Altair as vertices of "the Summer Triangle", and think of Lyra the harp playing "Swan Lake" as Cygnus flies down into the murky pool of the Milky Way.

- If you merely "cram" to pass the quiz, you will be doing yourself a great disservice. The stars will be around for the rest of your life; if you *learn* them now rather than just *memorize* them, they will be yours forever.

Good luck, good seeing, and clear skies …

Part IIa. Fall Naked-Eye Observing List

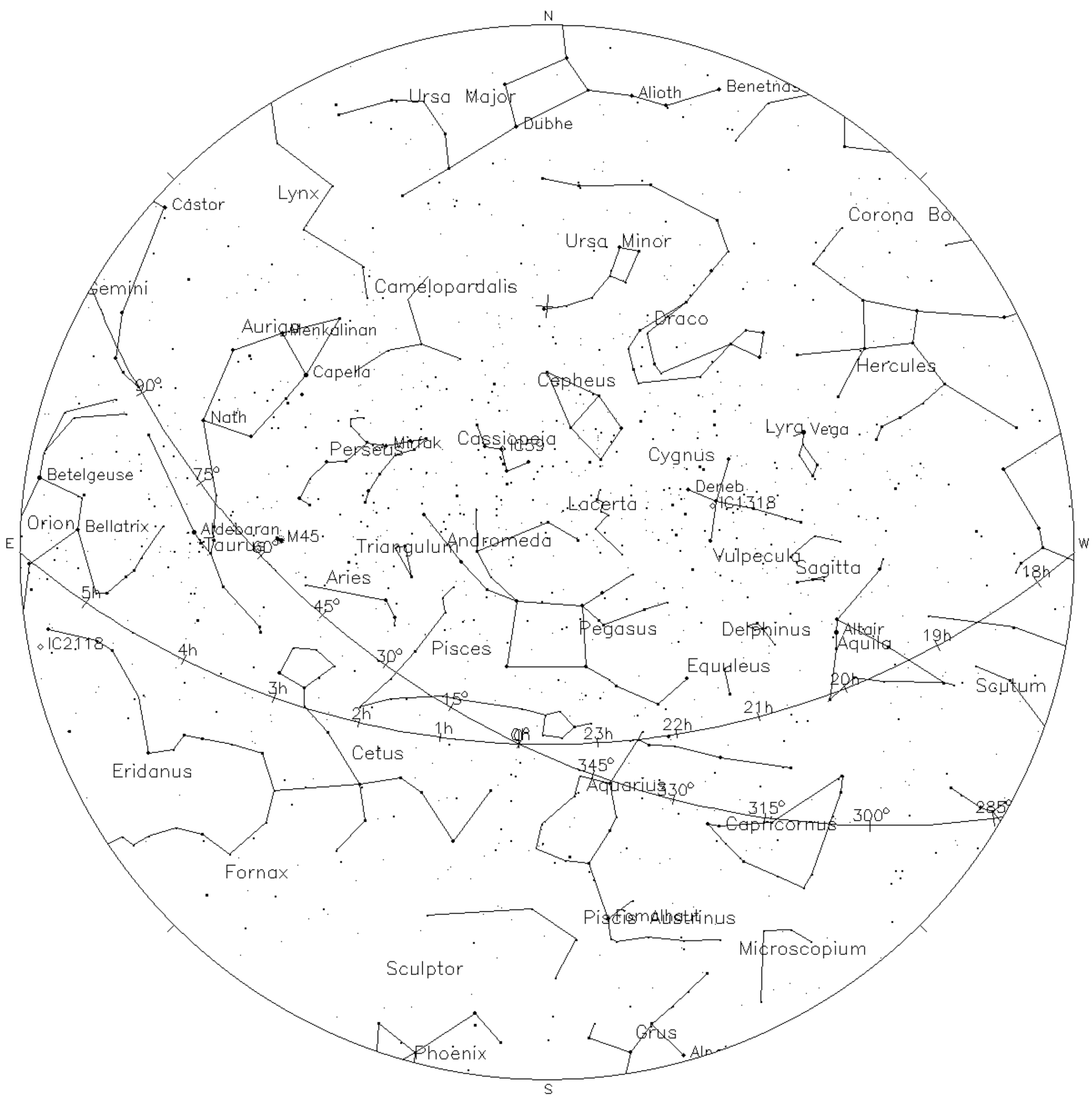
Constellations	Bright Stars
Ursa Minor *(little bear, little dipper)*	Polaris
Lyra *(lyre, harp)*	Vega
Cygnus *(swan, northern cross)*	Deneb
Aquila *(eagle)*	Altair
Cepheus *(king, doghouse)*	
Capricornus	
Aquarius	
Pegasus *(horse, great square)*	
Andromeda *(princess)*	
Pisces *(fishes)*	
Aries *(ram)*	
Cassiopeia *(queen, 'W')*	
Perseus *(hero, wishbone)*	
Taurus *(bull)*	Aldebaran
Auriga *(charioteer, pentagon)*	Capella
Orion *(hunter)*	Betelgeuse, Rigel
Gemini *(twins)*	Castor, Pollux

Other Celestial Objects or Regions

Mercury, Venus, Mars, Jupiter, Saturn (and bright comets if present)	*(check the web resources at the beginning of this manual)*
Ecliptic or Zodiac	*trace its path across the sky*
Celestial Equator	*trace its path across the sky*
Pointer Stars	*how to locate Polaris*
Great Andromeda Galaxy	*fuzzy patch in Andromeda*
Pleiades *(seven sisters)*	*star cluster in Taurus*
Hyades *(closest star cluster)*	*near Aldebaran*
Great Nebula in Orion (M42)	*center 'star' in Orion's sword*

Fall Constellations

(with ecliptic and celestial equator shown)



The Boulder Night Sky

October, 10:00 pm

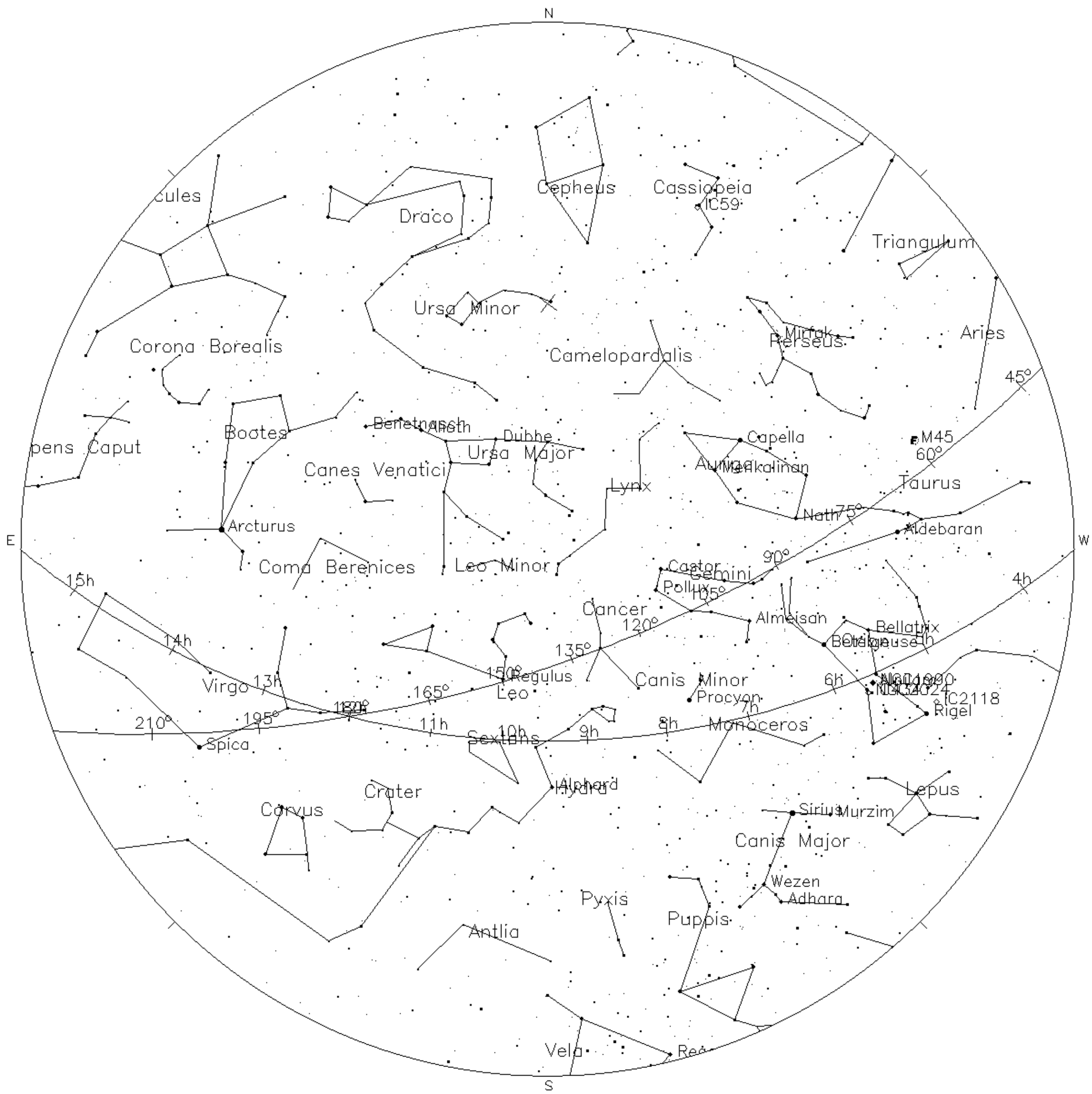
Part IIb. Spring Naked-Eye Observing List

Constellations	Bright Stars
Ursa Major *(big bear, big dipper)*	Alcor & Mizar
Ursa Minor *(little bear, little dipper)*	Polaris
Cassiopeia *(queen, 'W')*	
Cygnus *(swan, northern cross)*	
Perseus *(hero, wishbone)*	
Taurus *(bull)*	Aldebaran
Auriga *(charioteer, pentagon)*	Capella
Orion (*hunter*)	Betelgeuse, Rigel
Gemini (*twins*)	Castor, Pollux
Canis Major *(big dog)*	Sirius
Canis Minor *(small dog)*	Procyon
Cancer *(crab)*	
Leo *(lion)*	Regulus
Boötes *(herdsman, cone, kite)*	Arcturus
Virgo *(virgin)*	Spica

Other Celestial Objects or Regions	
Mercury, Venus, Mars, Jupiter, Saturn (and bright comets if present)	*(check the web resources at the beginning of this manual)*
Ecliptic or Zodiac	*trace its path across the sky*
Celestial Equator	*trace its path across the sky*
Pointer Stars	*how to locate Polaris*
Great Andromeda Galaxy	*fuzzy patch in Andromeda*
Pleiades *(seven sisters)*	*star cluster in Taurus*
Hyades *(closest star cluster)*	*near Aldebaran*
Great Nebula in Orion (M42)	*center 'star' in Orion's sword*

Spring Constellations

(with ecliptic and celestial equator shown)



The Boulder Night Sky

March, 10:00 pm

TELESCOPE OBSERVING

SYNOPSIS: You will view and sketch a number of different astronomical objects through the SBO telescopes. The requirements for credit for telescope observing may vary depending on the requirements of your instructor. The following is given only as a guideline.

EQUIPMENT: Observatory telescopes, observing forms, and a *pencil.*

Be sure to dress warmly - the observing deck is not heated!

Part I. Observing Deep Sky Objects

The two main SBO 20-inch observing telescopes are both operated by computer. The user may tell the computer to point at, for example, object number 206, or the observer may specify the coordinates at which the telescope should point. Deep sky objects are easily selected from the SBO Catalog of Objects found in the operations manual of each telescope. Additional objects may also easily be located with the 18-inch telescope using *TheSky* planetarium program.

Your instructor may point a telescope to at *least* one of each of the following different types of deep-sky objects (provided that weather cooperates, and the appropriate objects are visible in the sky at the time). Distinguishing characteristics to look for have been included in italics.

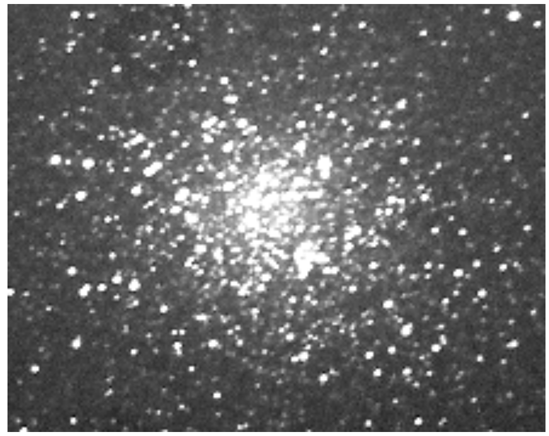
- ③ **Double or multiple stars**. *Separation of the stars, relative brightness, orientation, and color of each component*.
- ③ **Open clusters**. *Distribution, concentration, and relative brightness and color of the stars*.
- ③ **Globular clusters**. *Shape, symmetry, and central condensation of stars*.
- ③ **Diffuse nebulae**. *Shape, intensity, color, possible association with stars or clusters*.
- ③ **Planetary nebulae**. *Shape (ring, circular, oblong, etc.), size, possible central star visible*.
- ③ **Galaxies**. *Type (spiral, elliptical, irregular), components (nucleus, arms), shape and size*.

For *each* of the above objects that you observe:

I.1 In the spaces provided on the observing form, fill in the object's name, type, position in the sky (RA and dec), etc. Make certain to note what *constellation* the object is in, because this information is almost essential when using the reference books.

I.2 Observe through the telescope and get a good mental image of the appearance of the object. You may wish to try averted vision (looking out of the corner of your eye) to aid you in seeing faint detail. Take your time; the longer you look, the more detail you will be able to see.

I.3 Using a pencil, carefully sketch the object from memory, using the circle on the observing form to represent the view in the eyepiece. Be as detailed and accurate as possible, indicating color, brightness, and relative size.



I.4 Include an "eyepiece impression" of what you observed: a brief statement of your impressions and interpretation. Feel free to draw upon comparisons (for example, "like a smoke ring," or "a little cotton ball," etc.). Express your own enthusiasm or disappointment in the view!

I.5 If you wish (or if your instructor has required it), research some additional information on your objects. The Observatory lab room has some sources, as does the Math-Physics Library. Specific useful books are *Burnham's Celestial Handbook*, the *Messier Album*, and various textbooks. Read about the object, and then provide any additional information that you find is particularly pertinent or interesting.

Part II. Planetary Observations

Most of the planets (other than the Earth) are readily observed with the SBO telescopes. The difficult ones are Pluto (tiny and faint) and Mercury (usually too close to the Sun). Provided that they are available in the sky this semester (consult the "Solar System Calendar" section at the beginning of this manual):

II.1 Observe, sketch, and research at *least* two of the solar system planets, as in paragraphs I.1 through I.5 above. Pay particular attention to relative size, surface markings, phase, and any special features such as moons, shadows, or rings. You may wish to use different magnifications (different eyepieces) to try to pick out more detail.

NAME:

Object Name
Object Type
Constellation
R.A.
Dec.
Date
Time
Telescope size
Sky Condition

Description of Observation

Additional Information

Object Name
Object Type
Constellation
R.A.
Dec.
Date
Time
Telescope size
Sky Condition

Description of Observation

Additional Information

NAME:

Object Name	
Object Type	
Constellation	
R.A.	
Dec.	
Date	
Time	
Telescope size	
Sky Condition	

Description of Observation

Additional Information

Object Name	
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Telescope size	
Sky Condition	

Description of Observation

Additional Information

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Object Name
Object Type
Constellation
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Description of Observation

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Description of Observation

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Description of Observation

Additional Information

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Telescope size	
Sky Condition	

Description of Observation

Additional Information

Object Name	
Object Type	
Constellation	
R.A.	
Dec.	
Date	
Time	
Telescope size	
Sky Condition	

Description of Observation

Additional Information

OBSERVING LUNAR FEATURES

SYNOPSIS: You will investigate the Moon through telescopes and binoculars, and identify and sketch several of the lunar features.

EQUIPMENT: Sommers-Bausch Observatory telescopes and binoculars, lunar map, lunar observing forms, and a *pencil*.

Be sure to dress warmly - the observing deck is not heated!

Part I. Lunar Features

Listed below are several types of lunar features. Read the description of feature types, and identify at *least* one example of each, using either a telescope or binoculars. Locate and label each feature on one of the lunar outline charts below. (Note that one of the charts is presented in "normal view," which resembles the appearance of the Moon as seen through binoculars, while the other is a "telescope view," which is a mirror image of the Moon as it may appear through the telescopes. Use either or both charts at your convenience.)

You will encounter additional features not shown on the outline charts, such as small craters. Feel free to add them as you view them.

Feature types marked with "T" are best seen through a telescope, while those marked with "B" can be seen with binoculars.

I.1 **Maria**: These are relatively smooth and dark areas formed by ancient volcanic eruptions that filled even older giant impact craters. The maria comprise the "man-in-the-Moon." These were once thought to be seas, during the early days of the telescope. (B) *Shade in these dark patches with your pencil.*

I.2 **Craters with central peaks**: Many large craters have mountain peaks in their centers, which can reach 5 km in height. These peaks are produced by a rebound shock wave produced by the impact that formed the crater. (T)

I.3 **Craters with terraced walls**: As some large craters formed, their inner walls collapsed downward, pulled by gravity. This can happen several times, giving the inner crater wall a stair-stepped appearance. (T)

1.4 **Overlapping craters**: An impact crater may be partially obliterated by a later impact, giving clear evidence of which impact occurred earlier, and which occurred later. (T)

I.5 **Craters with rays**: Some younger craters have bright streaks of light material radiating from them. These rays are created by debris tossed out by the impact that formed the crater. Craters with bright rays are relatively "young" (less than 1 billion years old); the rays of older craters have been obliterated by subsequent geologic activity or impacts. Rays are most prominent near the time of the full Moon. (B)

I.6 **Walled plains**: A few very large craters have bottoms that are partially filled by mare lava. The appearance is that of a large flat area surrounded by a low circular wall. (T)

I.7 **Rilles:** Rilles are trenches in the lunar surface that can be straight or irregular. Although some of them look like dried riverbeds, they were not formed by water erosion, but rather by ancient flows of liquid lava. Straight rilles are probably geological faults, formed by ancient "moonquakes." (T)

I.8 **Mountains and mountain ranges**: The Moon's mountains are the remnant rims of ancient giant impact craters. Because of the Moon's low gravity and slow erosion, these mountain peaks can reach heights of 10 km. (B or T)

Part II. The Terminator

The **terminator** is the sharp dividing line between the sunlit and dark sides of the Moon's face.

II.1 If the Moon is not full on the night of your observations, carefully sketch the terminator on the chart. Include irregularities in the line, which give visual clues to the different heights in the lunar features (high mountains, crater edges, and low plains). (B)

II.2 Inspect the appearance of craters near the terminator, and those that are far from it. How does the angle of sunlight make the craters in the two regions appear different? In which case is it easier to identify the depth and detail of the crater? (If the Moon is full, look for craters near the edge of the Moon, and contrast with those near the center.) (T)

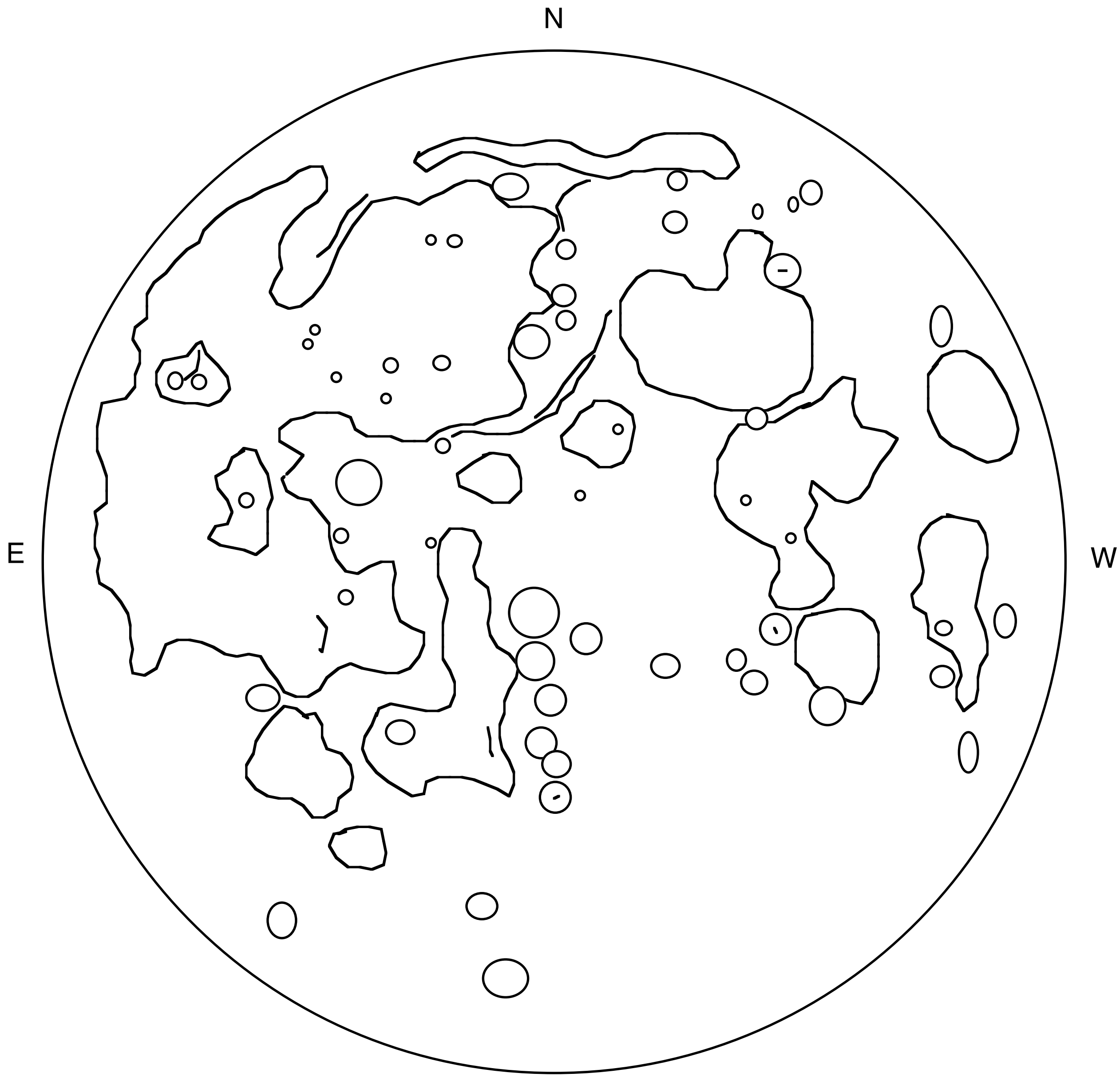
II.3 If you were standing on the Moon at the terminator, describe what event you would be experiencing.

Part III. Lunar Details

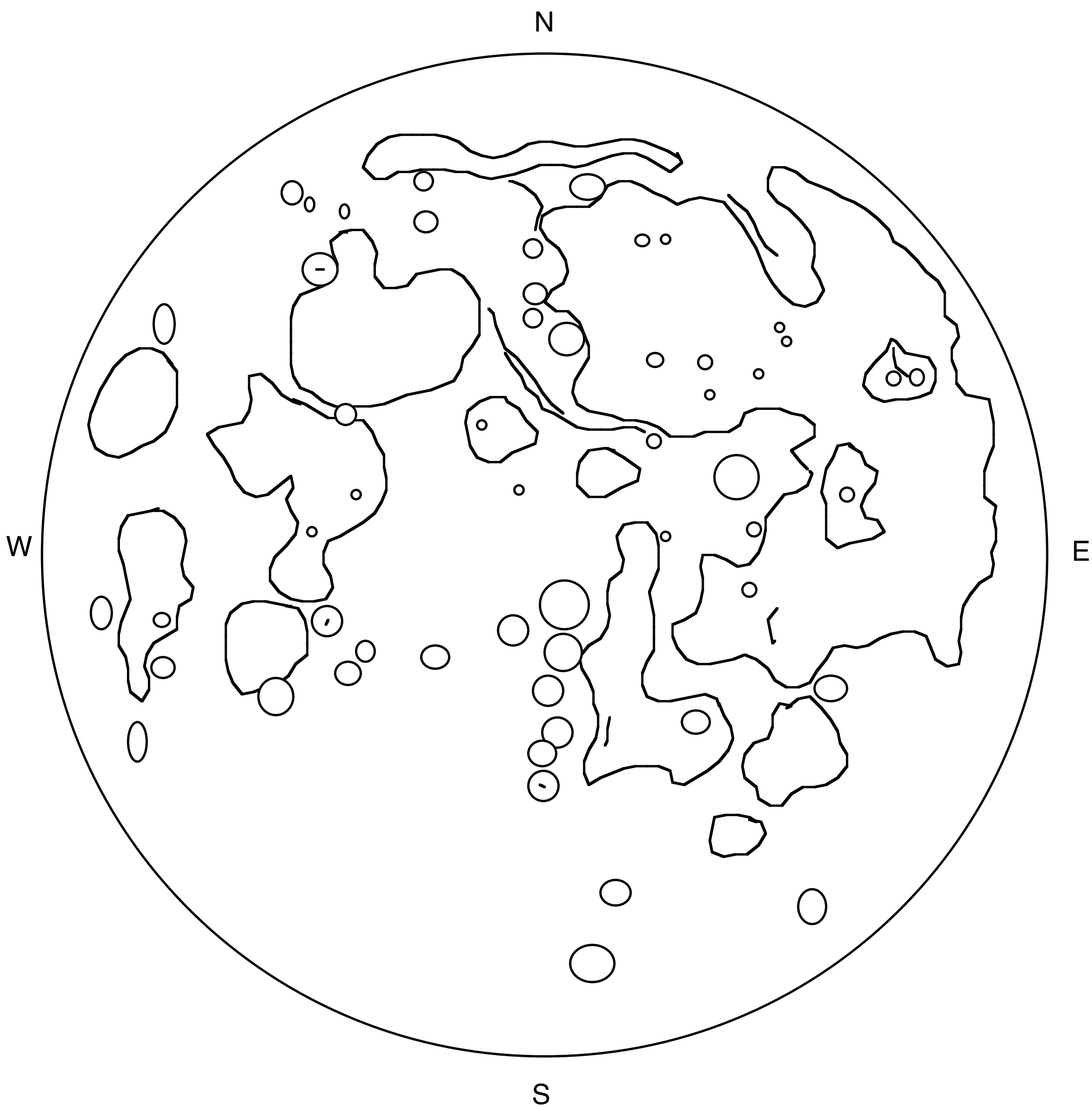
III.1 Select two lunar features of particular interest to you. Use the attached lunar sketch sheet to make a detailed pencil sketch of their telescopic appearance. Be sure to indicate their locations on an outline chart, so that you can later identify the features. (T)

Part IV. Lunar Map Identification

III.1 Compare your finished lunar outline charts and observing sheets with a lunar map, and determine the proper names for the features you have identified and sketched.



Binocular View



Telescope (Inverted) View

North may not be "up" in the eyepiece

Units Conversion Table

English to metric		
1 inch	=	2.54 cm
1 mile	=	1.609 km
1 lb	=	0.4536 kg
1 gal	=	3.785 liters

metric to English		
1 m	=	39.37 inches
1 km	=	0.6214 mile
1 kg	=	2.205 pound
1 liter	=	0.2642 gal

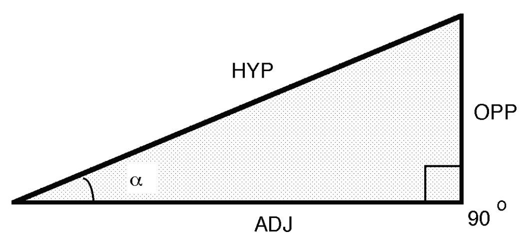
Metric Prefixes

Prefix	Abbre-viation	Value
deci-	d	10^{-1}
centi-	c	10^{-2}
milli-	m	10^{-3}
micro-	m	10^{-6}
nano-	n	10^{-9}
pico-	p	10^{-12}
femto-	f	10^{-15}
atto-	a	10^{-18}

Prefix	Abbre-viation	Value
decka-	da	10^{1}
hecto-	h	10^{2}
kilo-	k	10^{3}
mega-	M	10^{6}
giga-	G	10^{9}
tera-	T	10^{12}
peta-	P	10^{15}

Circles and Spheres

- circumference = $2\pi R$.
- area of a circle = πR^2.
- surface area of a sphere = $4\pi R^2$.
- volume of a sphere = $4/3\ \pi R^3$.

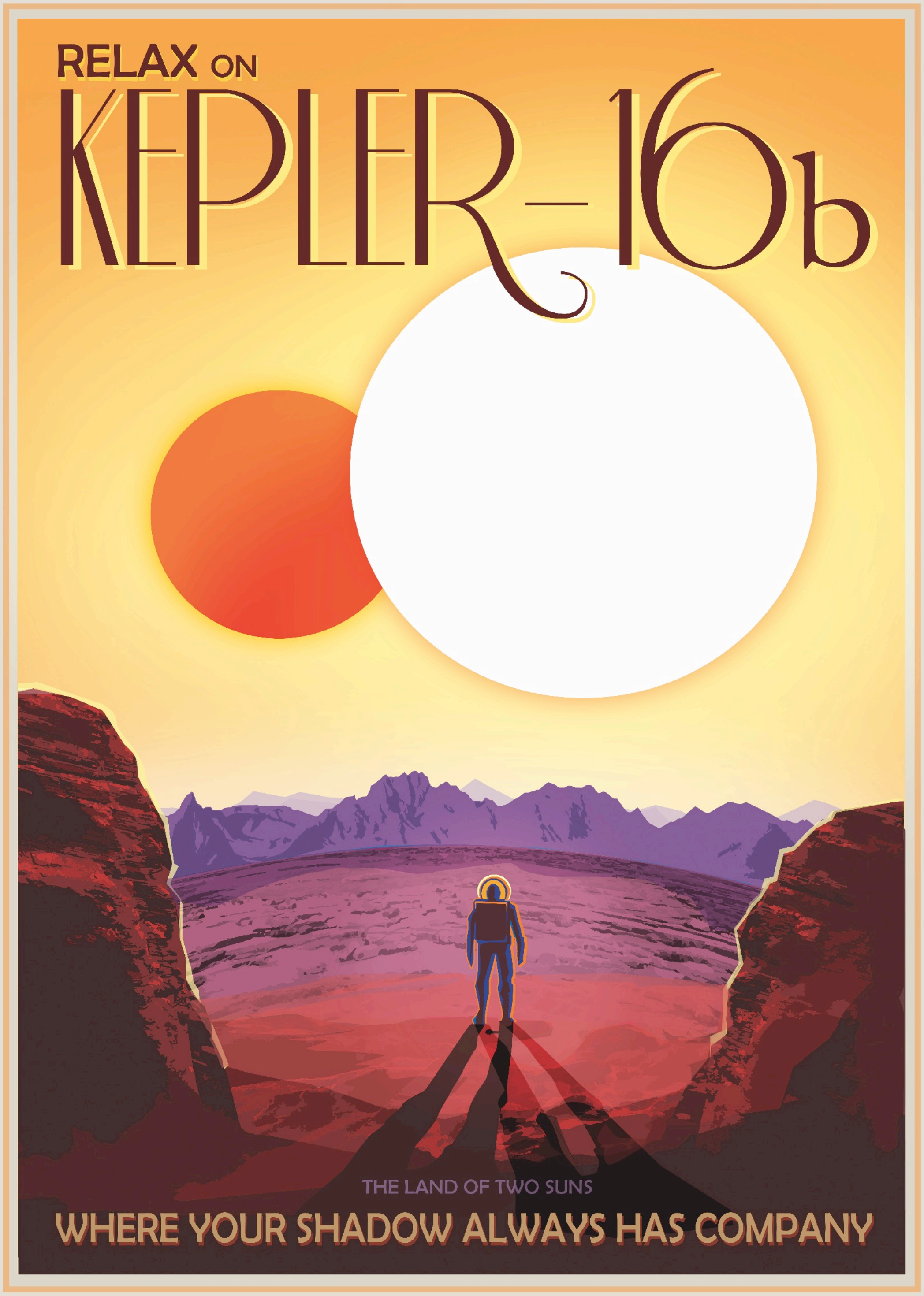


Triangles

- The Pythagorean theorem: $(opp)^2 + (adj)^2 = (hyp)^2$.
- Trigonometry functions are just ratios of the lengths of the different sides:

$$\sin\alpha = \frac{(opp)}{(hyp)} \qquad \cos\alpha = \frac{(adj)}{(hyp)} \qquad \tan\alpha = \frac{(opp)}{(adj)} .$$

Exoplanet Travel Bureau



Like Luke Skywalker's planet "Tatooine" in *Star Wars*, Kepler-16b orbits a pair of stars. Depicted here as a terrestrial planet, Kepler-16b might also be a gas giant like Saturn. Prospects for life on this unusual world aren't good, as it has a temperature similar to that of dry ice. But the discovery indicates that the movie's iconic double-sunset is anything but science fiction.

NASA's Exoplanet Exploration Program. Jet Propulsion Laboratory, Pasadena CA.
exep.jpl.nasa.gov