DEPARTMENT OF
ASTROPHYSICAL AND PLANETARY SCIENCES

ASTR 1010 Laboratory

Introduction to Astronomy

Fall 2011

University of Colorado at Boulder

Acknowledgements

The 1010 laboratory manual originated in the experiments compiled and developed over many years by Dr. Roy Garstang for the APAS 121/122 labs. In 1987 Dr. Garstang published the *Sommers-Bausch Observatory Manual of General Astronomy Projects*. A number of his 88 exercises were adapted for use in the new APAS 101 (now ASTR 1010) course that was initiated in 1988.

Since that time the manual has undergone considerable evolution and expansion under the guidance of faculty lab instructors, including Drs. Raul Stern, Scott Roberston, Larry Esposito, John Stocke, J. McKim Malville, Ted Snow, Fran Bagenal, Nick Schneider, Bob Pappalardo, Brian Hynek, Doug Duncan, and Seth Hornstein.

The Kepler's Laws simulator is part of the Planetary Orbit Simulator Module of the Nebraska Astronomy Applet Project. Supporting materials can be found at http://astro.unl.edu.

Virtually every teaching assistant who has conducted a lab in the APAS/APS/ ASTR 121/122/101/1010/1030 series has contributed to this manual by identifying areas of difficulty, making suggestions for improvements, or providing ideas that germinated into new experiments. Some recent major contributors from previous quarters include Mary Urquhart, Travis Rector, Kelsey Johnson, Amanda Sickafoose, Cori Krauss, John Weiss, James Roberts, Margaret Mitter, Colin Wallace, Joseph Parker, and Seth Jacobson.

Keith Gleason
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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

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★ - *Clear skies are required for this exercise*
☆ - *Clear skies are needed for a portion of the exercise*

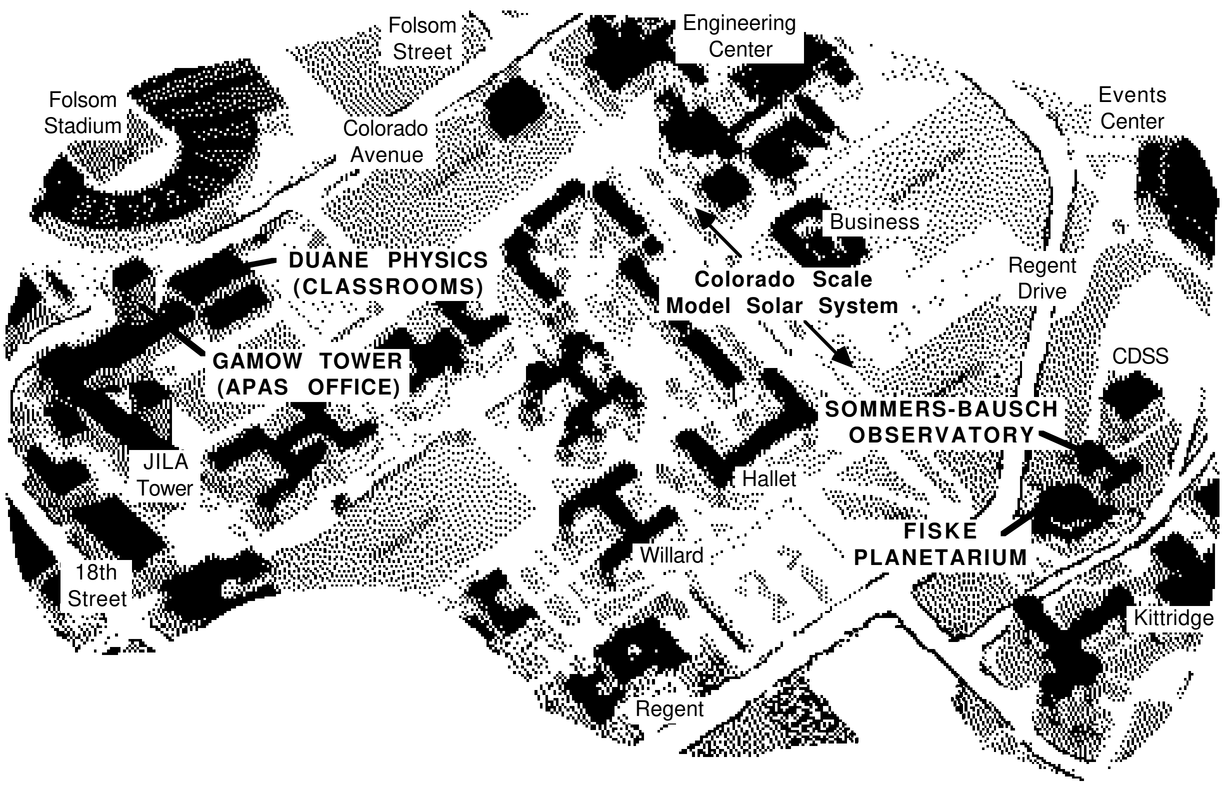
GENERAL INFORMATION

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 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 **nighttime 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, Fall 2011** (*this booklet*), available from the CU Bookstore. Replacement copies are available in Acrobat PDF format downloadable from the SBO website:

  http://cosmos.colorado.edu/sbo/manuals/astr1010/astr1010.html

- **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.
- Highly recommended: a **planisphere**, or rotating star map (available from Fiske Planetarium, the CU bookstore, other bookshops, and on line).

THE LABORATORY SECTIONS

Your laboratory session will meet for 1 hour and 50 minutes in the daytime once each week in the Sommers-Bausch Observatory (SBO), Classroom S175. Each lab section will be run by a lab instructor, who will also grade your lab exercises and assign you scores for the work you hand in. Your lab instructor 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. We concentrate 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. The 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. The 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.

NIGHTTIME OBSERVING

You are expected to attend nighttime observing labs. These are held in the evenings approximately every second or third week at the Sommers-Bausch Observatory, Mondays through Thursdays. Your lab instructor will tell you the dates and times. Write the dates and times of the nighttime sessions on your calendar so you do not miss them. The telescopes are not in a heated area, so dress warmly for the night observing sessions!

If you have a job that conflicts 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.

Your presentation of neat, well-organized, readable work will help you prepare for other courses and jobs where appearance certainly counts (and it makes your work much easier to grade!). By requiring you to explain your work clearly, we can ensure that you fully understand it. If you find writing clear explanations to be difficult, it could mean that you do not understand the concepts well. Your lab instructor can help you in this area; simply ask his or her assistance.

Some of the labs are designed to be written up as full reports. A few are of the "fill in the blank" type. In either case, please use the following guidelines:

1. Write the *title* and *date* at the top of the first page of the exercise.
2. Write an *introductory* sentence or two describing what you are doing in that exercise. For instance: "Today we used the heliostat to observe and draw sunspots."
3. *Number* the parts of your lab the same as the numbers in the lab manual: I.1, I.2, II.1, II.2, etc. This is particularly useful to the instructor in finding your responses to the questions.
4. Put *titles* on your figures, and *label* the columns in your tables.
5. Put *units* after your numerical answers. An answer of "100 mm" is very different from "100 km!"
6. Use *complete sentences* to answer questions. For example: "The largest planet is Jupiter" is much better than just "Jupiter."
7. Be certain to write your results *in your own words* and not the words of your lab partner or the lab manual.

HONOR CODE

The University of Colorado Honor Code will be strictly enforced. Plagiarism (including "frat file" plagiarism and "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.

TIPS FOR SUCCESS

To understand astronomy we need to understand laws of nature that govern the universe, as expressed by the science of physics. We will cover the physics necessary as we proceed in this course. To move beyond the "gee-whiz" aspects of astronomy, both scientists and students also need to use mathematics. In this course, you will need to be able to apply certain aspects of basic algebra and trigonometry. *This manual includes a summary of the mathematics you will need; we encourage you to review these sections as necessary*.

The "rule of thumb" for the amount of time you should be spending on any college class is 2-3 hours per week for each unit of credit, *outside of* lectures and labs. Thus, for a 4-unit class, you should expect to spend an additional 8 to 12 hours per week preparing and studying. In you are spending less time than this on a class, the class may be too easy for you, or you may not be learning as much as you could. If you are spending much more time than this, you may be studying inefficiently, or you may need additional background before taking the class.

We recommend the following strategies for success in your astronomy lab:

- Review the accompanying material on units and conversions, scientific notation, basic mathematics, and calculator usage. It is most useful to discuss with your lab instructor any problems you have with these concepts *before* you will need to use them. Use these sections of this lab manual as a reference in case you are having difficulties.
- Read the appropriate lab manual exercise *before* you come to the lab.
- Read relevant background material in the textbook *before* you come to lab.
- Complete the appropriate prelab questions *before* you come to the lab.
- Complete the whole of the lab exercise *before* the end of the lab period, when it is fresh in your mind, and your lab instructor can offer assistance. Avoid the temptation to "wrap it up later."

If you have difficulty with a specific lab exercise, ask for your lab instructor's help before the assignment is due. We will attempt to provide you as much assistance as necessary for you to learn the material in this class, provided that you make the effort to seek assistance. Procrastinating until the night before an assignment is due will result in it being too late to receive the assistance of your instructor.

If you find that you are having difficulties of any sort, feel free to talk with your lab instructor, your lecture professor, or your lecture teaching assistant. We are here to help, but we can do so only if we are made aware that help is needed.

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. Telescopes include 16, 18, and 24-inch Cassegrain reflectors, and a 10.5-inch aperture heliostat.

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. The 18-inch telescope also includes a new and very fast ST-2000XCM charge-coupled device (CCD) color camera, which enables students to image celestial objects through an 8-inch "piggyback" telescope.

In addition to the standard laboratory room, the Observatory has a computer lab that includes a Sun Ultra 450 / Dell PC server system running both UNIX and Windows NT. This system provides unparalleled computing power and internet access for all introductory astronomy students. It was 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 (ASTR 5750), 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 16-and 18-inch 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:

http://cosmos.colorado.edu

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. The Zeiss Mark VI star projector is one of only five in the United States. Two hundred additional slide and special effects projectors are controlled by a SPICE (Specialized Projector Interface Electronics) automation system.

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 starshow 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:

http://fiske.colorado.edu

CELESTIAL CALENDAR
Fall 2011

THE SUN

The Sun reached its highest altitude (+73.5°) at 11:16 a.m. Mountain Daylight Time on June 21st marking the **Summer Solstice**. On September 23rd it will be directly over the Earth's equator at 3:04 a.m. Mountain Daylight Time; this arrangement marks the **Autumnal Equinox**. Finally, at 10:30 p.m. Mountain Standard Time on December 21st the Sun will reach its lowest altitude (+26.5°), marking the **Winter Solstice**.

Our time-keeping method, by which we keep track (roughly) of the Sun's location in the sky, makes a one-hour jump backwards at 1:59:59 a.m. Mountain Daylight Time (MDT) on Sunday, November 6th - the next second of time will be referred to as 1:00:00 a.m. Mountain Standard Time (MDT).

There are no solar eclipses visible this fall from the United States; the next partial eclipse able to be seen from Colorado will occur in the late afternoon of May 20th, 2012.

THE MOON

Month	First Quarter	Full	Last Quarter	New
August	6	13	21	28
September	4	12	20	27
October	3	11	19	26
November	2	10	18	24
December	2	10	17	24

The Moon experiences a total eclipse on the morning of December 10h, 2011; unfortunately for those of us in Boulder, it will set behind the mountains shortly before complete totality occurs. However, morning twilight observers will be able to watch the early phases of the Moon passing into the Earth's shadow.

See http://eclipse.gsfc.nasa.gov/eclipse.html for information on past and future eclipses.

MERCURY

Mercury is always very close to the Sun as seen from Earth, which explains why many people live their lives without ever seeing the planet. But it is actually very bright and easy to see, if you know where and when to look. The best opportunities to see Mercury occur at the times of its greatest elongation, meaning its largest angular separation from the Sun. When Mercury is at its greatest western elongation, it precedes the Sun across the sky and is visible from Earth only in the morning (in the east), just before sunrise. When Mercury is at its greatest eastern elongation, it trails the Sun's motion and is best seen early in the evening (in the west), just after sunset.

Look for Mercury approximately a week before and after the greatest elongation. During this semester, the elongations of Mercury will occur as follows:

Western elongation September 5th & December 21st
Eastern elongation November 20th (very low in the evening sky)

Find Mercury at any of these times and join the elite club of people who have personally observed all five of the planets that are visible to the naked eye.

VENUS

Like Mercury, Venus is always near the Sun in our sky, although it wanders a bit farther from the Sun than Mercury (47º as opposed to 27º for Mercury). Normally Venus is, by far, the brightest planet in the sky, although at the beginning of the semeser it will be lost in the glare of the Sun. Venus undergoes superior conjunction with the Sun on August 16th, and will become visible as an “evening star” by early October. After this time, Venus can usually be spotted shortly after sunset just over the Flatirons in the west.

This coming summer, you won’t want to miss the “twice in a lifetime” spectacle of Venus transiting across the face of the Sun on June 5th, 2012. The last time this phenomenon was visible from Earth was in 2004 (but not seen from Colorado), and the next occurrence won’t be for another 105 years: December 10th, 2117!

EARTH

The third planet from the Sun is visible throughout the year, any time, day or night. Look down.

MARS

The red planet is a moderately bright morning sky object throughout the fall semester, shining at about 1st magnitude. Mars, otherwise known as Ares to the Romans, will start the semester in Gemini, preceding the rising Sun in the sky by a few hours. As the semester progresses Mars will appear to move into the constellations of Cancer and then Leo, as the Earth overtakes the superior planet and brings us closer to it. By the time Mars is at opposition to the Sun on March 3rd of next year, it will appear to have tripled in size and become five times brighter.

JUPITER

The largest planet in our Solar System, and considered to be the god of all gods to the Romans, Jupiter will be in the constellation of Taurus the Bull throughout the remainder of the year. At the start of the semester, Jupiter will be a morning object, but will rise earlier and earlier throughout the semester and finally rising as the Sun sets in late October. The last two months of the semester should afford beautiful telescopic views of Jove and its four Galilean moons.

SATURN

Saturn, the planet that could float in an extra-large sized bathtub, will be a beautiful site very early in the semester in the constellation of Virgo near the brilliant star Spica. However, by the end of September it will have disappeared into evening twilight enroute to conjunction with the Sun on October 13th. Following Earth's ring-plane crossing in 2009, Saturn's rings are now "opening up" again to our view, but remain less prominent than they sometimes appear (Galileo famously described Saturn's rings as looking like "ears" on the planet.)

URANUS AND NEPTUNE

The outermost gas giants will be up all night throughout most of the semester. Uranus is in the constellation of The Fishes near the "circlet of Pisces", where it barely reaches naked-eye visibility around opposition on August 22nd. Neptune is in the constellation of Aquarius. Although neither is overly spectacular in a telescope (and Neptune rarely appears as other than a blueish "star"), it is personally satisfying to glimpse these two … if only to know that you've seen them at least once in your life!

PLUTO

Pluto, the much maligned dwarf planet, may be found telescopically and with great difficulty in Sagittarius. The New Horizons spacecraft has been traveling for over 3 years on its 9-year journey to Pluto and is now past the orbit of Saturn. It is scheduled to arrive at the icy dwarf planet on July 14, 2015.

METEOR SHOWERS

These "shooting stars" are not stars at all but are instead small grains of dust, often left behind by a comet, that Earth runs into during its orbit around the Sun. The high-speed collisions cause the grains to light up briefly as they burn up in our atmosphere. Although one of the best showers (the Perseids) just occurred on August 12th, meteor showers occur throughout the year to varying degrees of brilliance and there are three good showers during the Fall semester. On October 21-22, the Orionids can be seen originating in the constellation or Orion, November 17-18 brings the Leonids (originating in the constellation of Leo), and the Geminids (the most reliable meteor shower of the year) peak on Dec 13-14 (in the constellation of Gemini). Note that the name of the meteor shower only alludes to what constellation the meteors will seem to come from; they can still occur all over the sky. To view the shower make sure you have dark skies, warm clothes, and a blanket on which to lie. There is no need for telescopes or binoculars; just your eyeballs are the best things for these events.

Much of these data were obtained from the following websites:
http://www.usno.navy.mil/USNO/astronomical-applications/data-services
http://www.astronomytoday.com/skyguide.html
http://www.theskyscrapers.org/meteors/
http://www.seasky.org/astronomy/astronomy_calendar_2011.html
http://www.rasnz.org.nz/SolarSys/10Planets.htm

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}

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. 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 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:

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

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:

$$K = {}^\circ C + 273 \qquad {}^\circ C = 5/9\,({}^\circ F - 32) \qquad {}^\circ F = 9/5\,K - 459$$

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 flash	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. 21.) 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 examples of scientific notation: 6×10^2, 4.8×10^5, 8.723×10^{-3}, -2.4×10^2.

  *In*correct examples of scientific notation: 34×10^5, $4.8 \times 10^{0.5}$, 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 $\$7 \times 10^{12}$ 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 $(5.795 \times 10^3) \times (3.26 \times 10^2)$. Rounding each to the nearest integer makes the approximation $(6 \times 10^3) \times (3 \times 10^2)$, which is 18×10^5, or 1.8×10^6. (The exact answer is 1.88917×10^6.)

Example: Estimate $(5 \times 10^{15}) + (2.1 \times 10^9)$. Rounding to the nearest integer this becomes $(5 \times 10^{15}) + (2 \times 10^9)$. 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 5×10^{15}. (The exact answer is 5.0000021×10^{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 3.29×10^1 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: 3×10^1 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.

MATH REVIEW

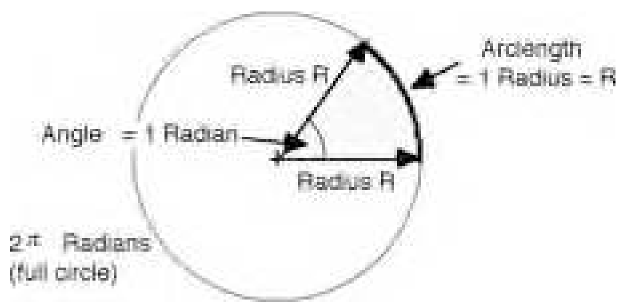
Dimensions of Circles and Spheres

- 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.

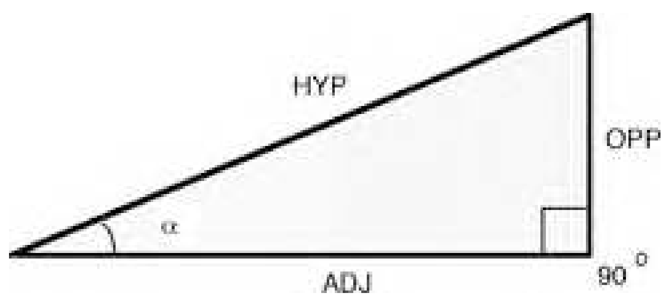
The conversion between radians and degrees is

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

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:

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

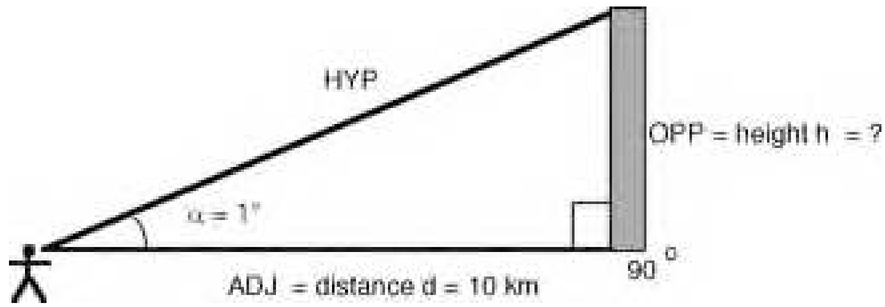
- The trig functions are just ratios of the lengths of the different sides:

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

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:

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

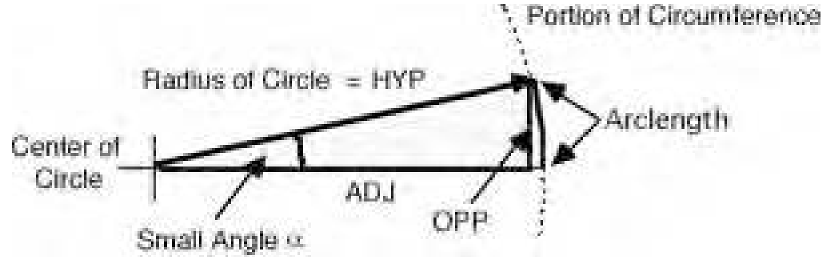
which we can reorganize to give

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

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 "nth power of b", or "b to the nth 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: $8^{1/3} = \sqrt[3]{8} = 2$ $\qquad 8^{2/3} = \left(\sqrt[3]{8}\right)^2 = 2^2 = 4$

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

ASTRONOMICAL WEBSITES

Astronomy Picture of the Day:
http://antwrp.gsfc.nasa.gov/apod/astropix.html

Myths, Fallacies, and Misconceptions in Astronomy:
http://www.badastronomy.com/bad/misc/index.html
Debunking Astrology: http://www.badastronomy.com/bad/misc/astrology.html

Some Current Missions:
Mars Reconnaissance Orbiter http://marsprogram.jpl.nasa.gov/mro/
Mars Exploration Rovers http://marsrovers.nasa.gov/
Mars Odyssey http://mars.jpl.nasa.gov/odyssey/
Cassini-Huygens Mission to Saturn http://saturn.jpl.nasa.gov/
New Horizons Mission to Pluto http://pluto.jhuapl.edu/
Hubble Space Telescope http://hubblesite.org/
NASA Jet Propulsion Laboratory http://www.jpl.nasa.gov/

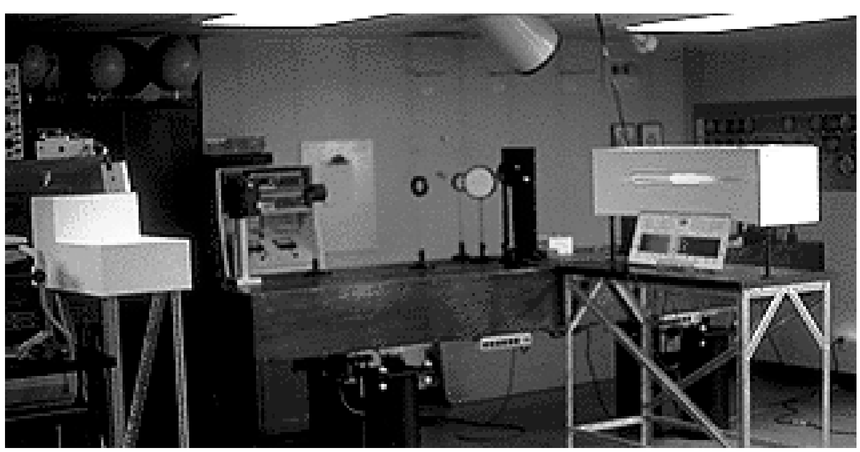
News:
Daily Space News http://www.space.com
More Daily Space News http://www.spacedaily.com

Historical:
Archaeoastronomy http://www.wam.umd.edu/~tlaloc/archastro/cfaar_as.html
History of Women in Astronomy http://astron.berkeley.edu/~gmarcy/women/history.html

Solar System:
Solar System Simulator http://space.jpl.nasa.gov/
The ~~Nine~~ 8 Planets - Guide to the Solar System http://nineplanets.org
Lunar and Solar Eclipse Information http://sunearth.gsfc.nasa.gov/eclipse/eclipse.html
General Comet Homepage http://sse.jpl.nasa.gov/planets/profile.cfm?Object=Comets

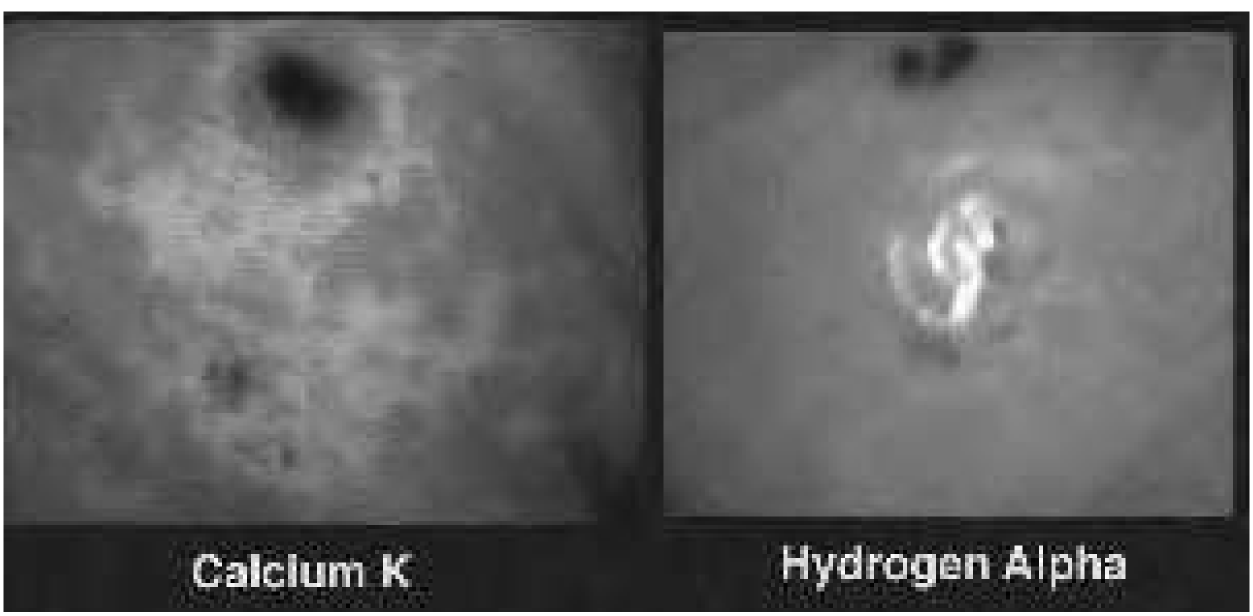
Beyond Our Solar System:
What's up in the sky now http://www.skyandtelescope.com/observing/ataglance
Interactive Sky Chart http://www.skyandtelescope.com/observing/skychart/
Constellations (SEDS site) http://www.seds.org/Maps/Stars_en/Fig/const.html
More Constellations http://www.hawastsoc.org/deepsky/constellations.html
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



PRELAB QUESTIONS

For each lab you must turn in your answers to the appropriate questions ***at the beginning*** of the lab period. For some questions, the answers may be found by simply reading the lab. Others may take a little more work. You are welcome to work with others to come up with your answers but all answers must be **in your own words.** Identical (or very similar) answers will receive a penalty deducted from their grade for the corresponding lab.

Colorado Model Solar System

1) Write down the scientific notation for 1 thousand, 1 million, and 1 billion.
2) In your own words, describe what an Astronomical Unit represents.
3) In your own words, describe what a light-minute represents.
4) Explain what angular size represents and how two things of the same angular size could be very different in actual size.

Motions of the Sun

1) The Earth *rotates* 360° in 24 hours. How much (in degrees) does the Earth rotate in 1 hour?
2) Using that information, explain the time zone difference between Washington, D.C. and San Francisco, CA. (You may want to look up the latitude and longitude of both cities.)
3) During a 24-hour period, how far in its 360° *orbit* does the Earth travel (in degrees)?
4) In your own words, explain why the Sun does not appear “in” your Zodiac constellation on the day you were born.

Motions of the Moon

1) The Moon completes one rotation around the Earth every $27^1/_3$ days. How far (in degrees) does the Moon move around the Earth in one day?
2) If the Moon completes one rotation around the Earth approximately every $27^1/_3$ days, why does each cycle of phases take about 29½ days? (Use a picture if you think it would be helpful.)
3) Describe how using two similar triangles relationship can allow you to solve for the size of the Sun and the size of the Moon.

Kepler’s Laws:

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 3^{rd} Law for period.

Collisions, Sledgehammers, & Impact Craters

1) Explain what the concept of density represents. (*Hint:* Look at the units for density.)
2) Why does smashing the brick does not result in changing its density?
3) When you smash the brick, do you *expect* more large pieces or small pieces?
4) Why should counting a small patch of craters on the moon show the same power law distribution as asteroids in the solar system?

Telescope Optics

1) In your own words, explain what is meant by the terms **object**, **image**, **focal plane,** and **magnification** as they are used in this lab.
2) How do the three types of reflecting telescopes constructed in this lab differ from each other?
3) Most telescopes used in current astronomical research are reflecting telescopes (rather than refracting). Why do you think this is the case?

Spectroscopy I

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?

Spectroscopy II

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? Should 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?

The Seasons

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?

Detecting Extrasolar Planets

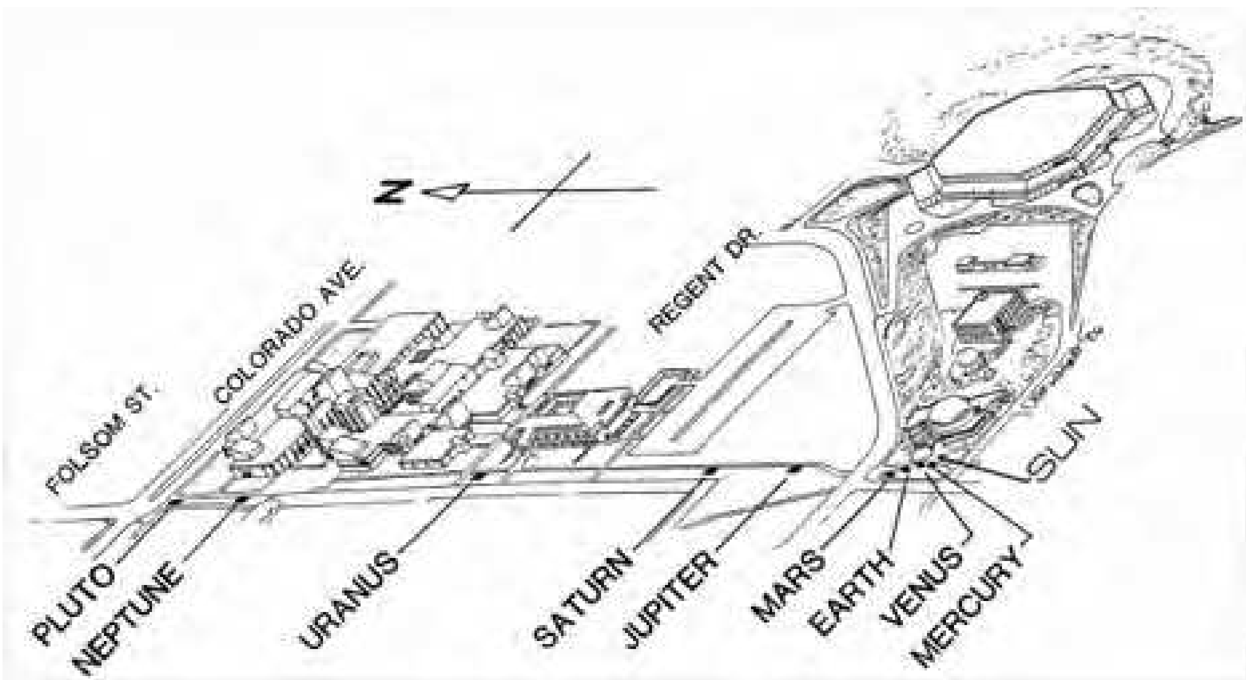
1) Summarize Kepler's 3rd Law **in words**. Then state the law mathematically, explaining the meaning of each symbol in the equation.
2) What is the equation for the area of a circle?
3) Other than the transit detection method, list (and briefly explain *in your own words*) two other methods that astronomers use to detect planets around other stars.

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, a stopwatch (*optional*) 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 18 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.

I. The Inner Solar System

Read the information on the pyramid holding the model Sun in front of Fiske Planetarium. Note that the actual Sun is 1.4 million km (840,000 miles) in diameter, but on a one-ten-billionth scale, it is only 14 cm (5.5 inches) across.

I.1 Pace off the size of the orbit of each of the four inner planets. Using your normal walking stride, count the number of paces (single steps, using your normal walking stride) from the model Sun to

(a) Mercury: __________

(b) Venus: __________

(c) Earth: __________

(d) Mars: __________

Contemplate the vast amount of empty space that lies between these planets and the Sun. But as the saying goes, “you ain’t seen nothin’ yet”: there is a whole lot more of "nothingness" to come!

I.2 Because the Sun is the size of a grapefruit, what appropriately-sized objects might you choose to represent the scaled size of each of the four inner planets?

As you pass each of the four innermost planets, jot down some of the important properties of each planet and answer the following:

I.3 (a) Which planet is most like the Earth in temperature?

(b) Which has the greatest range of temperature extremes?

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

(d) Which is the smallest planet?

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

(f) Which planet has a very long period of rotation?

The *real* Earth orbits about 150 million km (93 million miles) 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 Earth-Sun separation as a "yardstick."

I.4 What fraction of an AU does one of your paces correspond to in the model?

I.5 (a) Using your pace measurements from I.1, what is the distance in AU between the Sun and Mercury?

(b) Between the Sun and Mars?

(c) Between the Sun and Venus?

(d) Which of these planets comes closest to the Earth?

Another way to describe distance is to express it in terms of the time it takes light, travelling at 300,000 km/second (186,000 miles/sec, or 670 million mph!) to get from one place to another. We can measure distances within our solar system in units of *light-seconds* or *light-minutes*. We can also consider the distance between stars in units of *light-years*.

I.6 (a) How many seconds does it take for light to travel 1 AU, the distance from the Sun to the Earth? Your answer is the same as the distance from the Sun to the Earth as measured in units of *light-seconds*.

(b) Considering your answer to (a), what is the distance 1 AU as expressed in *light-minutes*?

I.7 (a) Mars is depicted in the model at its closest approach to Earth (that is, both the Earth and Mars are nearly aligned with and on the same side of the Sun). In this configuration, what is the distance, in *astronomical units*, between Earth and Mars?

(b) What is this distance as expressed in *light-minutes*?

In January 2004, the Opportunity and Spirit rovers descended onto the surface of Mars. Each of these vehicles is equipped with a camera and an on-board computer that enables it to recognize obstacles and to drive around them.

I.8 Explain why the Mars rovers are not steered remotely by an operator back on the Earth.

Now take a closer look at Earth's own satellite, the Moon. This is the farthest object to which humans have traveled. It took three days for the Apollo astronauts to cross this "vast" gulf of empty space between the Earth and the Moon.

I.9 (a) How many years has it been since humans first walked on the Moon?

(b) At the scale of the model, estimate how far (in cm or inches) humans have ventured into space.

I.10 Making the simplifying assumption that we could make the trip in a straight line over the smallest possible separation, roughly how many times farther would astronauts have to travel to reach even the *nearest* planet to the Earth?

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).

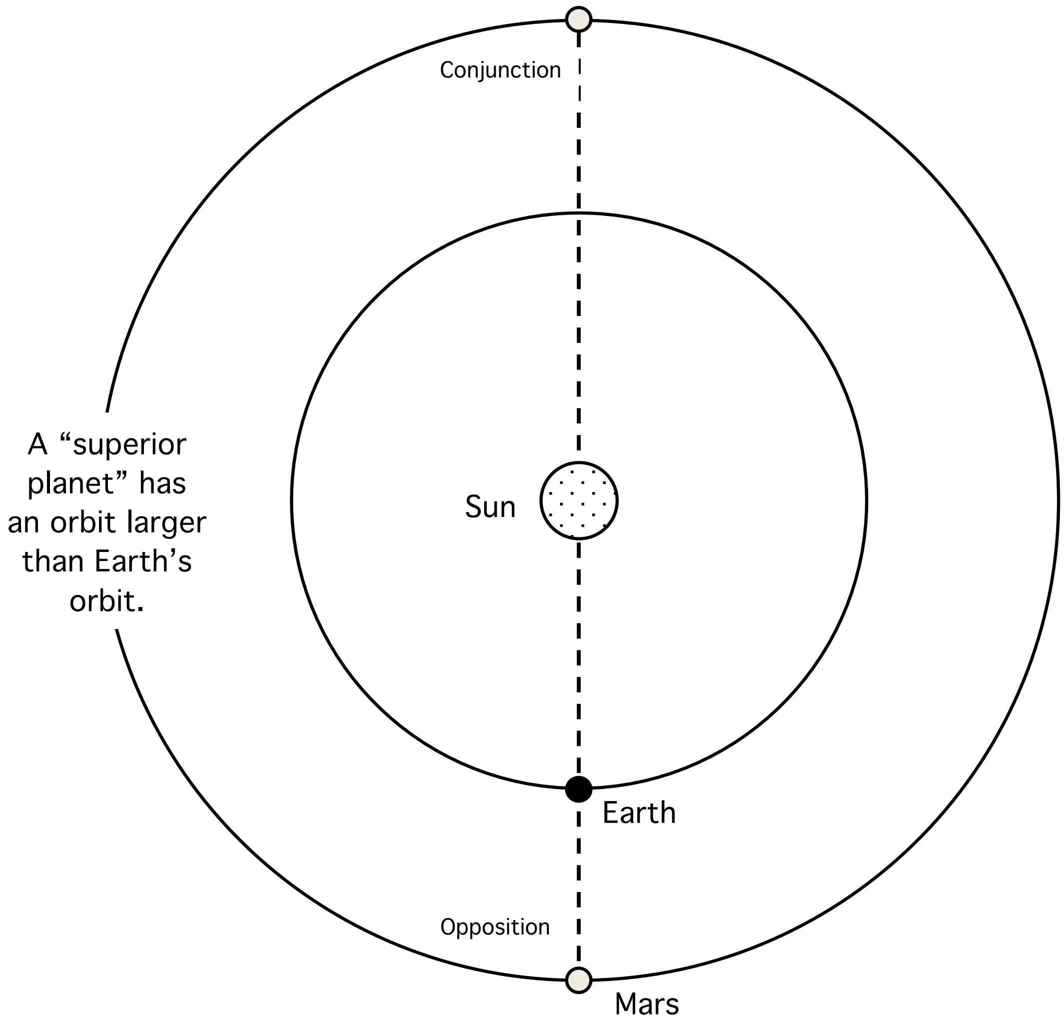
II.1 (a) Stretch out your hand at arm's length, close one eye, and see if you can cover the model Sun with your index finger. Are you able to completely block it from your view?

(b) Estimate the angle, in degrees, of the diameter of the model Sun as seen from Earth.

Note: the width of your index finger at arm's length is about one degree
Caution! Staring at the Sun can injure your eyes. *For the next question, be sure the disk of the Sun is covered by your finger!*

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 *model* Earth?

Now look towards Mars. This Sun-Earth-Mars arrangement is called *opposition*, since Mars lies in the opposite direction from the Sun as seen from Earth.

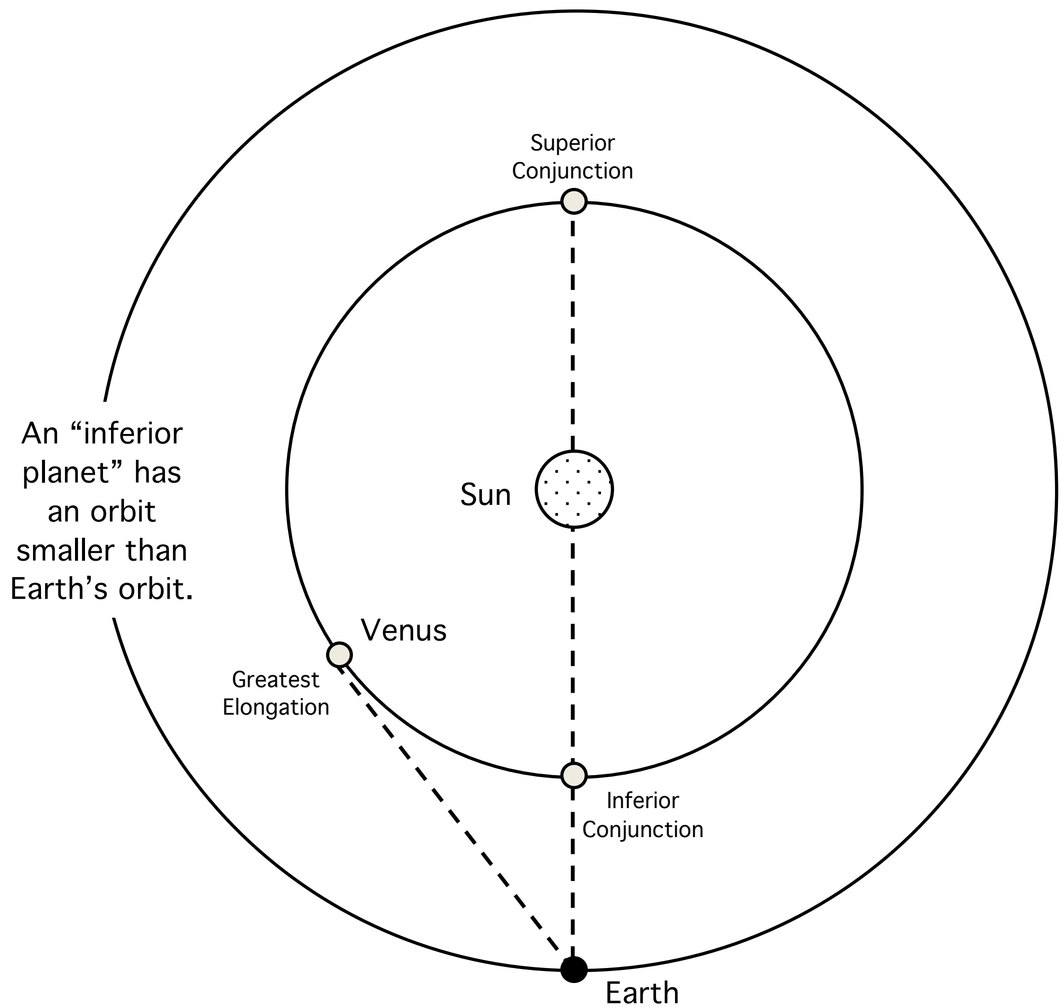


II.3 (a) When is a good time of day (or night) for humans to observe a planet in opposition? (*Hint:* if you can see Mars, is the Sun visible in the sky at the same time, or not?)

(b) When Mars is in opposition, will it appear larger or smaller to Earthlings than at some other point in its orbit?

II.4 Now turn toward Venus. What time of day are you simulating now? (Once again, consider the direction of the Sun!)

This configuration is called a *conjunction*, meaning that a planet appears lined up with the Sun as seen from Earth.



II.5 Based on the definitions shown in the drawing above, would Venus' conjunction with the Sun represented by the Colorado Model Solar System be called an *inferior conjunction* or a *superior conjunction*?

II.6 Although Venus is as close to Earth as possible in this configuration, it would *not* be a good time to observe the planet. Why not?

II.7 Explain why (as seen from Earth) Mars can appear both in conjunction with the Sun and in opposition with the Sun, but Venus (or Mercury) can *only* appear in conjunction with the Sun, never in opposition.

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.

III.1 Assuming the asteroids are scaled like the rest of the solar system model, would you be able to see Ceres as you passed by it? (*Hint:* See the scale value on page 31.) Support your answer with a calculation.

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

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 (a) What object would you choose to represent Jupiter, the solar system's largest planet?

(b) How many times larger (in radius or diameter) is Jupiter than the Earth?

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

(d) What moon orbits Jupiter at about the same distance as our Moon orbits the Earth?

There are four large moons of Jupiter that are easily seen with a telescope from Earth: Io, Europa, Ganymede, and Callisto (not all four are represented on the plaque). The outer three of these moons orbit Jupiter at distances of roughly 2.5, 4.0, and 7.5 inches, respectively at our scale. Ganymede is slightly larger than the planet Mercury, making it the 8th largest object in the solar system after the Sun!

III.3 (a) Use your hand measurement to compare the apparent size of the Sun as seen from Jupiter with your earlier measurement (in II.1) of the Sun from the Earth. (You may need to move a bit to see the Sun from your current position.)

(b) How does the temperature at the cloudtops of Jupiter compare with the temperatures of the inner planets? (The answer may not surprise you, considering what you just noted about the apparent size of the Sun.)

Next stop, the planet known for its beautiful rings, and the most distant solar system object that can be seen from Earth without the aid of a telescope.

III.4 On your way, count the number of paces (steps) between Jupiter and Saturn: ________ paces.

III.5 Compare the size of the entire inner solar system (from the Sun out to Mars) with the empty space between the orbits of Jupiter and Saturn.

III.6 When viewed from Earth, Saturn's rings appear to be the same angular size in our sky as the planet Jupiter. Explain how this can be so.

Now continue the journey onward to Uranus. On your way:

III.7 (a) Count the number of *paces* (steps) between Saturn and Uranus: ________

and

(b) also record the *time* (seconds) it takes for you to walk from the orbit of Saturn out to the orbit of Uranus: ________

(c) Considering your answers to questions (I.6.a) and (III.7.a), what is the distance between the orbits of Saturn and Uranus as measured *light-seconds*?

(d) Now compare your answers (using ratios) to parts (b) and (c). How much "faster than light" did you walk through the model solar system from Saturn to Uranus?

As you walk to Neptune, ponder the vast amount of “nothingness” through which you are passing. When you arrive at blue Neptune, answer the following:

III.8 (a) Which of the planets that you have just explored most resembles Neptune? Explain.

(b) How many complete orbits has Neptune made around the Sun since its discovery?

(c) What is the name of the only spacecraft to explore this planet, and when did it pass?

IV. The Dwarf Planet, Pluto

Now begin the final walk to Pluto. When you get there, you will be standing three-tenths of a mile, or one-half of a kilometer, from where you started your journey. You will also be standing about 33 times further away from the Sun than when you left the Earth.

IV.1 You may have been surprised by how soon you arrived at Pluto after leaving Neptune (compared to the other outer planets). Read the plaque, and then explain why the walk may have seemed shorter than expected.

IV.2 (a) Although you cannot actually see the model Sun from this location, describe how its size and brightness would appear from Pluto.

(b) How does the temperature on Pluto, at the outer edge of the solar system, compare with the temperatures in the inner solar system?

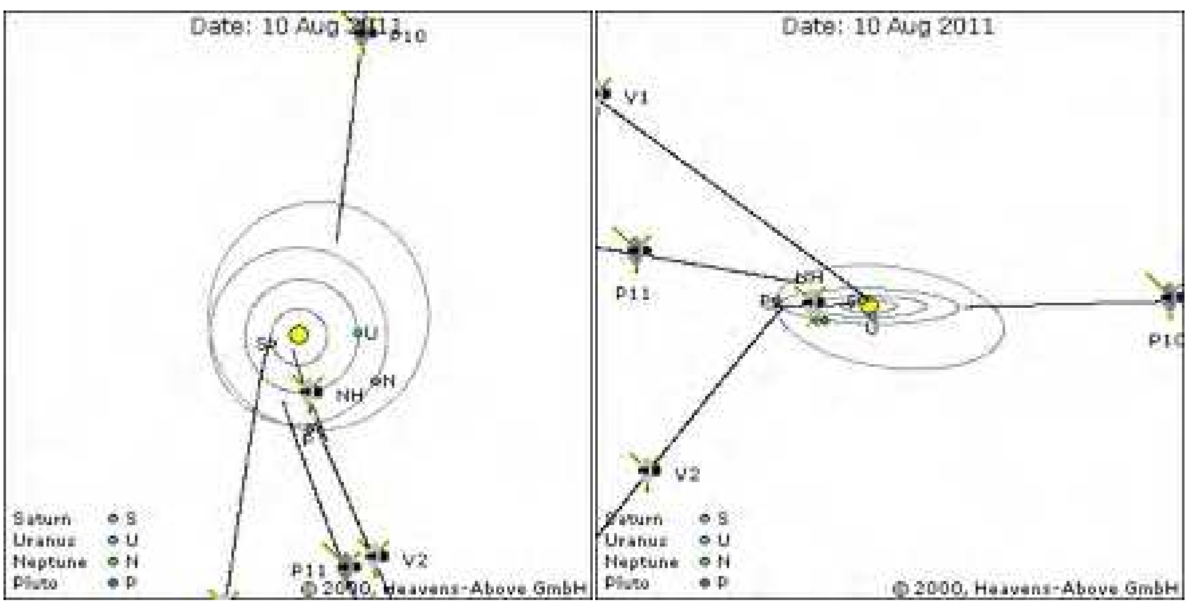
IV.3 In your opinion, should Pluto have remained classified as a planet? Why or why not?

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 88 AU from the Sun, Voyager 2 is still travelling outwards towards the stars, and still sending back data to Earth.

V.1 Voyager 2 uses a nuclear power cell instead of solar panels to provide electricity for its instruments. Why do you think this is necessary?



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.

VI. 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! 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.

*(**Note: Although Alpha Centauri is 4,000 km away in our model, it is still one of the brightest stars in the night sky due to its relative closeness compared to other stars. With this information, in mind, you might reconsider your answer to IV.2**)*

VI.1 Suppose there is an Earth-like planet orbiting the Sun-like star of Alpha Centauri, at the same distance as the Earth is from the Sun. Use your imagination to describe what the nighttime and/or daytime sky might look like to a resident of that planet. (Be sure to consider the effect/distance of all three stars).

VI.2 Given that the Alpha Centauri system is the *closest* star system to our own Sun, explain the difficulties involved with communicating with life forms (if they were to exist) on a planet located in that system or any other star system.

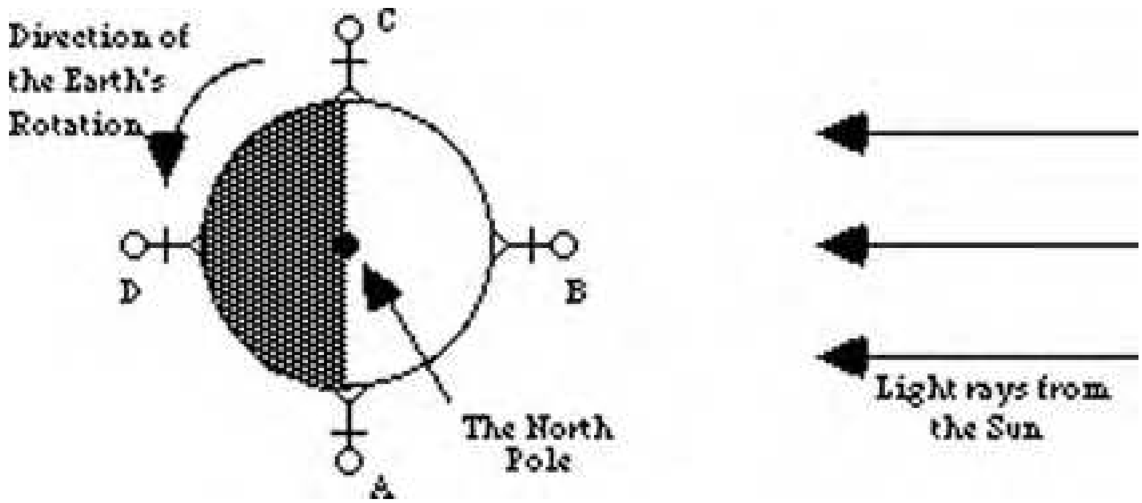
MOTIONS OF THE SUN

SYNOPSIS: The goal is to become familiar with the apparent motions of the Sun in the sky.

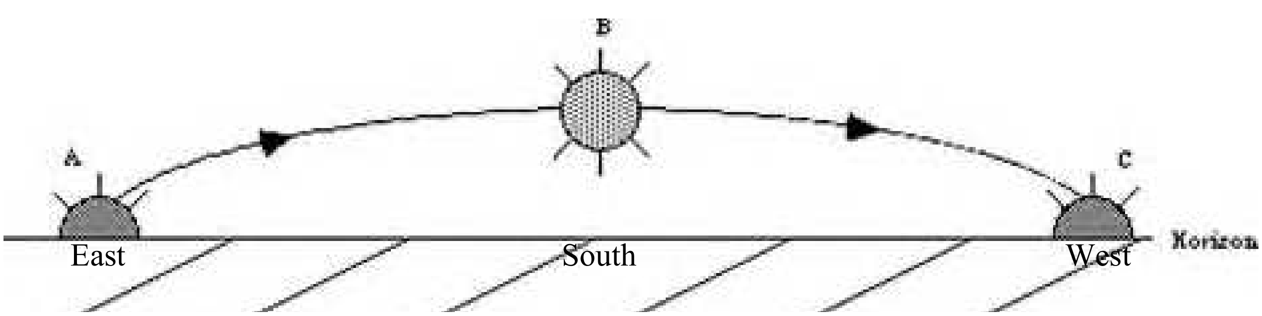
EQUIPMENT: A globe of the Earth, a light box, signs of the zodiac.

Part I. Daily Motion of the Sun

The daily motion of the Sun is caused by the Earth's rotation, rather than by the Sun actually moving across the sky. (This is not obvious from the vantage point of the Earth's surface and took civilization thousands of years to conclusively determine.) The diagram below shows an overhead view of the Earth and Sun:



We will now follow a person (the stick figure) as the Earth rotates. Starting at point 'A' this person is rotated into view of the Sun, and the Sun appears to rise (sunrise!). Noon is the time when the viewer is located at point 'B' and the Sun will be at its highest point in the sky. At point 'C' the person is being rotated out of view of the Sun, and sees sunset. Midnight is defined by point 'D'; which is opposite of noon. The Sun at points 'A,' 'B,' and 'C' as seen from the Earth are illustrated below:



In the next part, you will use the globe (the Earth) and a light box (the Sun):

I.1 Put the globe at one end of the table. At the other far end position the light box Sun such that it is illuminating the globe. Find Colorado on the globe; and position the globe such that Boulder (latitude 40°, longitude 105°) is facing the light box (like position 'B', i.e. noon.) Orient the globe so that the tilt of the Earth's axis is pointing perpendicular to the light box (not towards or away from the light box). In a moment you will see that this orientation represents the **equinoxes**; on these days the northern and southern hemispheres each receive 12 hours of sunlight. What fraction of the Earth is illuminated?

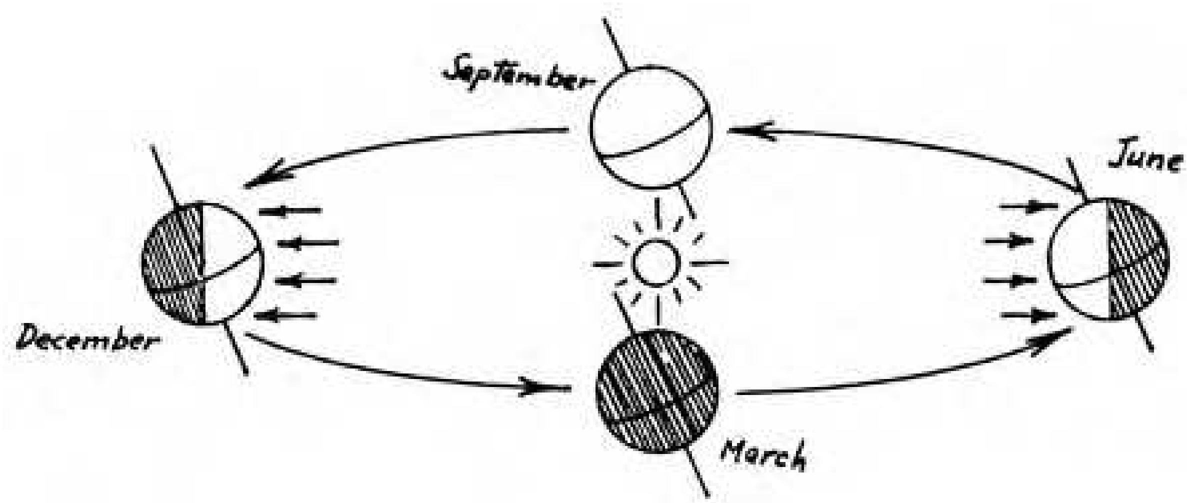
I.2 At the time Boulder is at noon:

- What major cities are experiencing sunrise and sunset? (pick one for each.)
- What small country is at the same latitude as Boulder but on the other side of the globe?
- What time is it there?
- What are the people of Tibet doing when it is noon in Boulder?
- Are the Honda Corporation offices in Tokyo likely to be open at this time?

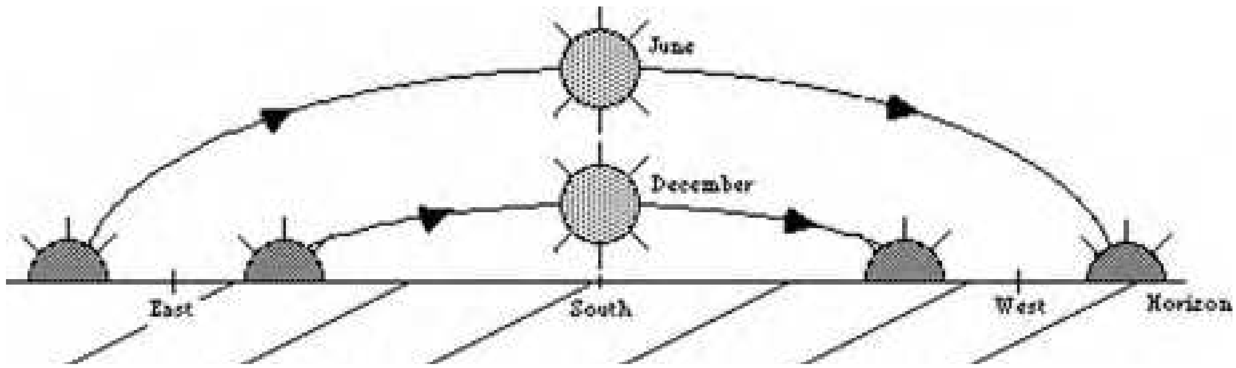
I.3 Rotate the globe such that Boulder is now at sunset. How much of the Earth is illuminated now? What time is it now for the country on the other side of the globe?

Part II. The Annual Motion of the Sun

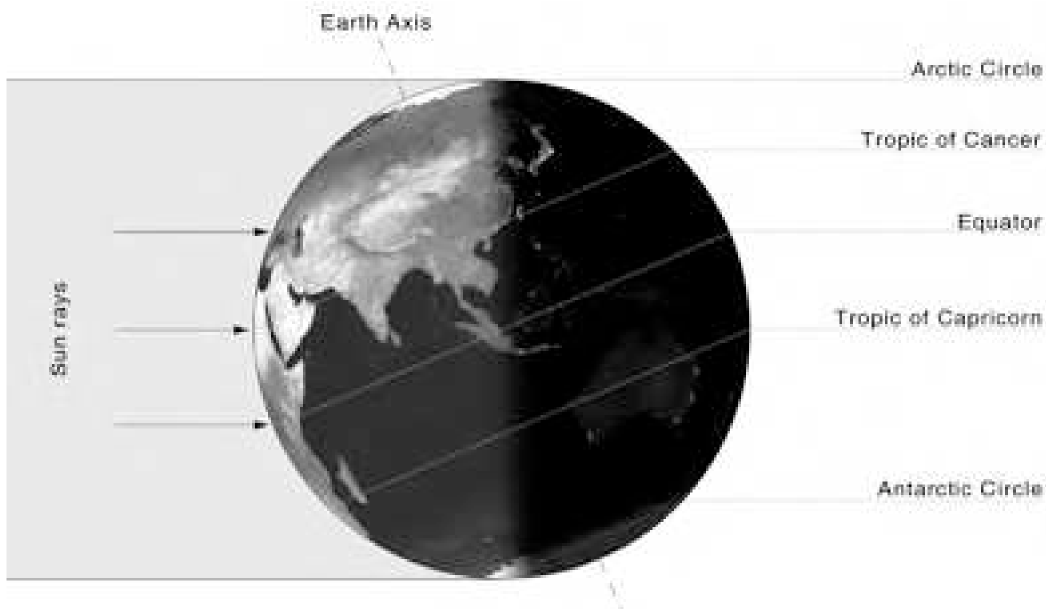
The position of the Sun in the sky also appears to change as the Earth orbits around the Sun. *This motion is not to be confused with the daily motion of the Sun described above!* If you think of the plane of the Earth's orbit- the ecliptic plane- being horizontal (parallel to the ground or table top) then the Earth's spin axis does not point directly upwards but is tilted 23.5º (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.)



Because of the Earth's tilt, the Northern Hemisphere receives more direct (overhead) sunlight for during the long days of June, and less direct (more "slanted") rays of sunlight during the short winter days. The Sun also rises higher in the sky during the summer (see next figure). Note that the winter Sun does not rise as high; nor is it up for as long.



If you were to measure the position of the Sun every day at Noon over the span of a year, you would notice that it slowly moves higher and lower in the sky in rhythm with the seasons. For example, on June 21st the Sun at noon is at its highest (northernmost) position, while on December 22nd the Sun is at its lowest (southernmost) position. These days are called the summer and winter solstices, respectively. **Solstice** literally means "Sun still"; on those two days the Sun appears to stop moving higher or lower in the sky, and effectively changes the direction of its seasonal motion. On the summer solstice, the sun "stops" its daily move toward the north and begins a daily descent toward the south; the opposite happens when the sun's motion stands still on the winter solstice.



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. From the globe and the illustration above answer the following questions:

II.1 From what direction do the stars rise as seen from (the ground) here in Boulder? North, east, south, or west? Rotate your globe to simulate this rising before moving on to II.2.

II.2 What direction do the circumpolar stars rotate around Polaris, the "North Star," as seen from (the ground) here in Boulder. Do they appear to move clockwise or counterclockwise?

II.3 Remember that country at the same latitude as Boulder but on the opposite side of the globe? What season is this part of the world experiencing?

II.4 Now go back to Boulder. Follow the 105° meridian south to a latitude of 40° south. What is there? You should find Easter Island just to the north. (Did you notice South America is much farther east than the U.S.?) What season is this part of the world experiencing?

II.5 The **Tropic of Cancer** (23.5° north latitude) marks the latitude where the Sun is at the **zenith** (i.e. directly overhead) on the summer solstice. Can the Sun ever be seen at the zenith from here in Boulder? If so, when? If not, why not? Use your globe to confirm your answer.

II.6 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?

II.7 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 of the globe study what is happening "down under" in Australia.

II.8 On the Northern Hemisphere's summer solstice is the Sun to the north or south, as seen from Australia? What season is Australia experiencing? Would this be a good time to ski the Snowy Mountains in New South Wales?

II.9 The **Tropic of Capricorn** marks the southernmost point at which the Sun can be seen at zenith. Find Lake Disappointment in the Great Sandy Desert of Australia. Is the Sun ever directly overhead there? If so, when?

II.10 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?

II.11 In Australia, do the stars rise in the east and set in the west? Which way do the stars revolve around the south celestial pole?

Part III. The Celestial Sky

With the twelve zodiac constellations placed in their proper locations around the classroom (your "**celestial sphere**"), consider how the nighttime sky appears, and how it changes, from your vantage point on the globe of the Earth as it travels in a counterclockwise orbit (if looking down from the ceiling) around the artificial "Sun":

III.1 Imagine that you are standing outdoors in Boulder at local midnight on the date of the summer solstice. What zodiac constellation will be on the meridian at that time? (*Hint:* It will be helpful for you to position your globe at the correct location and orientation for the summer solstice, and then imagine yourself standing on that globe at local midnight. From that vantage point, you can then determine which of the constellations are visible.)

III.2 Three months later it is the time of the autumnal equinox. Which zodiac constellation is now on the meridian at midnight?

III.3 Now, adjust your globe to make it 12 hours later, noontime on the day of the autumnal equinox. Which zodiac constellation is the Sun "in" at this time? (That is, what constellation is the Sun in front of?)

Two thousand years ago, the zodiac constellation that the Sun appeared in front of at any time coincided to the astrological "sign" on that date. However, because the Earth wobbles (precesses) on its axis, the astrological signs no longer coincide with the actual position of the Sun.

III.4 What is your astrological sign? Use the classroom models of Earth, Sun, and zodiac to recreate the position of the Earth in its orbit on your birth date, and determine which constellation the Sun is *really* "in" on that date.

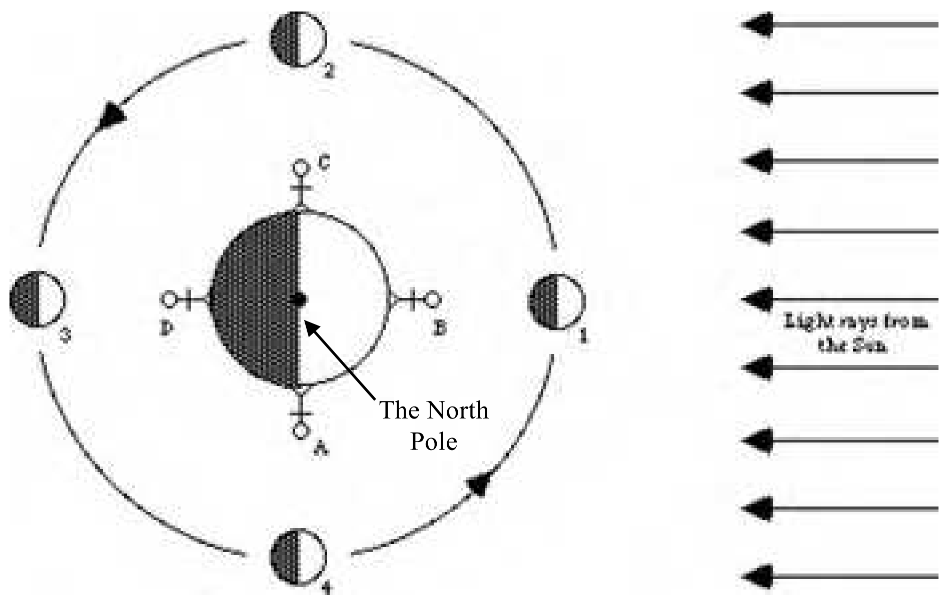
MOTIONS OF THE MOON

SYNOPSIS: The objective of this lab is to become familiar with the motion of the Moon and its relation to the motions of the Sun and Earth.

EQUIPMENT: A globe of the Earth, light box, Styrofoam ball, pinhole camera tube.

Part I. The Moon's Orbit

In the previous lab you learned how the time of day and the position of the Sun are related to the Earth's daily rotation. Now we will add the Moon and its orbit around the Earth. The diagram below shows the overhead view of the Earth and Sun from before, but now the Moon has been added:



The 'A,' 'B,' 'C,' and 'D' positions on the Earth are the same as before. The Moon orbits the Earth counter-clockwise (in the same direction the Earth rotates). *Note that half of the Moon is always illuminated (just like the Earth); even though it may not appear to be.*

First we will follow the Moon's progression from new to full (from position #1 to #3). As the Moon starts its orbit (at position #1) it is between the Earth and the Sun. This is a **new Moon**: we cannot see the Moon, both because the half of the Moon illuminated by sunlight is facing away from us, and because the Moon is close to the Sun in the sky at this time. As the Moon moves in its orbit, it moves away from the Sun, and we start to see the illuminated half of the Moon in the form of a crescent: at this time the Moon is called a **waxing crescent** because each night the crescent appears to grow ("waxing" means "growing"). When the Moon reaches position #2 in its orbit, half of it will be illuminated as seen from Earth: this is called **1st quarter**, because the Moon has completed the first quarter of its orbit (a bit confusing since half, not a quarter, of the Moon is visibly illuminated!). As the Moon starts to move behind the Earth (relative to the Sun), we see more and more of the illuminated half of the Moon. This is the **waxing gibbous** (the "growing fat") phase. When the Moon moves behind the Earth (the opposite side of the Earth from the Sun), we can look out to see the entire illuminated face: this is **full Moon** (position #3)**.**

As you can see from the progression above, the Moon spends half of its orbit "growing" as we first see none of it illuminated (new moon), and then half an orbit later we see the fully illuminated side. During the second half of the Moon's orbit, we see just the opposite:

After reaching full Moon at position #3 the Moon starts to move back in front of the Earth (relative to the Sun), and the illuminated portion begins to disappear from our view. This is the **waning gibbous** phase ("waning" means "shrinking"). Note that right side of the Moon is dark now, while before it was the left side that was dark. At position #4, only the left half of the Moon is illuminated: this is the **3rd (last) quarter** position. As the Moon continues on and completes its orbit, it goes through the **waning crescent** phase, and then back to the **new Moon**.

You will now experience firsthand the phases of the Moon, using the light-box and a ball.

I.1 Imagine that your head is the Earth and that you live on the end of your nose. Position the light-box such that your head is illuminated the same way as the Earth was in the "Motions of the Sun" lab. Slowly turn your head around counter-clockwise 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. 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?

I.2 Now hold the foam ball in your hand, with your arm extended and the ball at the height of your head. This will simulate the Moon. Position the foam-ball Moon such that it appears next to the Sun (the light box); this is the new Moon. The unilluminated side of the Moon should be facing you. Is it easy to see the Moon next to the bright light?

Face directly towards the Sun (the light box). What time of day is it on your nose?

I.3 While holding the Moon at arm's length, spin counter-clockwise (to your left). Keep your eyes on the Moon the entire time. Watch the phases of the Moon change as you move. You should see the illuminated half of the Moon come into view. Stop turning when half of the portion of the Moon <u>you can see</u> is illuminated (i.e. 1st quarter position). Which half of the Moon is being illuminated (right, left, top, or bottom)?

What is the angle between the foam ball, your head, and the light-box?

Does this agree with the diagram on the first page?

What time is it for you on Earth?

I.4 Continue to turn slowly to your left until the Sun is almost right behind you. You should see that the Moon is nearly full: you are now looking at the half of the Moon that is illuminated by the Sun. What time of day is it? If you move the Moon a little more 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.

I.5 Again continue to turn counterclockwise, holding the Moon at arm's length. Following the full Moon, which side of the Moon is now illuminated?

Move until the Moon is half illuminated (3rd quarter). What time is it now? Continue to slowly move the Moon back to new.

I.6 To summarize your understanding, sketch a copy of the Earth-Moon diagram on the first page of this exercise, and label the local time as seen by each person at positions A, B, C, and D. Label the phase of the Moon at positions 1, 2, 3, and 4.

Part II. Moonrise and Moonset

As you observed in the previous section, there is a relationship between the position of the Moon in its orbit and the time of day on Earth when you see it. What time of day you can see the Moon in the sky therefore depends on where the Moon is in its orbit; moreover, as you just saw, the position of the Moon in its orbit also determines the Moon's phase as seen from Earth.

Now use the globe of the Earth and the light-box as before in the "Motions of the Sun" lab, but now include the foam ball to simulate the Moon. Position the globe such that it is the Summer Solstice. Hold the ball and move it around the Earth to simulate the lunar orbit.

II.1 Position the globe such that Boulder is at noon and the Moon is at position #1 in its orbit. What phase of the Moon is visible?

At what time did the Moon rise, and when will it set? (*Hint:* You can rotate the Earth to see where Boulder will be when the Moon is on the horizon.)

II.2 Position Boulder back at noon, but now move the Moon to position #2. What is the Moon's phase now?

Where in the sky will the Moon appear to be as viewed from Boulder?

Where in the sky does the Moon appear to be in the country of Kyrgyzstan (a small country at roughly the same latitude as Boulder on the opposite side of the Earth)?

II.3 Now put the Moon at position #3. What phase is it?

At what time will it rise? (*Hint:* Think about what position Boulder would have to be at on the Earth to see it on the eastern horizon.)

At what time will the Moon set? (*Hint:* Notice that the Moon is on the opposite side of the Earth relative to the Sun.)

What phase of the Moon do people in the southern hemisphere see right now?

II.4 The Moon orbits counterclockwise around the Earth, cycling once through its phases in 29.5 days (a "sidereal" month). In doing so, the Moon rises (and sets) later each day, until it rises with the same phase at the same time as one sidereal month earlier. So if the moon rises (or sets) a total of 24 hours later after 29.5 days, how much later does the Moon rise (or set) each day?

II.5 Does the exact time of moonrise or moonset depend on where you are on the Earth? For example, does the Moon rise at a different *local* time (i.e. the time read on a clock) for Boulder and Kyrgyzstan? Explain why or why not. (*Hint:* Kyrgyzstan is 12 time zones ahead of Boulder. Be sure to consider your answer to II.4.)

II.6 The Moon is not the only Solar System object that shows phases: planets do as well. You have learned that the Moon shows a crescent phase when it is between the Earth and Sun. With this in mind, which planets can show a crescent phase as observed with a telescope from Earth? Why?

II.7 Even though it is usually regarded as a nighttime object, you can often see the Moon during the day. Go outside to see if the Moon is visible right now. If so, hold up the foam ball at arm's length in the direction of the real Moon. The foam 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.

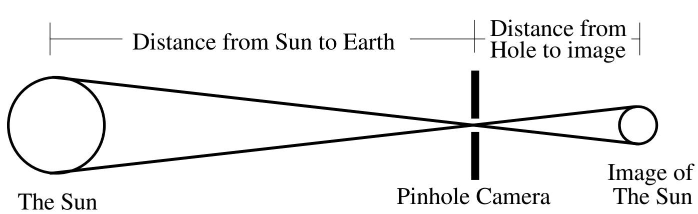
II.8 What phase is the Moon today? What phase will it be tomorrow? What phase will it be in one week?

Part III. The Size of the Sun and Moon

Warning! Looking directly at the Sun can permanently damage your eyes!

In order to measure the diameter of the Sun we use a **pinhole camera**, a cardboard tube with a piece of foil at one end with a tiny hole. The other end of this tube is covered in graph paper. *Being careful not to look at the Sun directly,* aim the tube up to the Sun with the graph paper facing you. You should see an image of the Sun on the graph paper.

III.1 Measure the diameter of the Sun's image, counting the marks on the graph paper. Each square on the graph paper is 1 mm across. What is the diameter of the Sun's image?

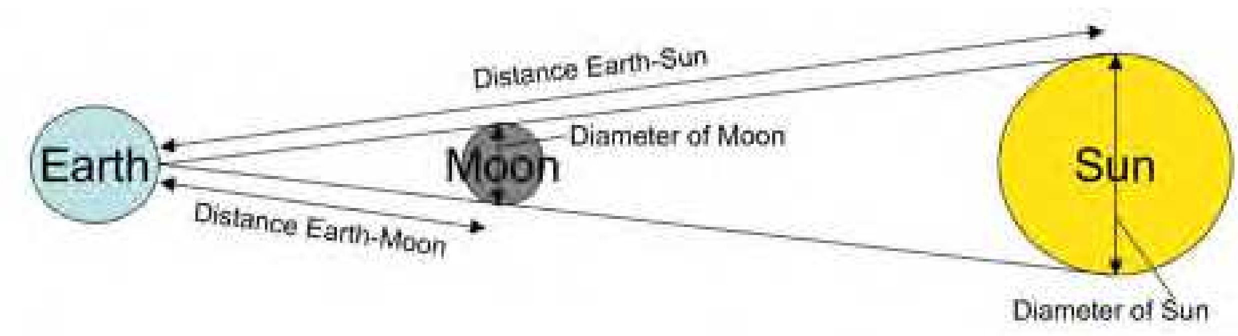


Examining the geometry of the pin-hole camera shown in the figure above, you can see that if the distance to the Sun is known, we can use the similar triangles relationship to solve for the diameter of the Sun. That is, we have the following:

$$\frac{\text{Diameter of the Image}}{\text{Diameter of Sun}} = \frac{\text{Distance of Image from Hole}}{\text{Distance of Sun from Earth}}$$

III.2 Assume that the distance between the Sun and Earth is 150 million kilometers (about 93 million miles). The distance of the image from the hole (the length of the tube) is 1 meter. Determine the diameter of the Sun, and compare this to its true value. If your number is not the same as the true value, explain why not.

Look at the diagram below, which shows the alignment with the Earth, Moon and Sun during a solar eclipse. It is a remarkable fact (and coincidence) that the Earth just happens to have a Moon of just the right size at just the right distance that, from the Earth, the Moon appears to be the same angular size as the Sun (about 1/2° or 30 arc minutes). Aha! We have a pair of similar triangles. We can use the similar triangles relationship again to determine the size of the Moon:



$$\frac{\text{Diameter of the Moon}}{\text{Diameter of Sun}} = \frac{\text{Distance of Moon to Earth}}{\text{Distance of Sun to Earth}}$$

III.3 If the distance of the Moon to the Earth is about 390 times less than the distance between the Sun and the Earth, what is the diameter of the Moon? Check to see if your number makes sense: the Moon's diameter is a little less than the width of the United States.

Part IV. Solar and Lunar Eclipses

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

IV.1 Hold the Styrofoam Moon 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?

Now simulate this arrangement with the Styrofoam Moon, the Earth globe, and the light-box. Does the Moon eclipse the entire Earth, or does only a portion of the Earth lie in the Moon's shadow?

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?

The Moon's orbit is not quite circular. The Earth-Moon distance varies between 56 and 64 Earth radii. 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. This produces a very brief total eclipse, perhaps lasting just a few seconds.

IV.2 If the Moon were at its *closest* point to the Earth during a solar eclipse, would it appear bigger or smaller than the Sun as seen from Earth?

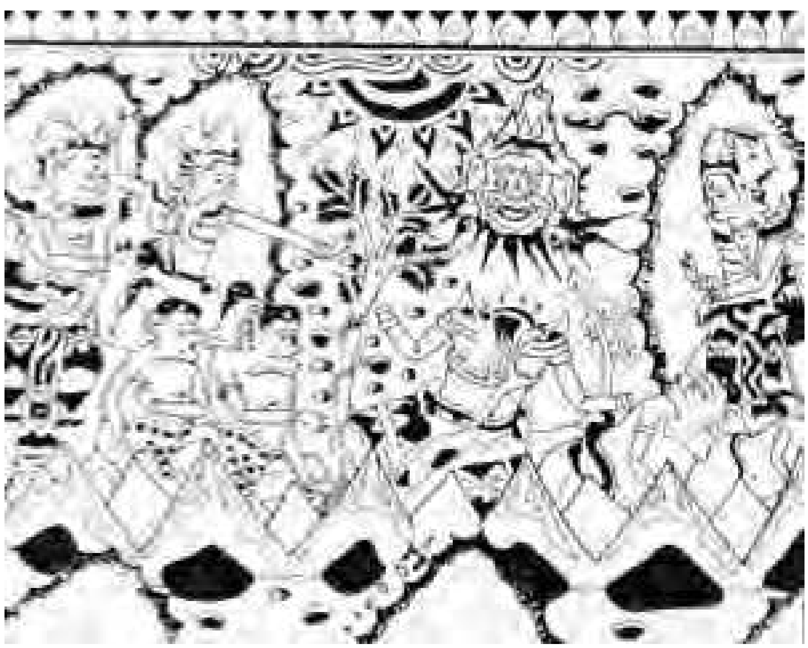
How would this affect the duration of the total eclipse?

If an eclipse occurs when the Moon was at its *farthest* distance from the Earth, describe what the eclipse (called an **annular** eclipse) would look like from the Earth.

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

IV.3 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?

IV.4 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?



Balinese Hindus call Rahu, the eclipse demon, Kala Rau. In this scene Kala Rau is losing his head as he is discovered sipping from the elixir of immortality. In anger, he circles the sky in pursuit of the two informers, the Sun and the Moon. When he catches either of them, his severed immortal head swallows them and an eclipse takes place. Then the ingested Sun or Moon drops out of Kala Rau's severed throat, and the eclipse ends.

Many people mistakenly think that a lunar eclipse should occur every time that the Moon is full. 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. But as mentioned above, 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.5 Hold the Styrofoam Moon at its true (properly-scaled) distance from the globe of the Earth. How big of an area would the shadow of the Earth be at this distance? (A general answer is all that is required here.)

First using the Styrofoam ball, and then by making a sketch, demonstrate how the Earth's shadow can miss the Moon, so that a lunar eclipse does not occur.

IV.6 What two conditions are necessary to obtain a lunar eclipse? Explain your answer.

THE ERATOSTHENES CHALLENGE

(or: A Pilgrimage to the Fortieth Parallel)

Purpose: 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 give you the opportunity to calibrate your paces in the *CU football stadium* (since the ancient Greeks measured distances in *stadia*).

Background:

Eratosthenes of Cyrene

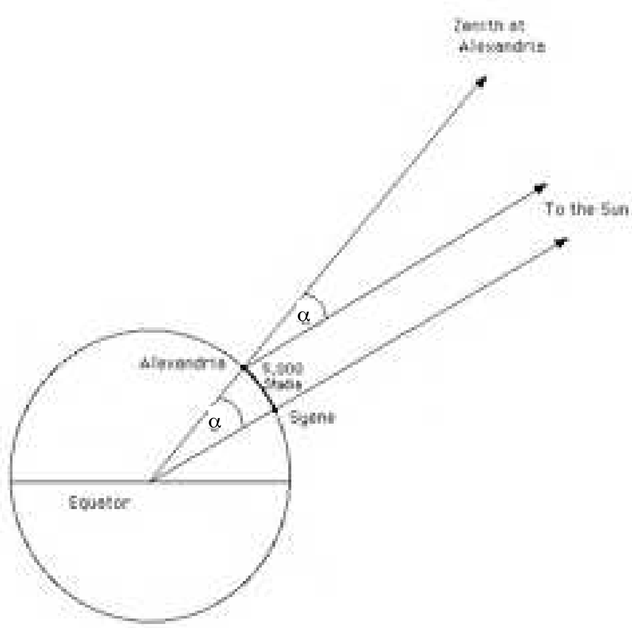
Born: 276 BC in Cyrene, North Africa (now Shahhat, Libya)

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 SBO. As shown in the photograph from space on page 4, Baseline curves gently north between Broadway Blvd and 30th Street. The white line is our best estimate for exactly 40 degrees North latitude based upon 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.

Each 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.

Turn in all measurements and all calculations that you make in the course of this exercise. You must describe in detail the method (route, etc.) your group used to make the necessary measurements. You will also need to compare the final result you obtain individually with your 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

North

South

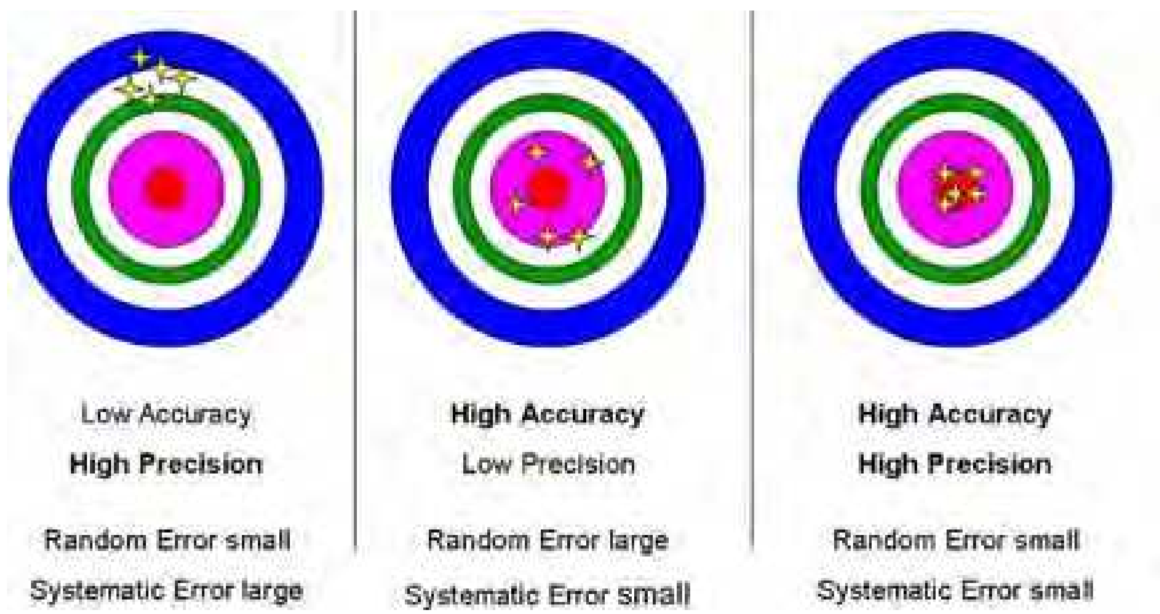
West

Food for Thought:

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)

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. (Your TA/LA can help you to come up with a reasonable method to estimate your precision.)

a) Typically, an experimental result is listed as: [value obtained] +/- [precision], e.g. 25,000 miles +/- 1000 miles for the circumference of the Earth. List your individual value (in miles) and its estimated precision here:

---

b) Why does averaging many results typically serve to reduce the measurement uncertainty?

Record your group's average here:

---

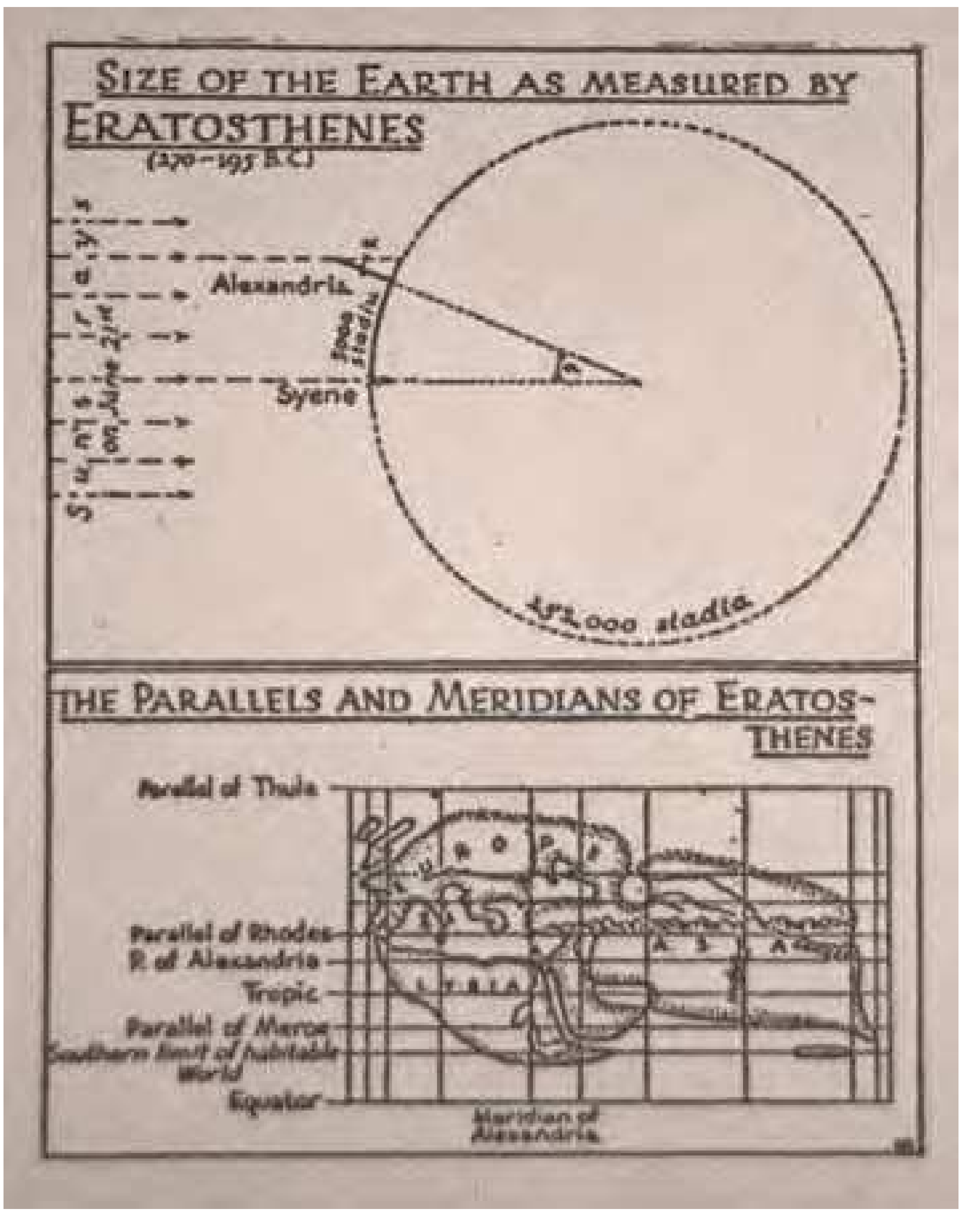
2. Accuracy (Systematic Error)

a) Discuss with your group what are potential systematic errors in your measurement of the Earth's circumference. These might include hidden assumptions in the derivation of the Eratosthenes Equation (page 2), assumptions involving using paces as the measuring device, in the "calibration" of your paces, or in the route employed. The more specific you are in the Table entries you make below, the better your grade for this observing project.

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

A **minimum** of two entries are required on this chart. (*Note:* A listing of "human error" is insufficient… be specific!) Think about how you can use the different measurements by different members of your group to estimate the amount of uncertainty in your measurements and use this discussion to help fill in the last column above.

b) Why does averaging many results typically *not* serve to reduce the systematic errors?


SIZE OF THE EARTH AS MEASURED BY ERATOSTHENES
Alexandria
Syene
252,000 stadia
THE PARALLELS AND MERIDIANS OF ERATOSTHENES
Parallel of Thule
Parallel of Rhodes
P. of Alexandria
Tropic
Parallel of Meroe
Southern limit of habitable World
Equator
Meridian of Alexandria

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 to the Nebraska Astronomy Applet Project, stopwatch.

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 COSMOS computer lab, click the globe at the bottom of the screen to launch Netscape.)

(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 you have not already done so, 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 (a) Can a planet move on a *circular* orbit?

(b) If your answer is "yes," where would the Sun be with respect to that circle?

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?

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 the solar system.)*

I.9 For an ellipse of eccentricity $e = 0.7$, calculate the ratio of perihelion (the point closest to the Sun) to aphelion (the point furthest from 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 would be for $e = 0$? What about $e = 1$?

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 perihelion to aphelion 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 2^{nd} Law tab.

- **Important**: Use the "clear optional features" button to remove the 1^{st} 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?

II.7 If the sweep segments were measured from the empty focus and not from the Sun, would Kepler's 2nd Law still be valid? Explain your reasoning. *(It might help your understanding to draw the orbit and draw the segments as measured from the empty focus.)*

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. What is the period of Halley's comet? How does Kepler's 2nd Law explain why we can only see the comet for about 6 months during each of those periods (unlike Uranus, which has a similar semi-major axis, which we can typically see for ~8 months *each* year)?

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.

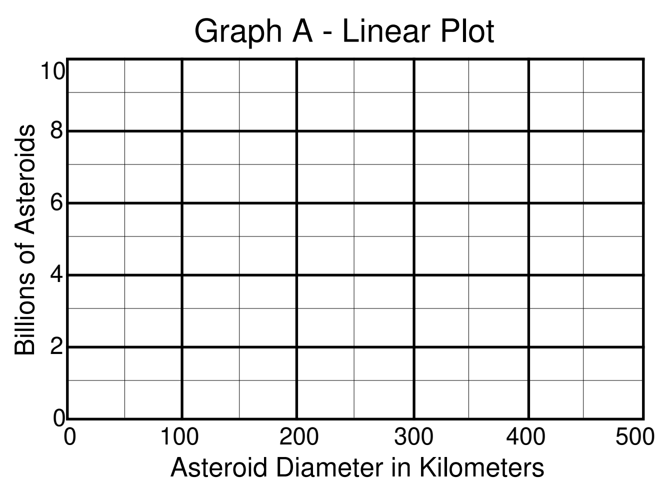
EQUIPMENT: Sledgehammer, brick, denim cloth, sieves, plastic bags, buckets, scale, safety goggles, calculator, graph overlays.

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**.

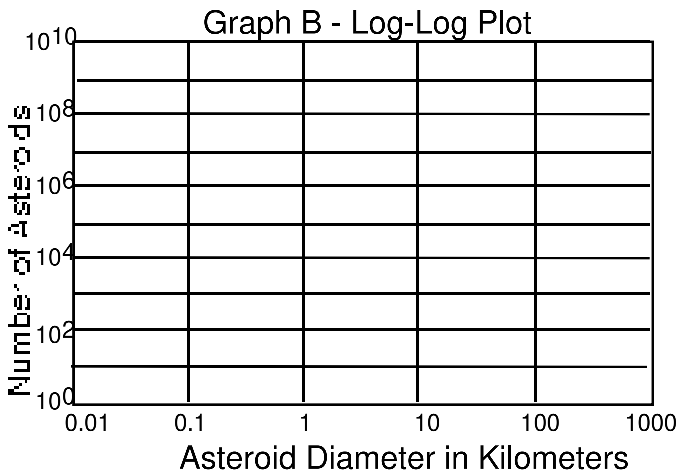
Size Distribution of Asteroids

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?

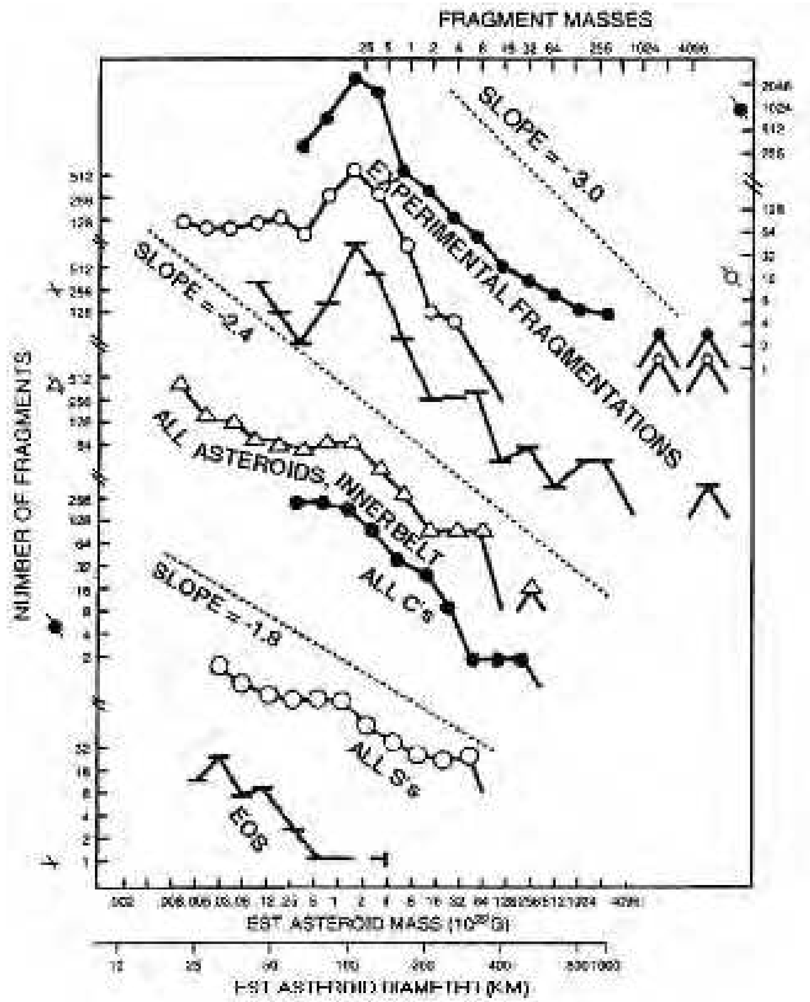
The trend of asteroid sizes approximates a **power law** of the form

$$N = A\ R^b$$

Here N is the number in a given Radius (R) interval on the logarithmic scale, and A is a constant of proportionality. 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.

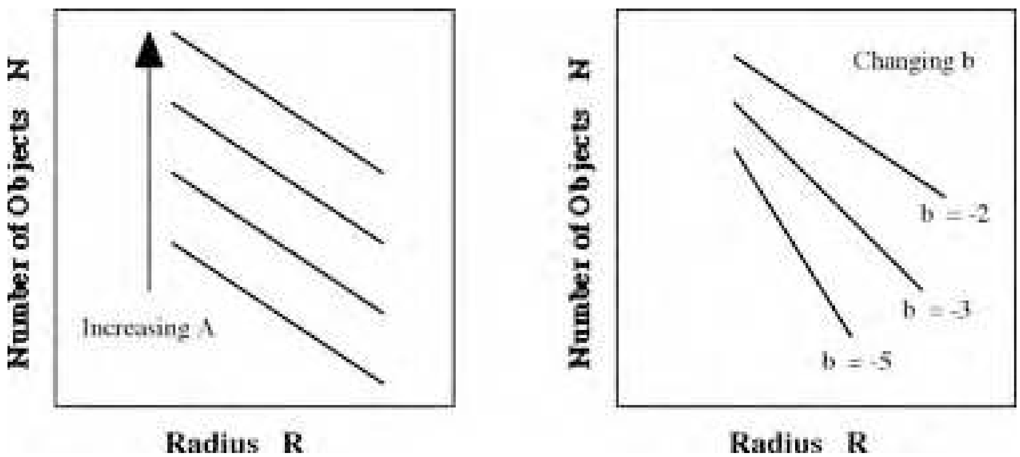


Comparison of size distributions of shattered rock fragments and asteroids: The top three curves are fragment distributions of artificial aggregate targets of rock with masses on upper scale. The bottom four curves show actual asteroids in the inner half of the asteroid belt, with masses on the lower 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)

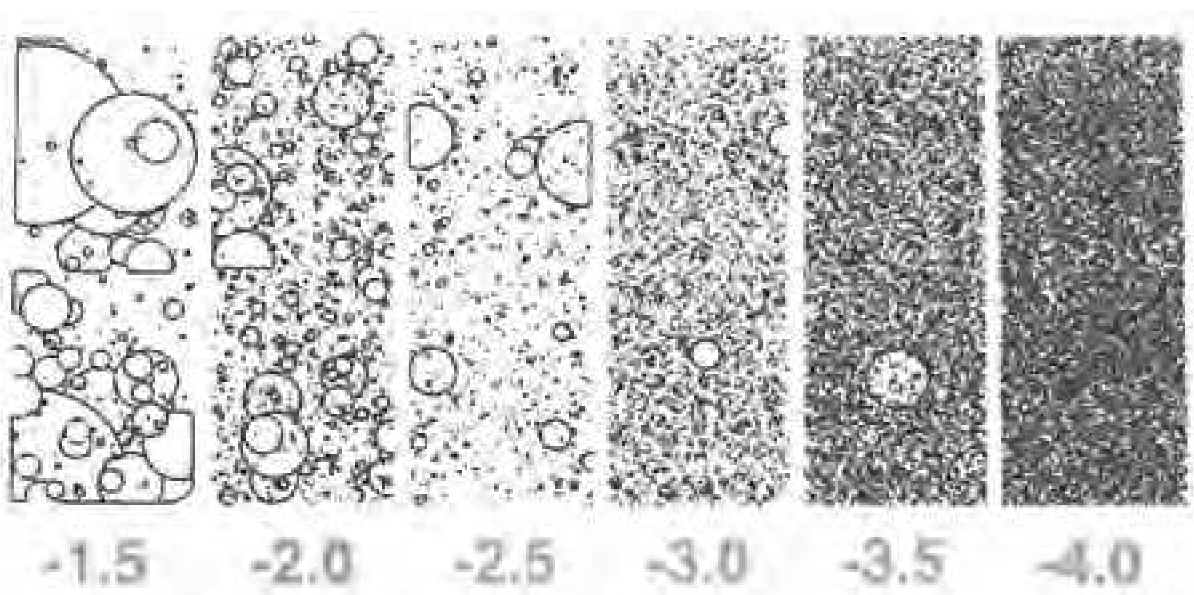
The power law distribution of the sizes of asteroids therefore suggests a **collisional fragmentation process**, the consequences of which are fascinating. The sizes continue getting smaller and smaller and the numbers continue to become greater and greater.

The equation $N = A R^b$ 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 on page 70 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 of these size distributions has more big particles and fewer small particles? Which has 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. (This is no accident, because the amount of mass equaling a gram was *defined* so that this would be true.). 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

How does it compare with the density of water? (Would your brick float in water?)

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

II.4 Wrap the brick in one sheet of cloth, and spread the other out on the ground. Place the wrapped brick in the middle of the spread-out sheet. (*Note:* The cloth containing the brick will not last for more than a few hits before it rips; its purpose is to hold the pieces together as well as possible so that you won't lose any. Be careful so that any pieces that do come out stay on the other sheet.)

II.5 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.) ***Each member of your group should hit the brick at least one time. The person hitting the brick MUST be wearing the goggles!***

II.6 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 the sieve while everything else will fall through. You will then use the *second* largest sieve, and so 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. Why not? (*Hint:* Can you make any conclusion about the size of the *largest* of these large fragments?)

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. Why won't we count these smaller fragments?

III. 5 Weigh the material in each baggie with your balance scale. Record the results in column 6 of the table on page 73. (*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

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

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 above. 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.)

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).

III.9 Compare the *actual* number you obtained from III.8 with the *estimated* number (column 8), which was based on brick density and assumed mean particle size.

You will probably find that your actual count is close to, but somewhat *larger* than, your calculated count. This is not any fault on your part, or error in the technique, but instead comes from a "sampling bias": there is a skewing of the data, because of a slightly incorrect assumption that was made in the estimation procedure. Can you explain the reason behind why the estimated number of particles is actually too small?

Part IV. Plotting and Analyzing Your Results

IV. 1 Using the log-log plot of the graph on the following page, 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!)

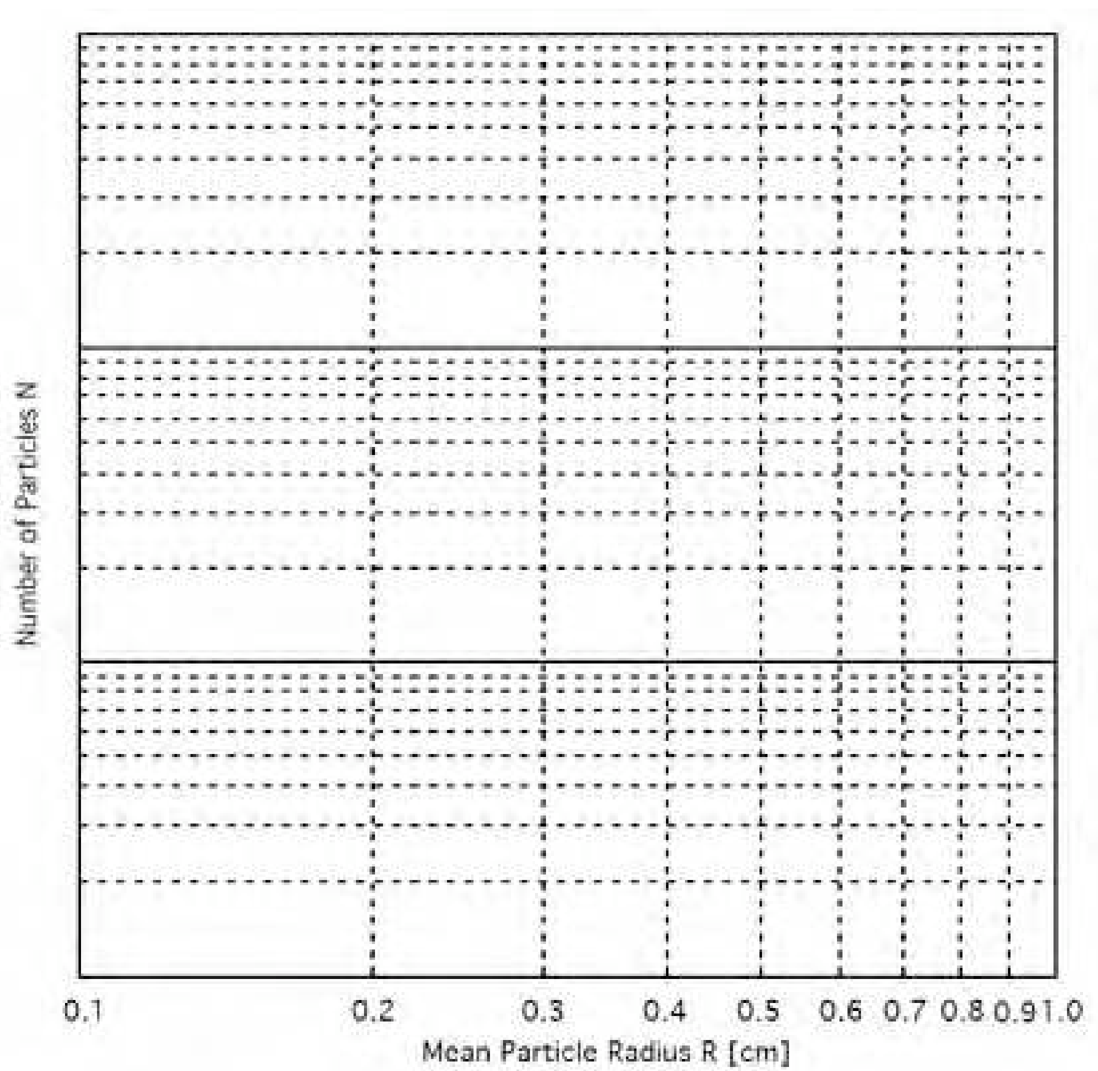
Does your data form *roughly* a straight line? If not, can you think of any reason why not?

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

Smashing Bricks: the Asteroid Collision Simulation



Part V. Size Distribution of Craters on the Moon

If asteroid sizes are related to collisional processes, and if those sizes follow a power law distribution, then it seems reasonable to expect that asteroid cratering of a much larger object (simply another collisional process) would also follow a power law distribution as well.

Photograph A at the back of this exercise shows an area of the Moon 196 by 296 kilometers on a side, for a total area of 58,016 square kilometers (km^2).

V.1 Using the Photo A Overlay, count the number of craters in Photo A that are smaller than 25 km in diameter, but larger than 5 km in diameter. (You can think of the process as "sieving the craters" through the overlay grids, just as you did the brick fragments.) Mark each crater as you count it. (*Hint:* Use different colored pens for grid size.) Enter your count for this "coarse" sieve in the appropriate box of the table below.

Photograph B is of a small portion of the upper-right area of Photo A (see the inset), only 24 x 30 kilometers on a side. It encompasses an area of 720 km^2, about 80 times smaller than Photo A.

V.2 Using the Photo B Overlay, count (as before) the number of craters in Photo B that are smaller than 5 km in diameter, but larger than 1 km in diameter. Enter your count in the table.

V.3 Now using only the small 12x15 km (180 km^2) box marked on Photo B, count and record the number of craters smaller than 1 km in diameter, but larger than 0.2 km in diameter.

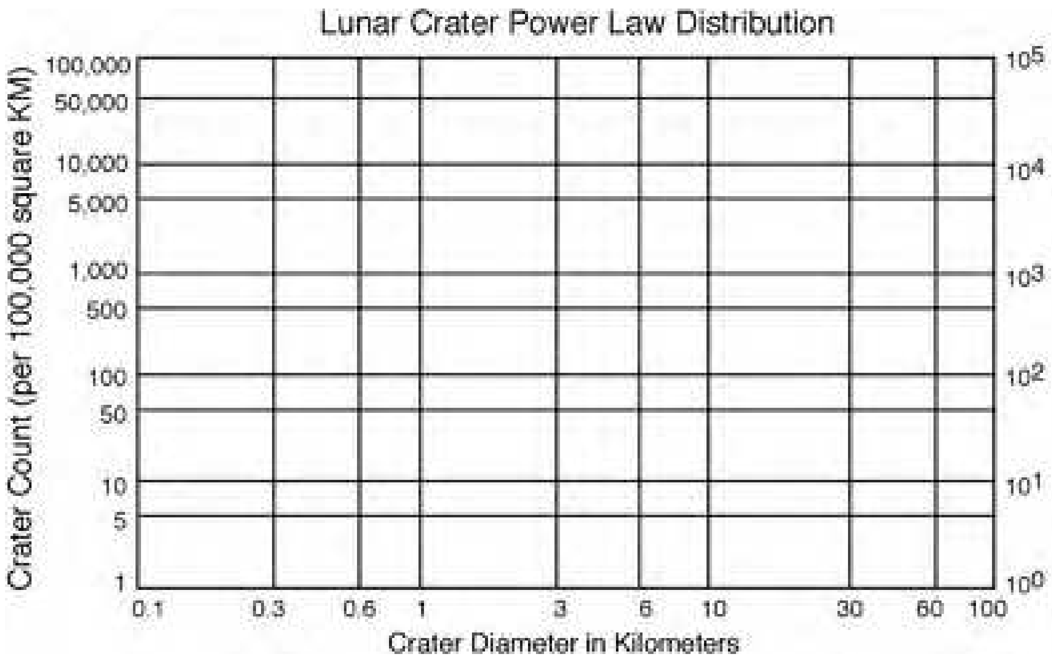
Counting Lunar Craters

#	*Larger Grid* *< km*	*Smaller Grid* *> km*	*Mean Diameter* *(km)*	*Measured Number of Craters*	*Multiplying Factor*	*Crater Count per 100,000* km^2
1	25	5	15	In All of Photo A =	100,000/58,016 = 1.724	
2	5	1	3	In All of Photo B =	100,000 / 720 = 138.9	
3	1	0.2	0.6	In Box on Photo B=	100,000 / 180 = 556	

Because of the successively smaller sampling areas associated with each successive count, we need to multiply our crater counts by a correction factor so that they will all correspond to the same standard-sized area (a process referred to as **normalization**). We adopt a standard area size of 100,000 square kilometers (equivalent to a square region 316 kilometers [196 miles] on a side).

V.4 Multiply your crater count by its appropriate multiplying factor given in the table, and enter the resulting crater count per 100,000 square kilometers in the last column the table.

V.5 Plot your resultant size distribution of craters for this region of the Moon on the log-log graph below.



V.6 Using the Lunar Crater Overlay transparency provided, estimate the slope b of the power-law distribution of crater sizes.

V.7 Given your measured size distribution of craters, what is the distribution of the sizes of the objects that produced the craters on the Moon?

V. 8 Using your results from Part IV, what can you determine about the processes that created this population of impactors?

Part VI. 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).

We can use the lunar crater record to estimate the numbers and sizes of impacts that have occurred in the past on the Earth. **As mentioned earlier, an asteroid of a given size will produce a crater about 10 times its own diameter.** Therefore, an asteroid 1 km in diameter will make a lunar crater about 10 km in diameter.

VI.1 From the power-law distribution you plotted above, how many objects 1 km in diameter (producing 10 km craters) have occurred on the lunar surface in a 100,000 km^2 area?

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:

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

VI.2 What is the surface area (in square kilometers) of the Earth?

VI.3 How many times bigger is the Earth's surface area than the crater-counting standard area of 100,000 km^2 on the Moon?

VI.4 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?

The surface geology of the Moon has remained fairly undisturbed (except for impacts) since the last maria-building lava flows, which ended roughly 3.5 billion (3,500,000,000 or 3.5×10^9) years ago. We expect the Earth to have encountered a similar rate of impacts over that same time period.

VI.5 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 VI.4 you calculated the total number of impacts. If these impacts have been occurring over the last 3.5 billion years, how can you calculate the frequency of impacts per year?) Is this number larger or smaller than 1? What does that mean?

VI.6 On average, about how frequently do such impacts of this size occur on the Earth? (*Hint:* Question VI.5 asked you to calculate impacts per year, this question is asking for years per impact.)

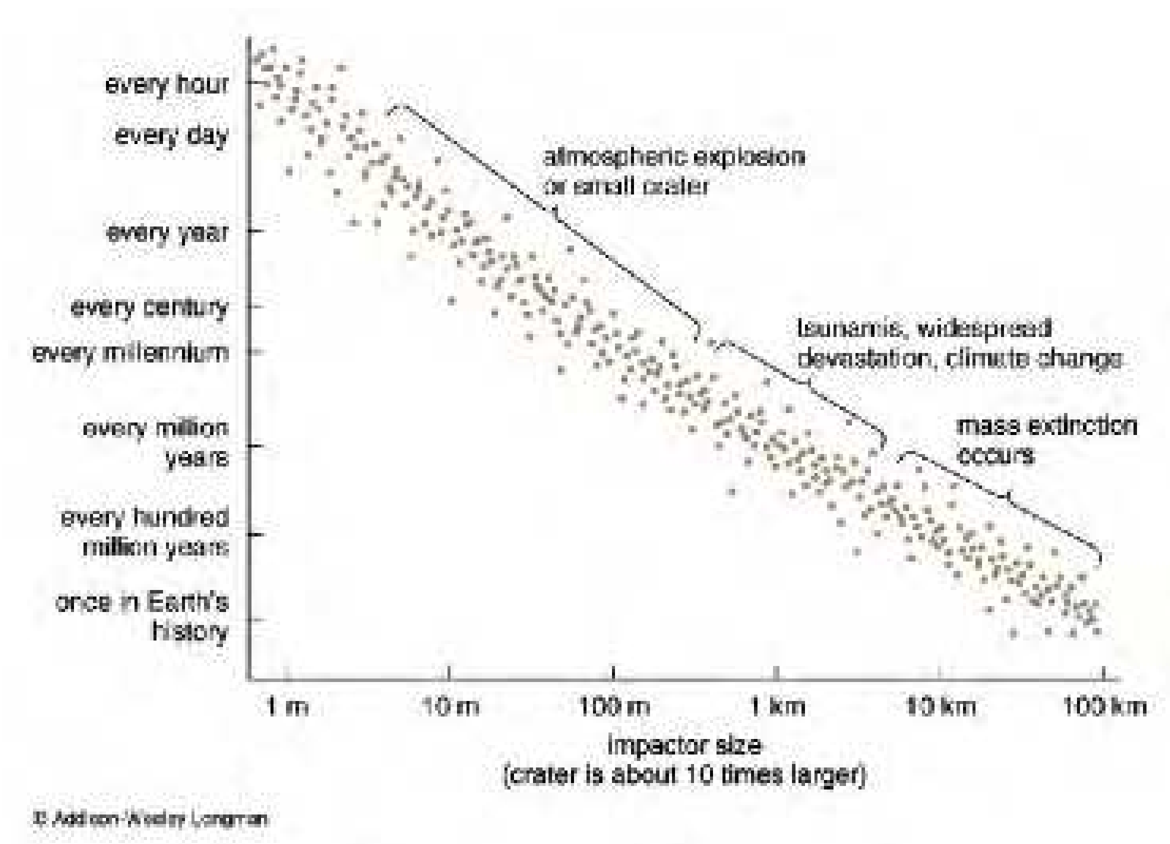
Based only on your measurements, what are the approximate odds that a 1-km diameter object will strike the Earth in your lifetime? (Such an impact, incidentally, would bring about continent-wide devastation, global atmospheric disruption, and likely an end to human civilization!) (*Hint*: You calculated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

VI.7 Compare your assessment of typical collision frequency with the estimates shown in the graph below. How does your estimate compare?

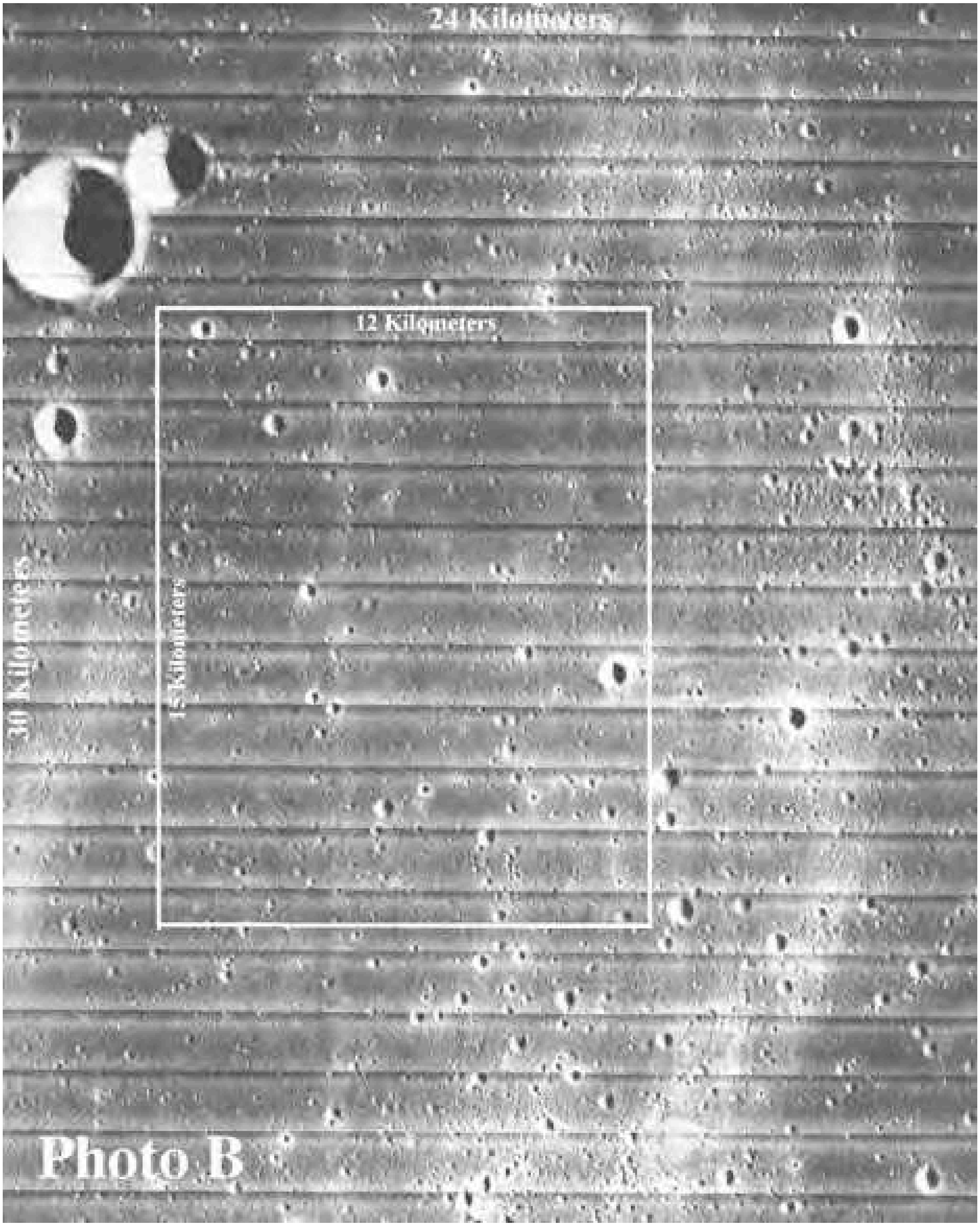
Some scientists believe that the impact rates in this plot may be a bit too high. Based on the results you obtained, would you agree or disagree with that point of view?

VI.8 Have your opinions changed about the NASA Near Earth Asteroid program? Why or why not?

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.




196 Kilometers
Photo A
Photo B
N
296 Kilometers


24 Kilometers
12 Kilometers
30 Kilometers
15 Kilometers
Photo B

TELESCOPE OPTICS

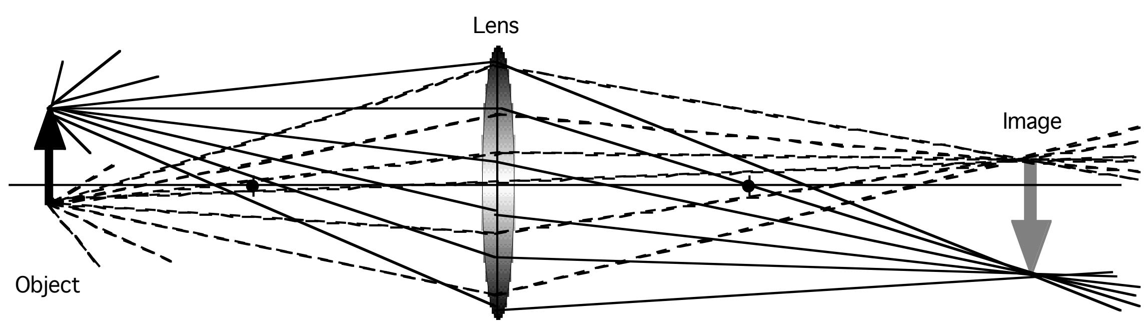
SYNOPSIS: You will explore some image-formation properties of a lens, and then assemble and observe through several different types of telescope designs.

EQUIPMENT: Optics bench rail with 3 holders; optics equipment stand (flashlight, mount O, lenses L1 and L2, image screen I, eyepieces E1 and E2, mirror M, diagonal X); object box.

NOTE: Optical components are delicate and are easily scratched or damaged. Please handle the components carefully, and avoid touching any optical surfaces.

Part I. The Camera

In optical terminology, an **object** is any source of light. The object may be self-luminous (such as a lamp or a star), or may simply be a source of reflected light (such as a tree or a planet). If light from an object happens to pass through a **lens**, those rays will be bent (refracted) and will come to a **focus** to form an **image** of the original object.



Here's how it works: from *each* point on the object, light rays are emitted in all directions. Any rays that encounter the lens are bent into a new direction, but in such a manner that they all converge through one single point on the opposite side of the lens. Thus, one point on the actual object will focus into one corresponding point on what's called the **focal plane** of the lens. The same thing is true for light rays emanating *from every other point* on the object, although these rays enter the lens at a different angle, and so are bent in a different direction, and again pass through a (different) unique point in the focal plane. The image is composed of an infinite number of points where all of the rays from the different parts of the object converge.

To see what this looks like in "real-life," arrange the optical bench as follows:

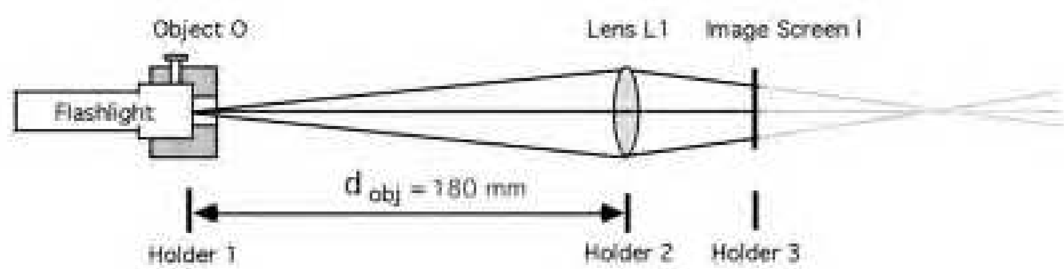
First, loosen the clamping knob of holder #1 and slide it all the way to the left end of the optics rail until it encounters the stop (which prevents the holder from sliding off of the rail). Clamp it in place.

Next, turn on the flashlight (stored in the accessory rack) by rotating its handle, and take a look at its illuminated face. The pattern you see will serve as the physical **object** in our study.

Insert the large end of the flashlight into the large opening of the Object Mount O, and clamp it in place with the gold knob. Install the mount and flashlight into the *tall* rod holder of holder #1 so that the flashlight points to the right and down the rail. (Allow the rod to drop fully into the holder so that the mounting collar determines the height of the flashlight; rod collars are used to insure that all components are positioned at the same height. Please do not adjust the rod collar unless instructed to by your TA.)

The white mark on the backside of each holder indicates the location of the optical component in that holder; thus, measuring the separation between marks is equivalent to measuring the separation of the optical components themselves. Use the meter stick to measure the separation of the white marks so as to position holder #2 at a distance 180 mm (18 cm) from holder #1; clamp it in place. Install lens L1 in the holder so that one of its glass surfaces faces the flashlight.

Finally, put the image screen I (with white card facing the lens) in holder #3 on the opposite side of the lens from the flashlight. Your arrangement should look like this:



The separation between the lens and the object is called the **object distance** d_{object}; because you've positioned the object (flashlight) 180 mm from the center of the lens, the object distance in this case is 180 mm.

On the white screen, you will see a bright circular blob, which is the defocused light from the object that is being bent through the lens. Slowly slide the screen holder #3 back and forth along the rail while observing the pattern of light formed on the screen. At one unique point, the beam of light will coalesce from a fuzzy blob into a sharp image of the object. Clamp the screen at this location where the image is in best **focus**.

The following question asks for a prediction. You will NOT be marked down if your prediction is wrong so record your prediction honestly BEFORE moving on.

I.1 Predict what will happen to the image if you swap the positions of the flashlight (object) and the image screen. Explain your reasoning.

I.2 Swap the object and image screen (*Hint:* Leave the holders in place so you can return to this arrangement, just take the posts out of the holders.) Was your prediction correct? If not, explain what you see.

Return to your original setup before continuing.

The term **magnification** refers to how many times larger the focused image appears, compared to the actual size of the object:

$$\text{Magnification (definition)} = \frac{\text{Image Size}}{\text{Object Size}} \qquad (1)$$

I.3 What should the units of magnification be?

I.4 What is the magnification produced by this optical arrangement?
Observed magnification = ______________
Explain how you calculated this magnification.

You probably won't be surprised to learn that the distance between the lens to the in-focus image is called the **image distance**, d_{image}. In optical terminology, distances are always given in terms of how far things are from the main optical component (in this case, the lens).

Instead of directly measuring the magnification, you can also calculate it from the ratio of image distance to the object distance:

$$\text{Magnification (calculated)} = d_{image} / d_{object} \qquad (2)$$

I.5 Use the meter stick and the two white marks on holders #2 and #3 to determine the image distance from the lens; record your result to the nearest millimeter: d_{image} = ______

I.6 Show that equation 2 gives you (at least approximately) the same value for the magnification that you determined in I.3: *Calculated magnification* = ___________

Now let's find out how things change if the object is a little further from the lens. Unclamp and move holder #2 to the right, so that the distance between the object and the lens is somewhat larger than before (say, 200 mm or so). Now move the image screen I to find the new image location.

I.7 (a) When you increased the distance to the object from the lens, did the image distance get closer or farther away from the lens? ___________________________

(b) Did the magnification get greater or less? ____________________

(c) Move the lens a small amount once again, and verify that you can still find an in-focus image location on the opposite side.

Hopefully, you've found that a lens can be used to produce a magnified image of an object, and that the magnification can be varied. But it is also possible to make a *de-magnified* image instead (that is, *smaller* than the original object).

I.8 Move lens L1 (by sliding holder #2) to a position so that the image size is *less* than the original object size. What is the new object distance? ________ What is the new image distance? _______ What magnification (using Equation 2) does this imply? _______. What is the measured image size? __________ Does the magnification using Equation 1 agree with the magnification you calculated using Equation 2?

Now let's see what will happen if we use a *different* lens. Replace lens L1 with the lens marked L2, but otherwise leave the positions of the holders in exactly the same place.

I.9 Refocus the image. What is the new image distance with this lens? d_{image} = ______ What is the magnification produced by this arrangement? ________. Indicate whether you determined the magnification by definition (equation 1) or calculation (equation 2): _____

By now you have seen that, for any given lens, and distance of an object from it, there is one (and *only* one) location behind the lens where an image is formed. By changing either the lens or the distance to the object, or both, the location and magnification of the image can also be changed.

The optical arrangement you have been experimenting with is the same as that used in a **camera**, which consists of a lens with a piece of photographic film (or a digital chip) behind it, which records the pattern of light falling onto it. The film/chip is held at a fixed location, which is represented in our optical arrangement by screen I in holder #3.

I.10 Using your experience above (question I.6): if you move closer to an object that you're trying to photograph (smaller object distance), will the lens-to-film/chip distance (image distance) in your camera have to get larger or smaller to keep the image in focus? ________________________

I.11 How do you think cameras achieve the proper focus?

In many cameras it is possible to swap lenses, so that the same camera will yield much larger images of distant objects (i.e., a "telephoto" lens).

I.12 Which of the two lenses produced a larger image under the same conditions? ______ Which would more likely be considered to be a "telephoto" lens? __________

Part II. The Lens Equation

Because object and image distances from a lens seem to be related in a predictable manner, you probably won't be surprised to learn that there is a mathematical relationship between the two. It's called the **lens equation,** and for any given lens it looks like this:

$$\frac{1}{f} = \frac{1}{d_{object}} + \frac{1}{d_{image}} \qquad (3)$$

The value *f* in the formula is called the **focal length** of the particular lens being used. This is a *property of the lens itself*, and doesn't change regardless of the location of the object or the image. Notice that the formula actually relates the reciprocal ("one over"; also called the "inverse") of the values of *f*, d_{object}, and d_{image}, instead of the actual values themselves.

> HELPFUL HINT: When using your calculator with the lens formula, it is much simpler to deal with the *reciprocals* of the numbers, rather than with the numbers themselves. Look for the calculator reciprocal key labeled $\boxed{1/x}$ or $\boxed{x^{-1}}$. To compute
>
> $\frac{1}{2} + \frac{1}{4}$, press the keys: $\boxed{2}$ $\boxed{1/x}$ $\boxed{+}$ $\boxed{4}$ $\boxed{1/x}$ $\boxed{=}$.
>
> You should get the result 0.75 (= 3/4). Now since 1/f equals this quantity, just hit $\boxed{1/x}$ again to determine $f = \frac{1}{0.75} = 1.33$.

II.1 Calculate the focal length *f* of lens L1, using your measured image distance d_{image} and object distance d_{object}. You can use either the arrangement from step I.3, or from step I.6, or from both (to see if they give about the same answer). Focal length *f* of Lens L1 = _______________.

II.2 What is the focal length of lens L2 (using the information measured in step I.9)? Focal length *f* of Lens L2 = __________________.

II.3 Which lens, L1 or L2, has the longer focal length? __________. Considering what you found out in I.9, does a telephoto lens have a longer or shorter focal length than a “normal” lens? _____________

II.4 Using the Lens Equation (3), explain why your experiment in I.2 produced the results it did.

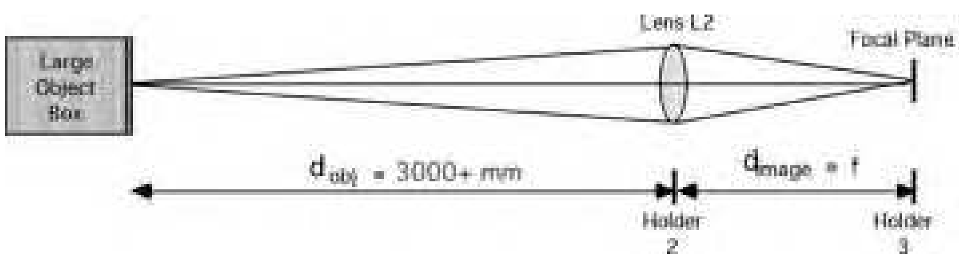
Part III. The Refracting Telescope

In astronomy, we look at objects that are *extremely* far away. For all practical purposes, we can say that the object distance is *infinitely* large. This means that the value $1/d_{object}$ in the lens equation is *extremely* small, and can be said to equal zero. Thus, for the special case where an object is very far away, the lens equation simplifies to:

$$\frac{1}{f} = 0 + \frac{1}{d_{image}} \qquad \text{or simply} \qquad d_{image} = f$$

In other words, when we look at distant objects, images are formed behind the lens at a distance equal to (or very nearly so) its focal length. Because *everything* we look at in astronomy is very far away, images through a telescope are *always* formed at the focal length of the lens.

We can now look at an object that is far enough away to treat it as being "at infinity." Remove the flashlight and mount from holder #1 and replace them in the optics storage rack. Instead, use the large object box *at the opposite end of the table* for your light source. It should be at least 3 meters (10 feet) from your optics bench. Focus the screen. Your arrangement should look like this:



III.1 Measure the image distance from the markings on the optics rail. Confirm that this is fairly close to the value of the focal length of lens L2 that you calculated in II.2. Measured image distance = _____________________.

Your measurement will be slightly larger than the true value of *f,* simply because the illuminated object box isn't *really* infinitely far away; however, since we can't take this telescope outside, we will treat your measurement in III.1 as the actual focal length of the lens.

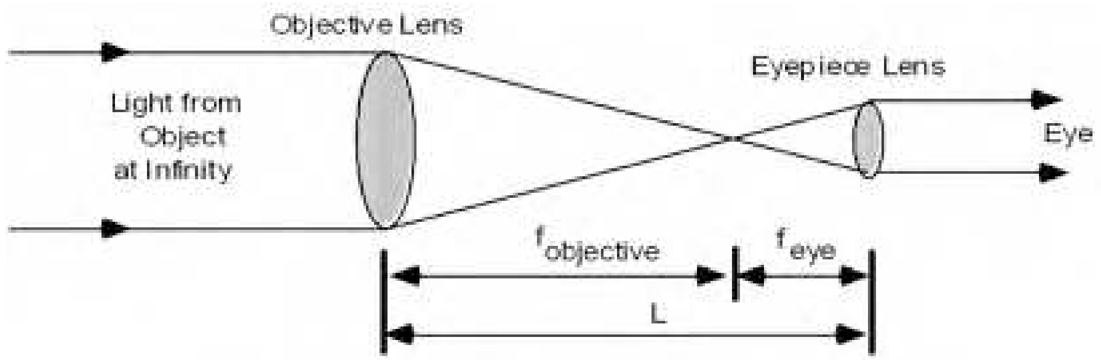
If the screen were not present, the light rays would continue to pass through and beyond the image that forms at the focal plane. In fact, the rays would diverge from the image as if it were a real object, suggesting that *the image formed by one lens can be used as the object for a second lens*.

III.2 Remove the white card from the screen to expose the central hole. Aim the optics bench so that the image passes into the opening.

III.3 From well behind the image screen, look along the optical axis at the opening in the screen. You should be able to see the image once again, "floating in space" in the middle of the opening! If you move your head slightly from side-to-side you should get the visual impression that the image doesn't shift around but instead seems to be fixed in space at the center of the hole. By sliding the screen back and forth along the rail, you can also observe that the opening passes around the image, while the image itself remains stationary *as if it were an actual object*.)

Notice that the image is quite tiny compared to the size of the original object (a situation that is always true when looking at distant objects). In order to see the image more clearly, you will need a magnifying glass:

III.4 Remove screen I from its holder and replace it with the magnifying lens E1. Observe through the magnifier as you slowly slide it back away from the image. (*Hint:* Your eye should be right next to the magnifying lens.) At some point, a greatly enlarged image will come into focus. If you run off the end of the rail you will have to move the whole arrangement towards the light. Clamp the lens in place where the image appears sharpest. Your arrangement will be as follows:



You have assembled a **refracting telescope**, which uses two lenses to observe distant objects. The main telescope lens, called the **objective lens,** takes light from the object at infinity and produces an image exactly at its focal length $f_{objective}$ behind the lens. Properly focused, the magnifier lens (the **eyepiece**) does just the opposite: it takes the light from the image and makes it appear to come from infinity. The telescope itself *never forms a final image*; it requires another optical component (the lens in your eye) to bring the image to a focus on your retina.

To make the image appear to be located at infinity (and hence observable without eyestrain), the eyepiece must be positioned behind the image at a distance exactly equal to *its* focal length, f_{eye}. Therefore, the total separation L between the two lenses must equal the sum of their focal lengths:

$$L = f_{objective} + f_{eye} \tag{4}$$

III.5 Measure the separation between the two lenses (L), and use your value for the objective lens focal length ($f_{objective}$, measured in step III.1) and equation (4) to calculate the focal length of eyepiece E1 (f_{eye}). L: __________ f_{eye}:___________

Earlier, we used the term "magnification" to refer to the actual *physical size* of the image compared to the actual *physical size* of the object. This cannot be applied to telescopes, because no final image is formed (and besides, the physical sizes of objects studied in astronomy, like stars and planets, are *huge*). Instead, we use the concept of **angular magnification**: the ratio of the *angular* size of an image appearing in the eyepiece compared to the object's actual *angular* size. In other words, we're referring to how much bigger something *appears* to be, rather than to how big it actually is.

The angular magnification *M* produced by a telescope can be shown to be equal to the ratio of the focal length of the objective to the focal length of the eyepiece:

$$M = \frac{f_{objective}}{f_{eye}}. \quad (5)$$

III.6 Calculate the magnification of the telescope arrangement you're now using (objective lens L2 and eyepiece E1): ______________

Equation 5 implies that if you used a telescope with a *longer* focal length objective lens (make $f_{objective}$ bigger), the magnification would be greater. But the equation also implies that you can increase the magnification of your telescope simply by using an eyepiece with a *shorter* focal length (make f_{eye} smaller).

III.7 Eyepiece E2 has a focal length of 18 mm. Use equation 5 to calculate the magnification resulting from using eyepiece E2 with objective lens L2: ____________

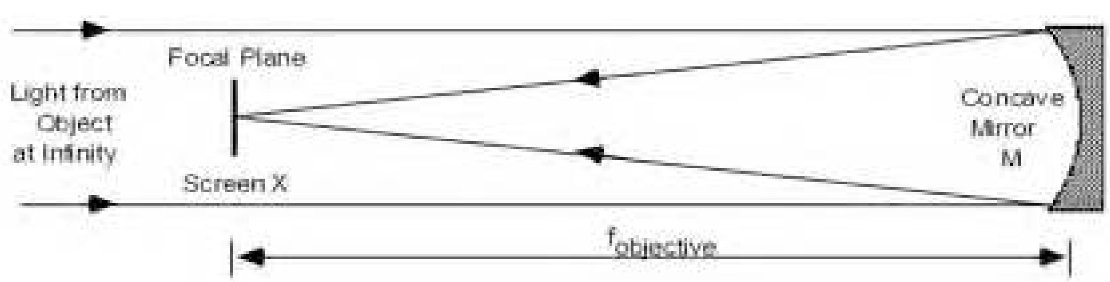
III.8 Replace eyepiece E1 with E2, and refocus. Did the image get bigger or smaller than before? _________. Is your observation consistent with the calculation of III.7? ______

Consumer Tip: Some inexpensive telescopes are advertised as "high power" ("large magnification") because most consumers think that this means a "good" telescope. You now know that a telescope can exhibit a large magnification simply by switching to an eyepiece with a very short focal length. Magnification really has nothing to do with the actual quality of the telescope!

Part IV. The Reflecting Telescope

Concave mirrored surfaces can be used in place of lenses to form **reflecting telescopes** (or **reflectors**), rather than refracting telescopes. All of the image-forming properties of lenses also apply to reflectors, except that the image is formed *in front* of a mirror rather than behind. As we will see, this poses some problems! Reflecting telescopes can be organized in a variety of configurations, three of which you will assemble below.

The **prime focus** arrangement is the simplest form of reflector, consisting of the image-forming objective mirror and a flat surface located at the focal plane. A variation on this arrangement is used in a **Schmidt camera** to achieve wide-field photography of the sky.



IV.1 Assemble the prime-focus reflector shown above:

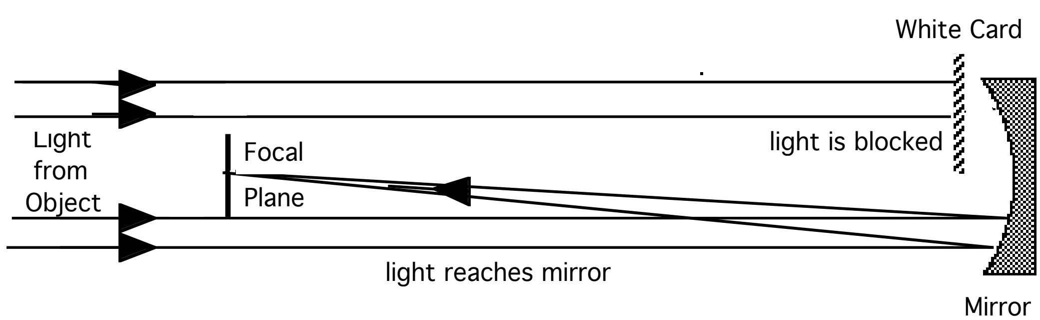
- First, return all components from the optical bench to their appropriate locations in the optics storage rack.
- Next, slide holder #3 all the way to the end stop away from the light source, and slide holder #2 as far right as possible until it is touching holder #3.
- Install the large mirror M into holder #2, and carefully aim it so that the light from the distant object box is reflected straight back down the bench rail.
- Place the mirror/screen X into the *tall* rod holder #1, with the white screen facing the mirror M.
- Finally, move the screen back and forth along the rail until you find the location where the image of the object box is focused onto the screen. (Tip: you can use the white card from the image screen to find the image that is being reflected from the mirror, which will let you know if you need to rotate the mirror so that the beam is directed at screen X).

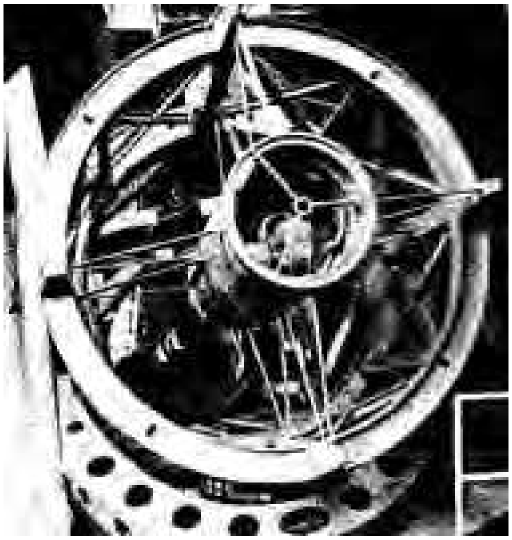
IV.2 Is the image right-side-up, or inverted? ___________________

IV.3 Measure the focal length *f* of the mirror M just like you did with the refractor: use your meter stick to measure the distance from the mirror to the image location. Focal length of the mirror = ____________

Because the screen X obstructs light from the object and prevents it from illuminating the center of the mirror, many people are surprised that the image does not have a "hole" in its middle.

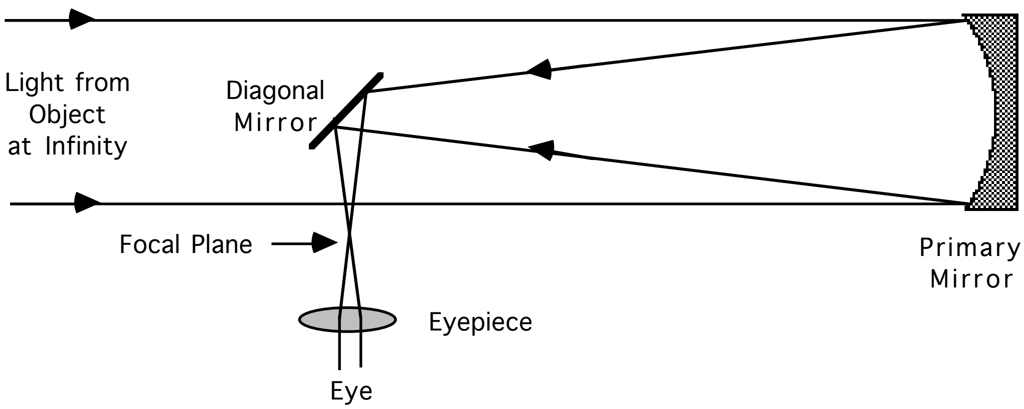
IV.4 Hold the white card partially in front of the objective mirror in order to block a portion of the beam, as shown below. Note that no matter what portion of the mirror you obscure, the image of the distant object box stays fixed in size and location on the screen. This is because *each small portion of the mirror forms a complete and identical image* of the object at the focus! However, as you block more and more of the mirror, does the image change in brightness? ____ Explain why or why not:_______________
____





The prime focus arrangement cannot be used for eyepiece viewing, because the image falls inside the telescope tube. If you tried to see the image using an eyepiece, your head would also block all of the incoming light. (This, however, is not the case for an extremely large mirror: for example, the 200-inch diameter telescope at Mount Palomar has a small cage in which the observer can actually sit inside of the telescope at prime focus, as shown here!)

Isaac Newton solved the head-obstruction problem for small telescopes with his **Newtonian reflector**, which uses a flat mirror oriented diagonally to redirect the light to the side of the telescope, as shown below. The image-forming mirror is called the **primary** mirror, while the small additional mirror is called the **secondary** or **diagonal** mirror.



IV.5 Convert your telescope to a Newtonian arrangement:

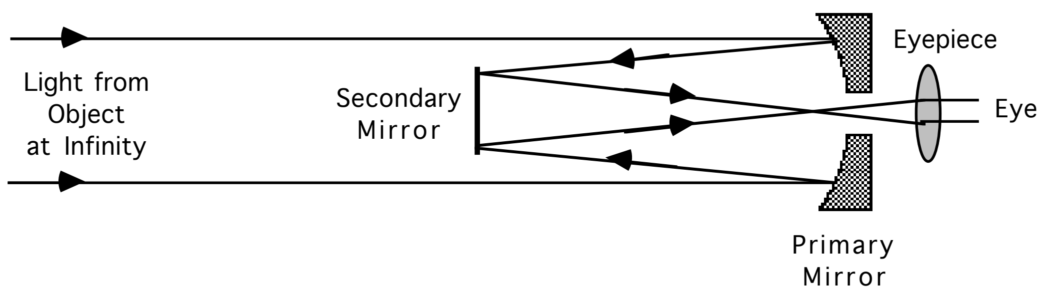
- Reverse the mirror/screen X so that the *mirror* side faces the primary mirror M and is oriented at a 45° angle to it.
- Install eyepiece E1 in the *short* side rod holder of holder #1, and look through the eyepiece at the diagonal mirror (see diagram above).
- Now rotate the diagonal mirror slightly until you see a flash of light that is the bright but out-of-focus image of the distant object. Clamp the diagonal mirror in place.

Now, while looking through the eyepiece, slowly slide holder #1 towards the mirror (about 50 mm or so) until the image comes into sharp focus.

Congratulations! You've constructed a classical Newtonian telescope, one of the most popular forms of telescopes used by amateur astronomers!

IV.6 Use equation 5 and your knowledge of the mirror M's focal length and eyepiece E1's focal length (steps IV.3 and III.5, respectively) to determine this telescope's magnification: ___________________

Large reflecting telescopes (including the 16-inch, 18-inch, and 24-inch diameter telescopes at Sommers-Bausch Observatory) are usually of the **Cassegrain** design, in which the small secondary redirects the light back towards the primary. A central hole in the primary mirror permits the light to pass to the rear of the telescope, where the image is viewed with an eyepiece, camera, or other instrumentation.



IV.7 Re-arrange the telescope into a Cassegrain configuration as shown above.

- Remove the eyepiece E1 from its short holder in holder #1, and transfer it instead to holder #3 behind the mirror.
- Carefully re-orient the secondary mirror (still in holder #1) so that it reflects light directly back towards the hole in the primary mirror.
- Now slide holder #1 towards the mirror until it is only about 35% of its original separation from the mirror (about 1/3rd of the mirror focal length found in IV.3).
- While looking through the eyepiece, rotate the secondary mirror in holder #1 slightly until you see the flash of light that is the image of the object. Then move holder #1 slightly towards or away from you until you can see an in- focus image.

IV.8 Do you think that the magnification of this image is any different from the magnification you observed with the Newtonian arrangement? Why or why not?

Note: in a *real* Cassegrain telescope, the magnification *would* in fact be different because the secondary mirror is not actually flat, but instead is a convex shape. This permits the size of the secondary mirror to be smaller than the flat secondary you are using here, and thus allows more light to strike the primary mirror.

IV.9 How does the overall length of the Cassegrain telescope design compare with that of the Newtonian style? ____
Can you come up with one or more reasons why the Cassegrain design might have advantages over the Newtonian? Explain your ideas:

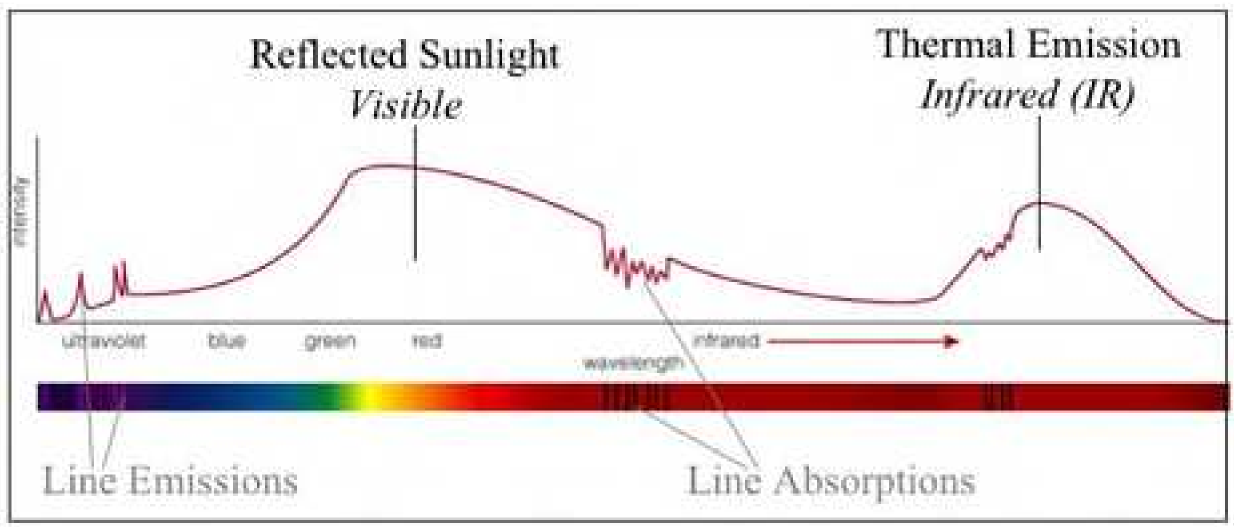
IV.10 Why does the hole in the primary mirror *not* cause any additional loss in the light-collecting ability of the telescope? ____

IV.11 If time permits, compare the *actual* optical and astronomical equipment that has been provided by the teaching assistant (35-mm film **camera**, small **refractor**, **Schmidt** telescope camera, **Newtonian** reflector, **Cassegrain** reflector) with the different telescope styles that you have just assembled. Note especially that, except for having enclosed tubes and more sophisticated controls, each design you assembled is essentially identical to "the real thing"!

SPECTROSCOPY I – Light & Color

Learning Goals: Distant objects need to be studied by means of 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?

A **spectrum** is the intensity of light at different wavelengths. **Spectra** of planets have a typical "double hump" – Reflected sunlight in the visible part of the spectrum and infrared emission due to their own thermal emission ("glow") coming from inside the planet. Most of this lab is concerned with the visible part of the spectrum. Figure 1:



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" – emit, transmit, reflect, absorb.

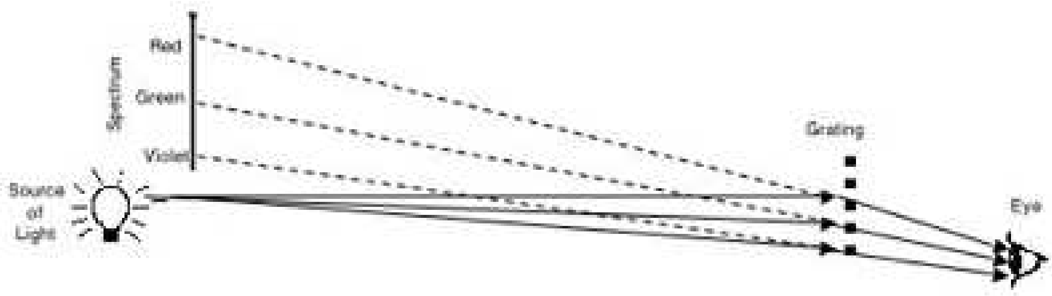
Equipment: Light bulb, set of 3 filters, grating or spectroscope.

Turn on the light bulb.

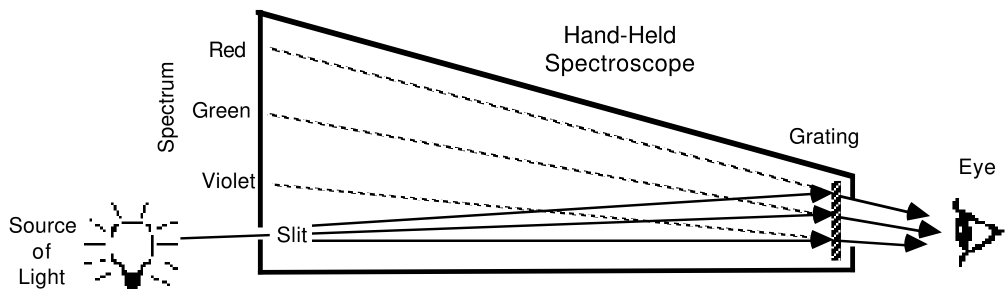
I.1 List ALL the objects in the room that are **emitting visible light**. (*Hint:* there are not very many.)

I.2 Can you tell what colors are present within white light by simply looking at the bulb? Why or why not?

A **grating** is a device that allows you to view a spectrum. The plastic sheet in the slide holder (the same as the small pieces that may have been handed out in class) has the property of being able to disperse ("split up") the light into its component colors (wavelengths, energies).

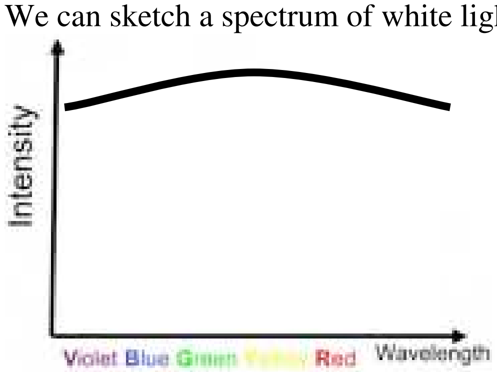


A **spectroscope** is another device for viewing a spectrum. Light enters the spectroscope through a slit and strikes a grating. Each color forms its own separate image of the opening. A slit is used to produce narrow images, so that adjacent colors do not overlap each other.

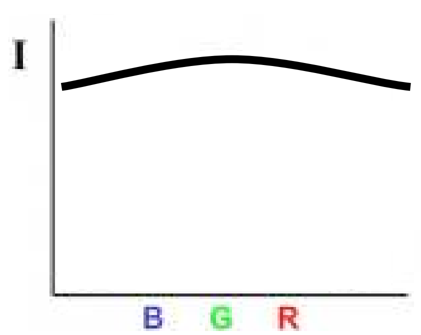


I.3 Use the grating or spectroscope to look at the light bulb - What do you see?

We can sketch a spectrum of white light like this:



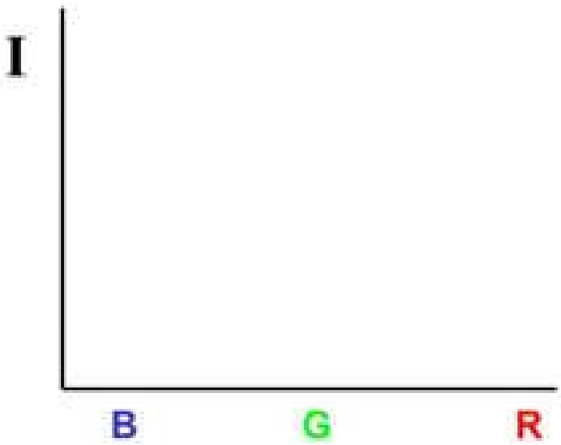
or, to simplify, like this

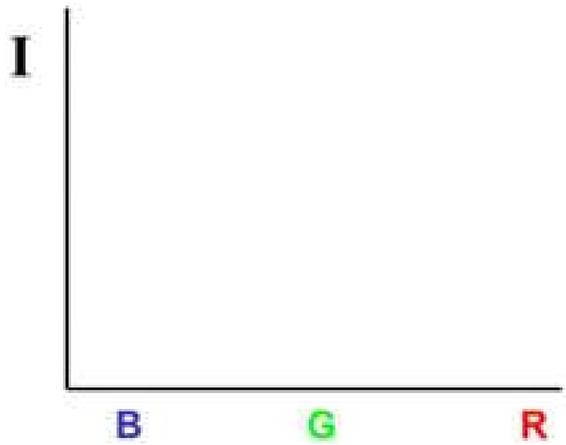


I.4 Look at the light through the various filters. Draw the spectra of the light being ***transmitted*** - "let through" - by the different filters.

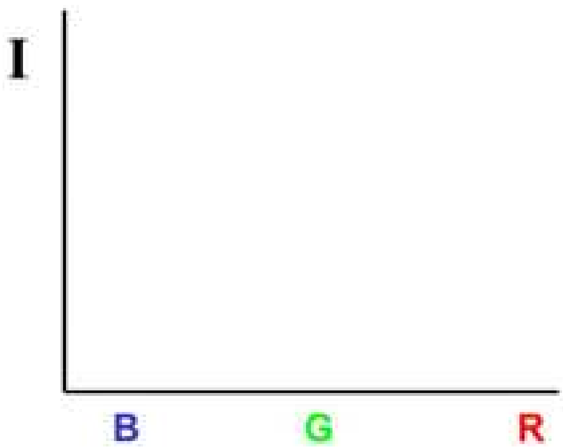
Filter: ________________

Filter: ________________





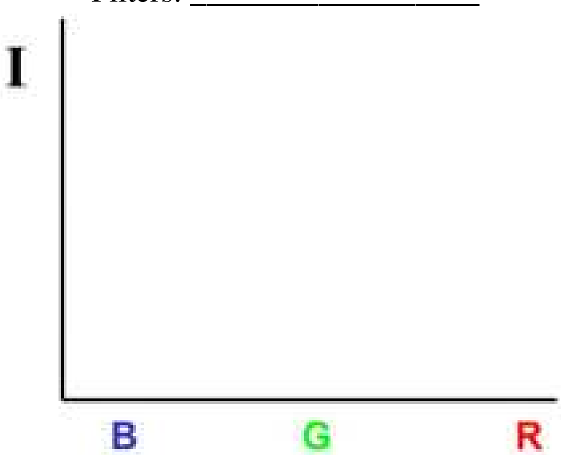
Filter: ________________

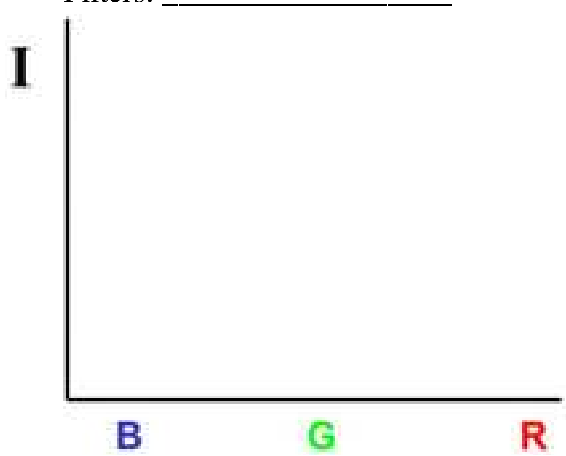


I.5 What happens when you add filters together? Try different combinations.

Filters: ________________

Filters: ________________





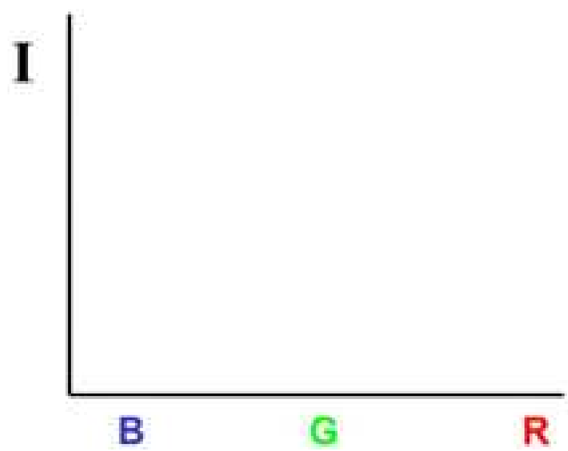
I.6 Explain what is happening in your drawings for I.5

I.7 If the Sun is out, look at the solar spectrum from the Heliostat with different filters. Explain what you see.

I.8 Think about the white light hitting your shirt/sweater. What color(s) is it? What colors are **reflected** by your shirt/sweater?

What colors are **absorbed**?

I.9 Draw the spectrum of light reflected by your shirt/sweater.



Part II – The White Room (aka The Not-So-Dark Room) – 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.

II.1 *Predict* what will happen if you look at the sheet with colored lettering under a single light.

II.2 Try it. What effects do you see? Explain what is causing this effect (*Hint:* What color is the paper the letters are written on?)

II.3 Turn up two colors at a time. What do you get?

II.4 Hold up and object off the table so it casts a shadow. What do you notice about the shadow? Explain what is causing this effect.

II.5 What happens when you add all 3 colors – what do you get?

II.6 In part I.5 you saw one result when you used multiple filters, this time you (hopefully) saw a different result. Explain why the two experiments produced different results.

Part III – The Yellow Room – *(Be sure to bring your spectroscope!)* The yellow room is a room illuminated by four different types of lights that all emit a very similar yellow color but do it very differently. The main light you will deal with is a sodium lamp that emits yellow light at only <u>one</u> wavelength – "monochromatic light."

III.1 **Before you enter the room** make a prediction: what will your shirt/sweater look like in the sodium light?

III.2 What was it like in the sodium light? How did the color of your shirt change?

III.3 Check out the alien babies – guess what color they are. Then turn on the room light.

III.4 Explain what is happening in both III.2 and III.3. *(Be sure to look at the sodium lamp using your spectroscope to aid your explanation.)*

III.5 Now close the cover for the sodium lamp and look at the various objects in each of the other lights (only uncovering one lamp at a time). Describe how a few objects look under each light.

III.6 Based on your observations in III.5, *predict* what each of the lights' spectra will look like through the spectroscope. (You can predict either using words or by drawing a predicted spectrum for each bulb.)

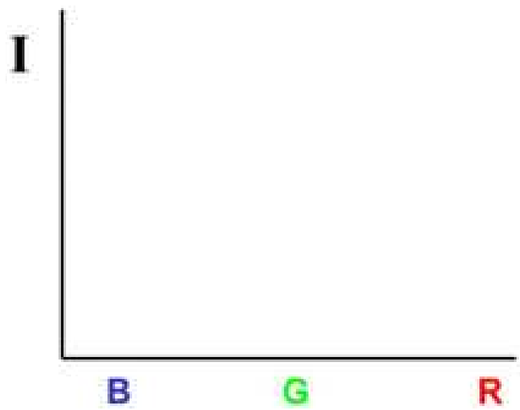
III.7 Now use your spectroscope, to examine the spectrum of each light. Were your predictions correct? If not, correct your descriptions here. Explain why the objects look the way they do in each of these lights.

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

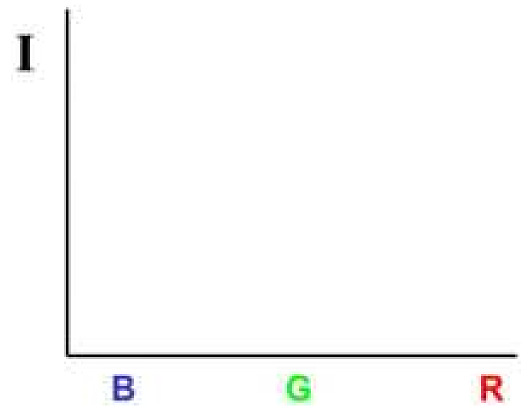
Part IV – Red, White and Blue Planets – The goal of this section is to apply your experience with white light and filters to studying planetary objects. You will not need your spectroscope for this section.

IV.1 Examine the images provided of planetary objects. Sketch the spectra of sunlight reflected by the different objects (Remember: that's what the images are showing us – reflected sunlight)

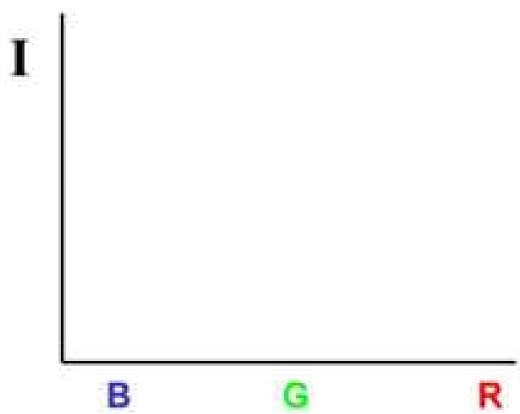
Io



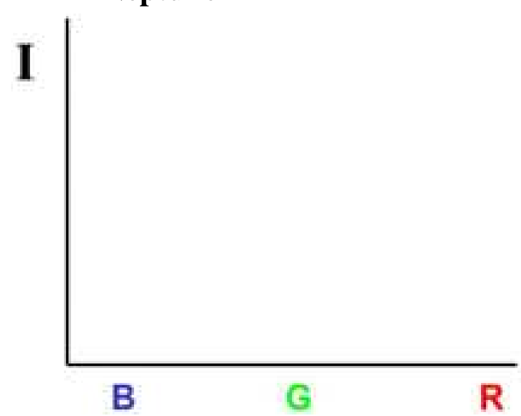
Mercury



Mars

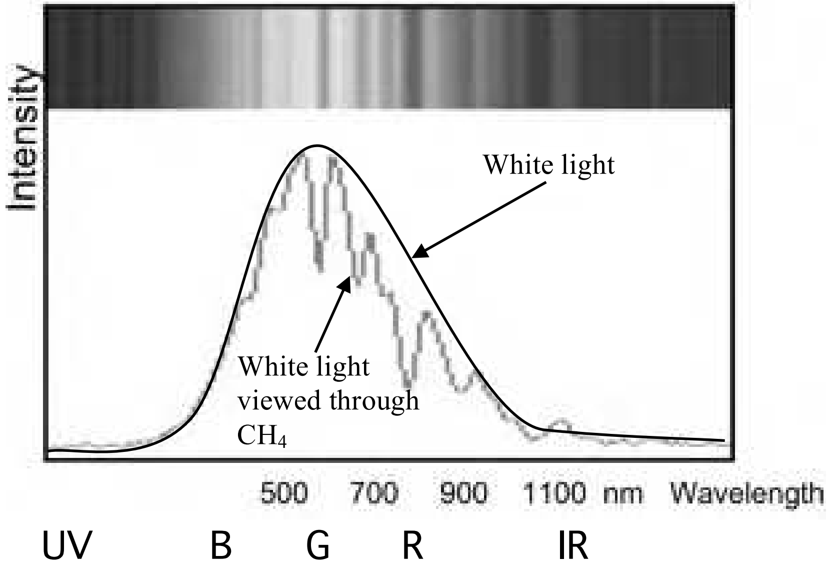


Neptune

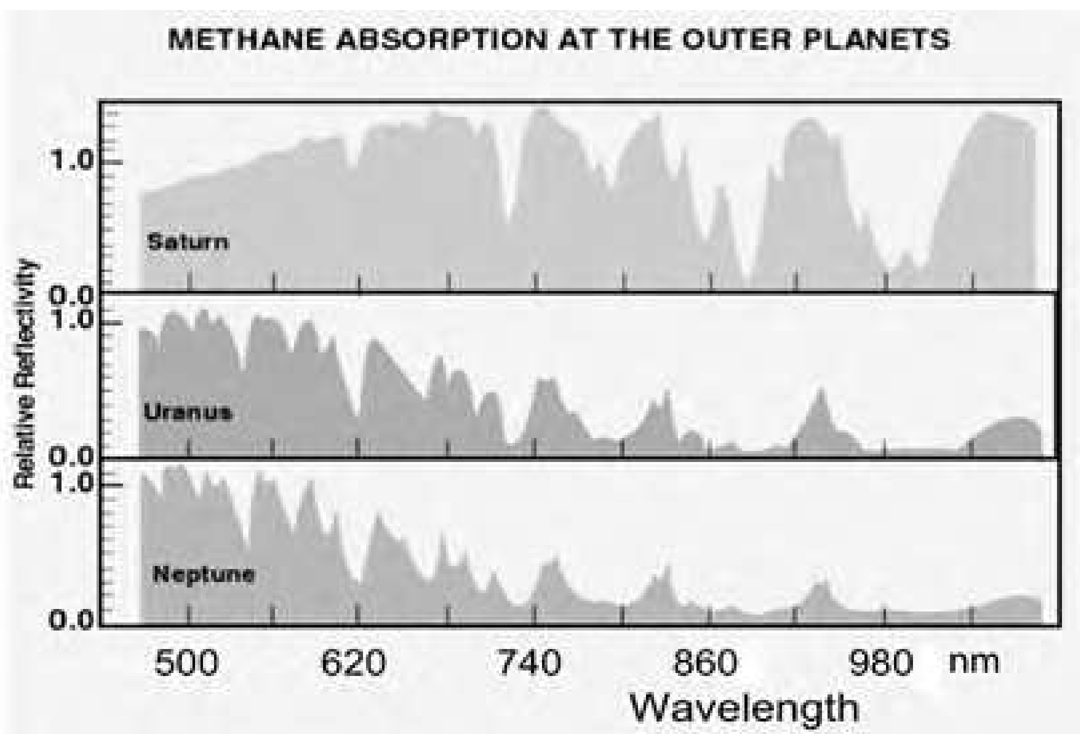


IV.2 What happens to the image of Earth when you look at it with a blue filter? With a red filter?

Here is a spectrum of white light and white light that has passed through methane gas (CH_4).



IV.3 What colors of the spectrum are absorbed by methane? What colors of light are transmitted by methane? (Simplify – think about the BGR scale we used above).



IV.4 The 3 plots above are spectra of reflected light from Saturn, Uranus, and Neptune. Which planet(s) seem(s) to have the most methane in its atmosphere?

IV.5 Deep in the atmosphere of Neptune there is a dense layer of (white) water clouds. Above the water clouds there is a thick layer of methane gas that acts like a blue filter. (There are also small, isolated clouds of condensed, liquid, methane that form higher up in the atmosphere.) Use the white cardboard disks (representing the planet Neptune stripped down to a deep cloud layer, white "methane" clouds, and multiple layers of blue plastic (representing layers of methane gas) to explore what produces the various color cloud features on Neptune.

a. What color cloud do you think is producing the dark spot on Neptune? Explain.

b. Neptune has small, isolated clouds varying from bright white to blue. What does the color of these cloud patches tell us about how deep they are in Neptune's atmosphere? (*Hint:* You might try "building" Neptune to see if you can create a few cloud patches of the varying colors.)

Part V – Planets and People at Infrared Wavelengths – This last section of the lab concerns the IR "hump" of the spectrum to the right of Figure 1. Remember that planets and people both emit thermal emissions in the infrared part of the spectrum.

V.1 Do you think any of the objects in the room are emitting infrared light? Which? How could you tell? (Tricky – think whether your eyes can detect IR. Could you use other senses to detect IR?)

V.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 IR camera is using a false color representation that does not necessarily follow the temperature-color relationship you may have learned in class.)

V.3 Examine the black plastic garbage bags as well as the clear plastic disk. Describe and explain what you see. Why do these objects look so different in the IR camera? (*Hint:* This is directly related to the greenhouse effect that you'll learn about when discussing planetary atmospheres.)

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

LEARNING GOALS:

- 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?

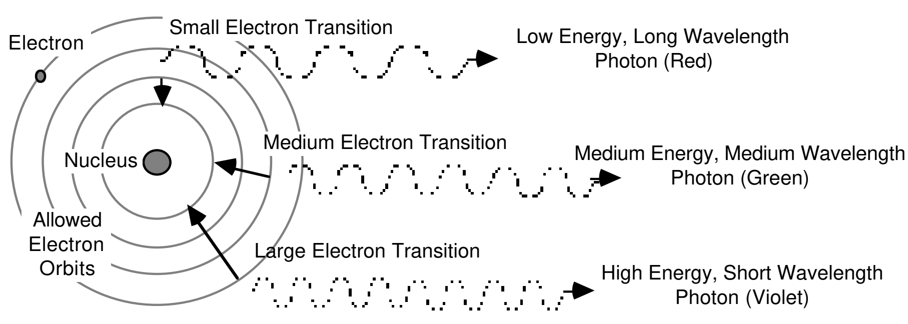
EQUIPMENT: Hand-held spectroscope; spectrum tube power supply and stand; helium, neon, nitrogen, air, and "unknown" spectrum tubes; incandescent lamp; and the heliostat.

WARNING: There is high voltage on the spectrum tube. You can get a nasty shock if you touch the ends of the tube while it is on. Also, the tubes get hot and you can burn your fingers trying to change tubes. Let the tubes cool or use paper towels to handle them.

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. A photon is a wave of electromagnetic radiation whose wavelength (distance from one wave crest to the next) is inversely proportional to its energy: high-energy photons have short wavelengths while low-energy photons have long wavelengths. 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 Using the model of electron transitions, explain how an atom can give off light.

(a) What can you infer about the transitions if an atom gives off both red light and blue light?

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

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

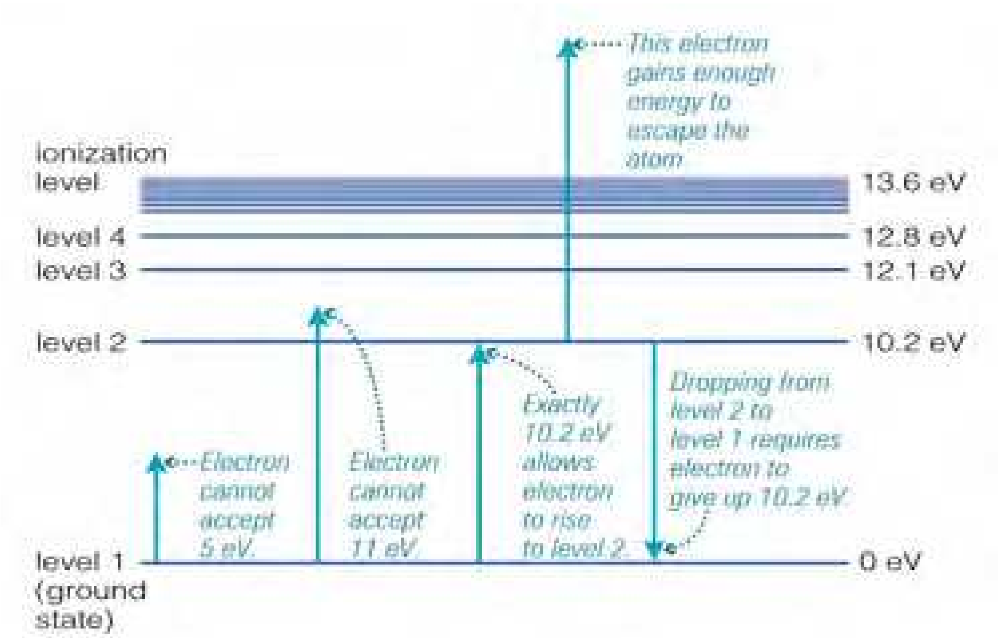
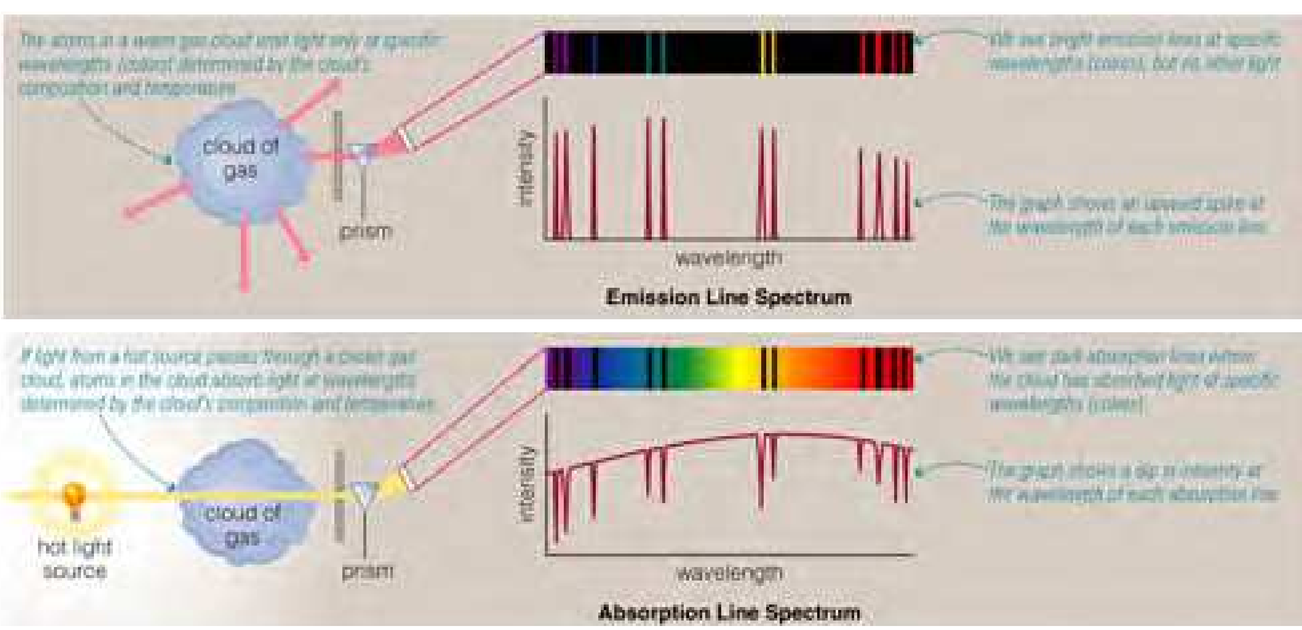
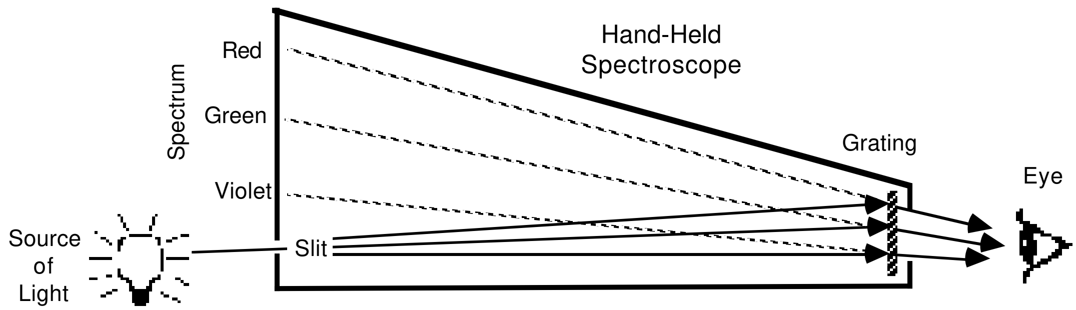


Figure 5.12 from the textbook showing the energy levels for an electron in a hydrogen atom. The electron can change energy levels only if it gains or loses the amount of energy separating the levels. If the electron gains enough energy to reach the ionization level, it can escape from the atom, leaving behind a positively charged ion. (The energy levels are labeled in units of electron-volts or eV where 1eV=1.6 x 10^{-19} joules)

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 component colors (wavelengths, energies).



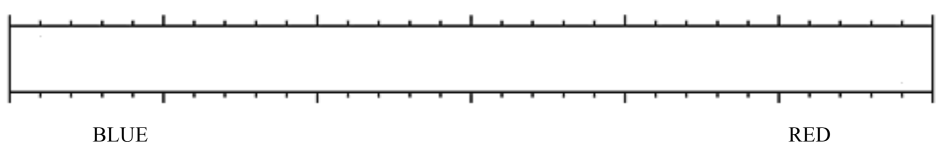
Part II - Continuum and Emission Line Spectra

Look at an ordinary lamp.

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:

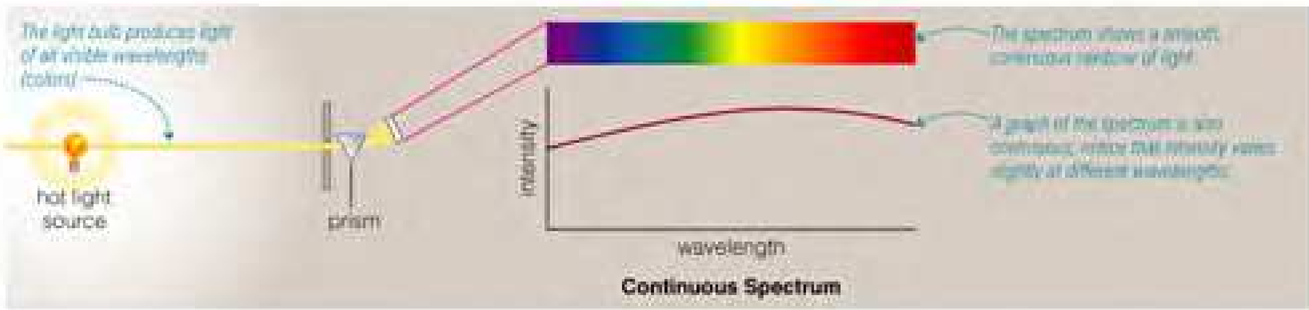


(a) Describe what you see.

(b) Are there any discrete spectral lines?

(c) What color in the spectrum looks the brightest? Or what color is in the middle of the bright part of the spectrum?

A *solid* glowing object, such as the filament of a regular light bulb, 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.



Continuous Spectrum

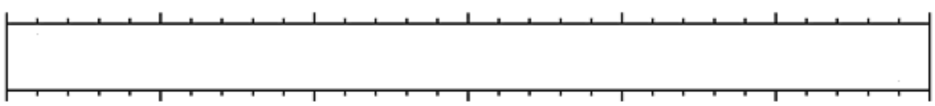
For each of these gases (Helium, Neon and Nitrogen):

- 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 or use paper towels to handle them.

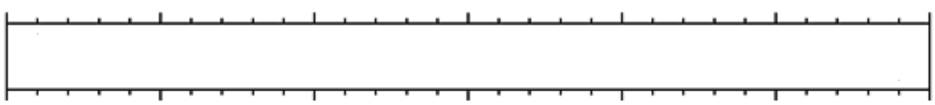
II.2 What colors do you see? Make a sketch - of the distinctly separate spectral lines (colors) of the light emitted by the element you are looking at on the frame below - use colored pencils or crayons if you wish.

Helium



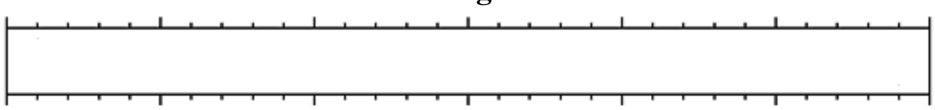
BLUE RED

Neon



BLUE RED

Nitrogen



BLUE RED

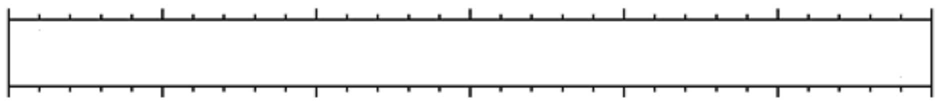
II.3 For each of these elements, how does the overall color of the glowing gas compare with the specific colors in its spectrum?

- 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.

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



BLUE RED

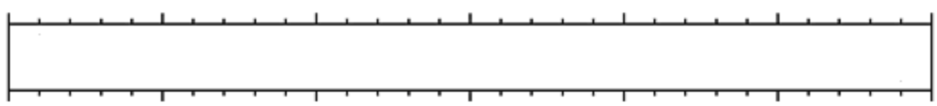
II.5 Which components of the spectrum originate from the gas?

II.6 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.



BLUE RED

III.2 Identify the composition of the gas in the tube by comparing your spectrum to the spectra described in the tables below.

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)

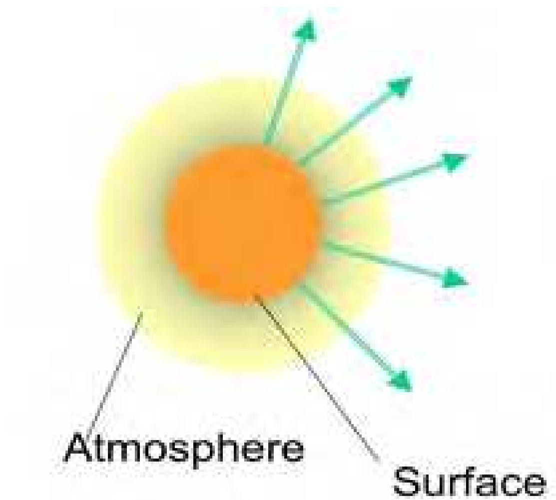
Mercury	
607	Orange
578	**Yellow**
546	**Green**
492	Blue-Green (dim)
436	**Violet**
405	Violet (dim)

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 its atmosphere?

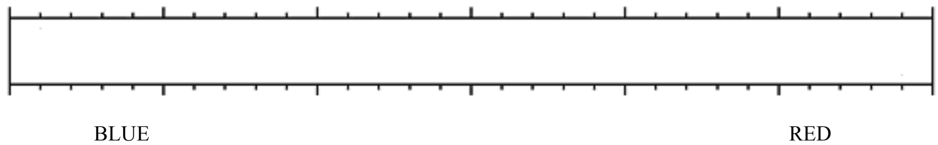
Your TA will also put light from a couple of gas tubes through the same optics that will produce emission lines above/below the solar spectrum. Can you identify these gases in the solar spectrum?

IV.3 How many lines of hydrogen can you find in the solar spectrum?

IV.4 Have your TA identify the sodium absorption lines. What color are they in? What color are sodium (emission) streetlights? 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

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.

SUGGESTED REVIEW: Unit conversions (page 13) and angles and trigonometry (page 22).

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. Start 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?

ALTITUDE OF THE SUN

When the Sun first appears on the horizon at sunrise, shadows are extremely long. As the Sun rises higher in the sky, the lengths of shadows become shorter. Hence, the *length* of the shadow cast by a gnomon can also be used to measure the **altitude** of the Sun (the angle, in degrees, between the Sun and the point on the horizon directly below it).

The figure below shows that the shadow cast by a gnomon forms a right-triangle. The Sun's *altitude* is the angle from the horizontal ground to the top of the gnomon, as seen from the tip of the shadow. The *tangent* of that angle is the *opposite* side of the right-triangle (the height of the gnomon, *H*) divided by the *adjacent* side of the triangle (the length of the shadow, *S*). Mathematically, this relationship is: tan(altitude) = H/S. We have prepared a 1-meter high gnomon (H = 1000 mm) on a stand to help you make the measurement.

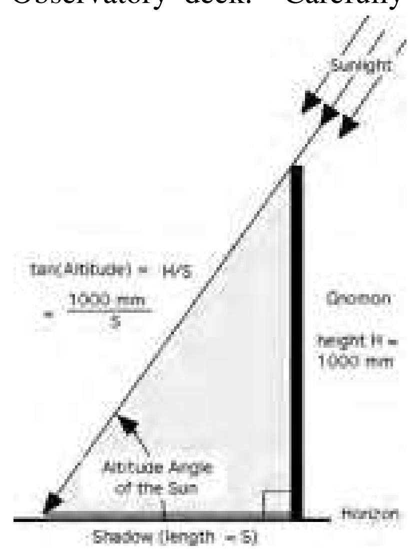
I.3 Carry the gnomon and a metric tape-measure to the Observatory deck. Carefully measure the shadow length S from the base of the gnomon to the tip of the shadow: S = ____________

I.4 Calculate the tangent value for the solar altitude:

$$\tan(altitude) = \frac{H}{S} = \frac{1000\ mm}{\_\_\_\_\_} = \_\_\_\_\_\_\_\_$$

I.5 Now use the "arc-tangent" function on your calculator to determine what angle, in degrees, has a tangent equal to the number you obtained in I.4:

Solar altitude = ________



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.6 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-square-centimeter's worth of sunlight.

I.7 Place a piece of white paper on the horizontal base, and draw an outline of the patch of sunlight that falls onto it.

I.8 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.9 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:

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

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.10 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.11 On the weekly **Solar Altitude Chart**, carefully plot a symbol showing the altitude (I.5) 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.12 On the weekly **Solar Intensity Chart**, carefully plot a point that shows the relative solar intensity (I.9) that was measured at the corresponding sundial time (I.1). Again, use the appropriate symbol.

I.13 On the weekly **Solar Diameter Chart**, plot your measurement of the diameter in mm (I.10) vertically for the current date (horizontal axis). (There may be as many as three points plotted in a single day from three different classes.)

I.14 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. During 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.

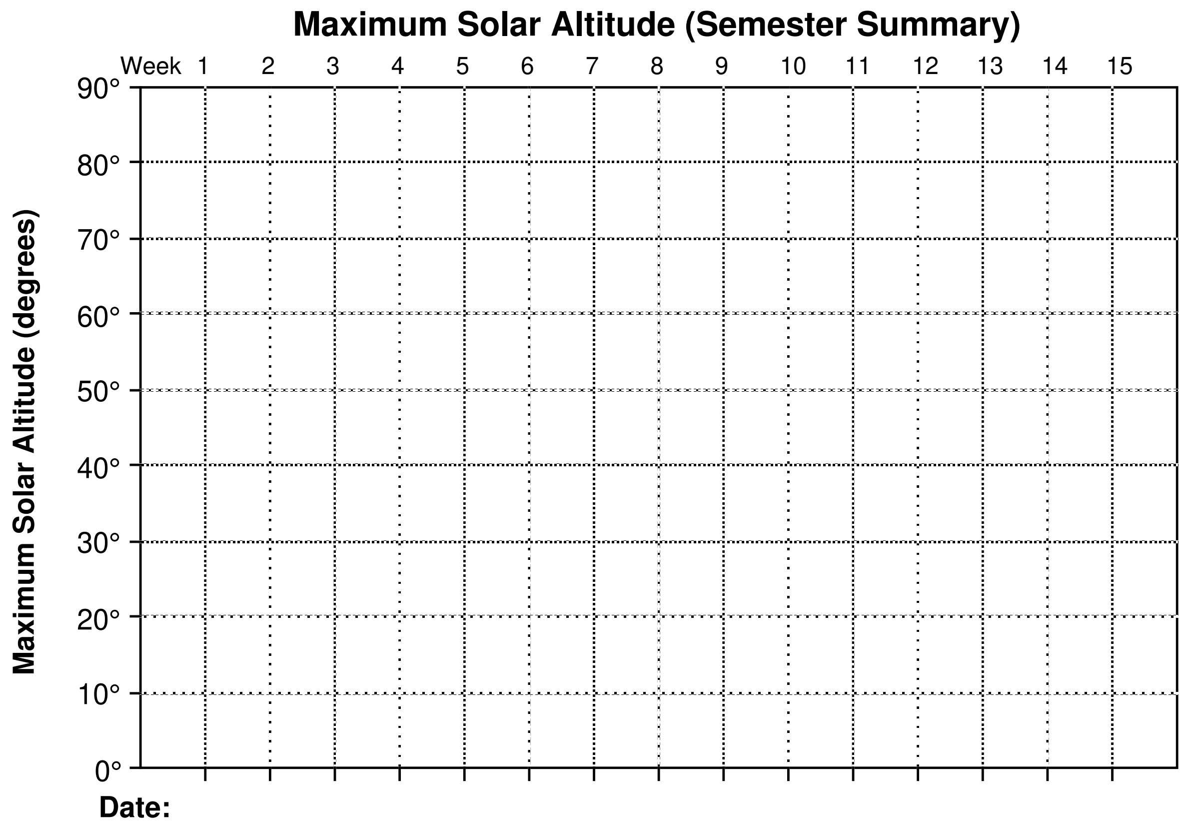
Solar Data

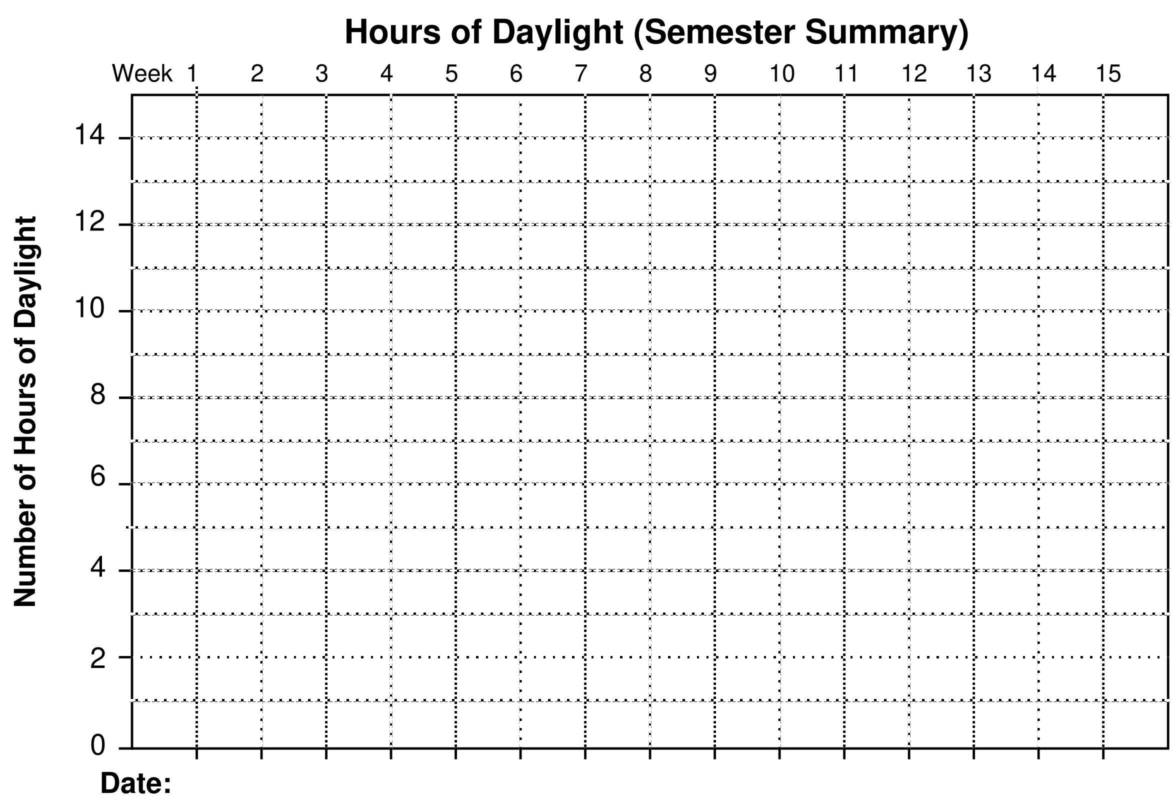
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Week #	**Date**	**Maximum Solar Altitude (deg)**	**Number of Daylight Hours**	**Maximum Solar Intensity**	**Solar Diam. (mm)**	**"Weight" of Sunlight (grams)**	**Solar-Const. Hours**	**KWH/ Meter^2 per Day**
1								
2								
3								
4								
5								
6								
7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

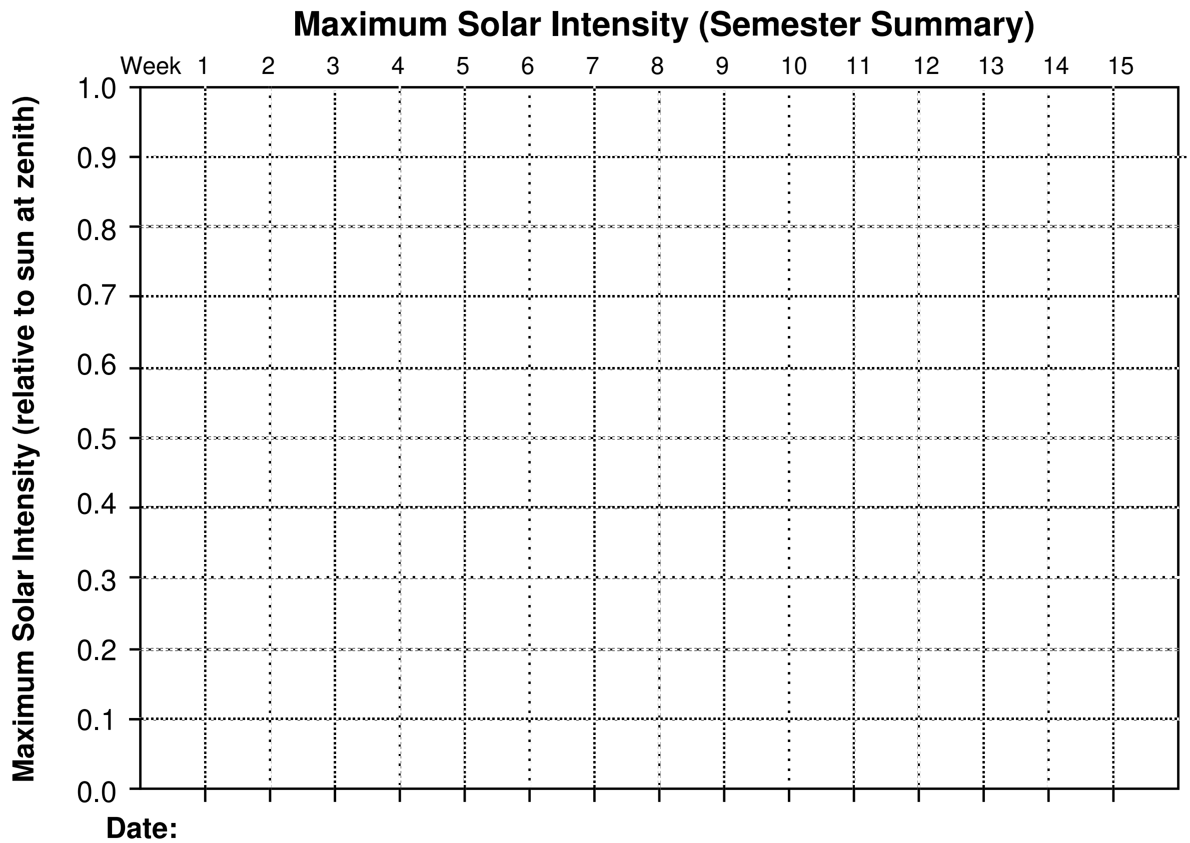
II.2 Also each week, transfer your new data from columns (a) through (e) in the table above to your own personal *semester summary graphs* on the next two pages: Maximum Solar Altitude, Hours of Daylight, Maximum Solar Intensity, and Solar Diameter. Be sure to include the appropriate date at the bottom of each chart.

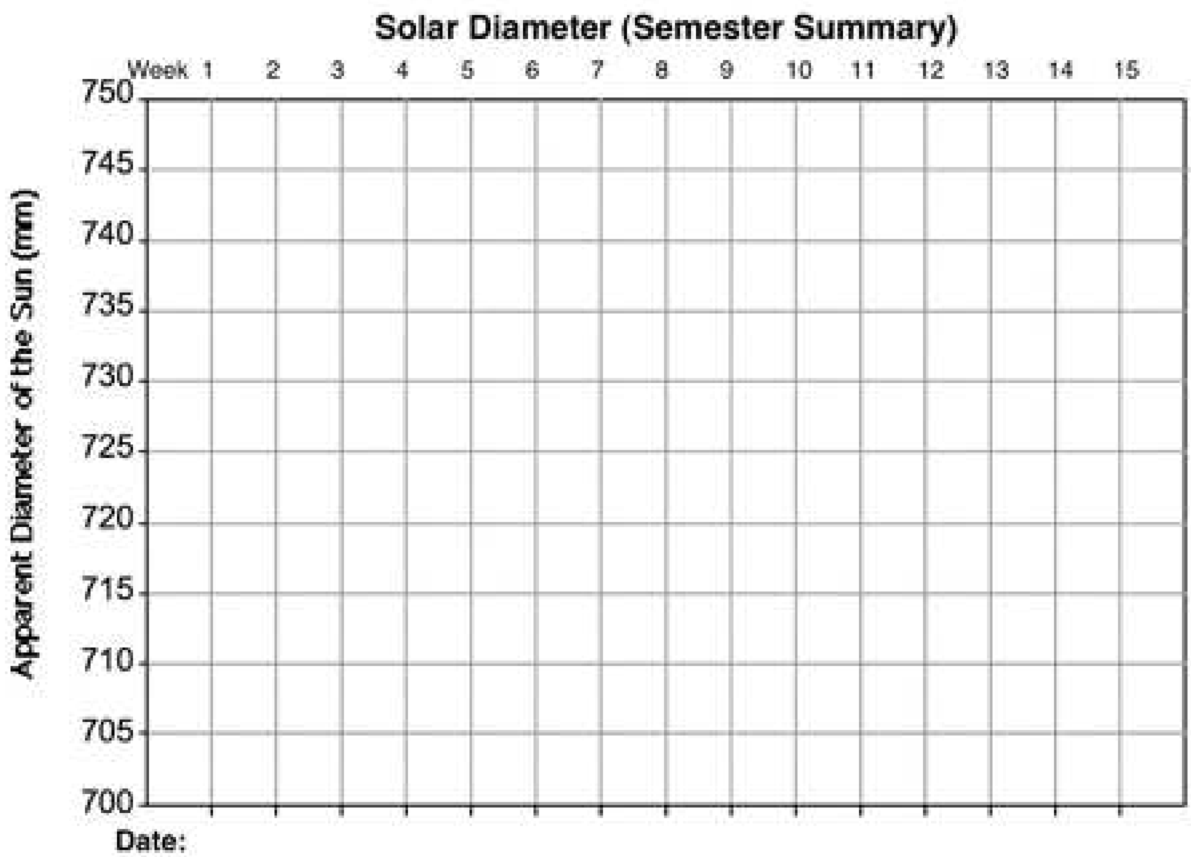
II.3 You have been elected as the head of your *Survivor* tribe. You must determine, and prove, on which day of the year the Summer Solstice occurs (but you have no written calendar). How would you do this?

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
750
745
740
735
730
725
720
715
710
705
700
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? (Consult the Solar System Calendar at the beginning of this manual for the exact date.) On that date, how many hours of daylight did we have?

Explain or sketch how we could deduce our **latitude** on the Earth, using the observed maximum altitude of the Sun on the date of the equinox. (*Hint:* see page 110.) Based on this reasoning and your measurement, what is the latitude of Boulder?

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 grown 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 one square meter on the Earth directly facing the Sun is a quantity known as the **solar constant**, which has a carefully-measured value of 1388 watts/m^2. That is, a one-square-meter 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 A simple trick for measuring an irregularly shaped area is to calibrate and weigh the paper itself! Use scissors to cut out a rectangular area corresponding to 10 solar-constant hours, and carefully weigh it on an accurate gram scale. Now calculate what *one* solar-constant hour "weighs": __________

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

To do this, cut out the shape of the area under the curve of one of the Solar Intensity Charts, weigh it as well, and 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 square meter 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 ratio 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.)

$$\frac{Final\ Week's\ KWH}{First\ Week's\ KWH} = \frac{\quad}{\quad} \times 100\% = \_\_\_\_\_\_ \quad Percent\ Change\ in\ Solar\ Energy$$

A ratio greater than 1 implies than an increase in energy was received over the semester, while a ratio smaller than 1 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?

$$\text{Diameter ratio} = \frac{Final\ Week's\ Diameter}{First\ Week's\ Diameter} = \frac{\quad}{\quad} = \_\_\_\_\_\_\_\_\_\_$$

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 (more northerly) latitude in the northern hemisphere? If we were at a lower (more southerly) latitude in the northern hemisphere? If we were at the same latitude as Boulder, but in the southern hemisphere?

DETECTING EXTRASOLAR PLANETS

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 Kepler spacecraft successfully launched and began its 3.5-year mission. The Kepler mission is NASA's first mission 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 hope to 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 Kepler's 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 the diameter 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").

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?________________

II.4 What percent of the star's light do you predict the planet will block? *Record your calculations below*.

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 Predict the effect of changing the orbital distance of the planet and record your prediction. Be as specific as possible.

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?

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! It is up to you to decide which planets to use and how to make them.

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 what types 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 ~6000 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 will monitor the brightness of more than 100,000 stars over a period of 3.5 years and be able to measure brightness changes of as little as .002%! How successful do you think Kepler will be in detecting Earth-size planets? Explain your answer. *(Note: This question is not asking if Kepler is capable of detecting Earth-size planets… the designing scientists made sure of that! This question is asking if you, personally, think the mission will be a success.)*

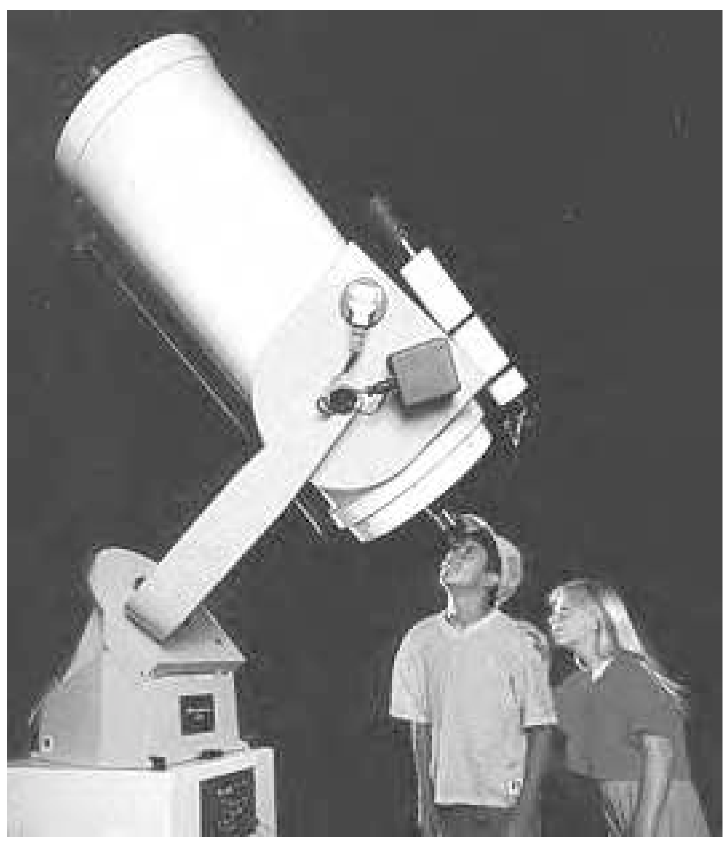
If you wish to explore the concepts a little further, your TA has modeling clay available. Create your own planets and predict what the light curve will look like. Some outcomes may surprise you! Please clean up your lab station before you leave.

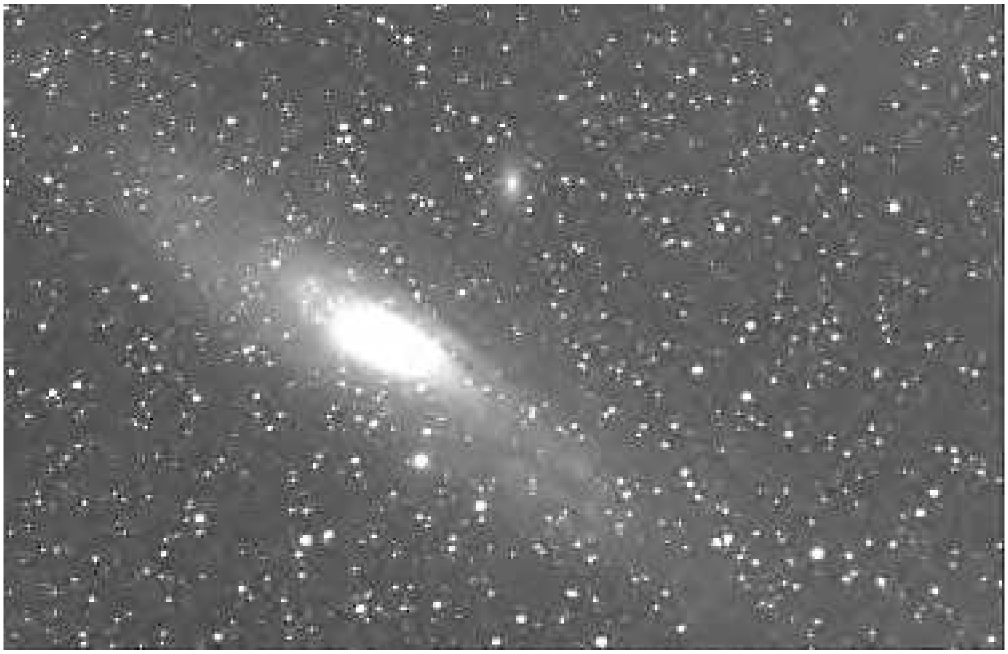
For more information on the Kepler Mission, see http://www.nasa.gov/kepler (or follow the Kepler mission on twitter at http://twitter.com/NASAKepler).

NIGHTTIME OBSERVING PROJECTS

The Moon

SBO 16” Telescope





Messier 31, the nearest Spiral Galaxy …

… acquired with the piggyback CCD imaging system mounted on the …

… SBO 18” Telescope

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 this 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:

- Independent stargazing by yourself or with a friend.
- Attending the nighttime observing sessions at the Observatory, and receiving assistance from the teaching assistant(s) or classmates.
- Attending Fiske Planetarium sessions.
- All of the above.

Observing and study tips:

- 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. It may also be possible to later take the Fiske written quiz and use it to replace your oral quiz score if you feel it will improve your grade.

- If your textbook came with a CD of planetarium software, this 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 June 15th at 11 p.m. Mountain Daylight Time, line up 10 p.m. with the June 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 II. 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, Uranus, Neptune, Pluto, Asteroids, Comets	*any planets visible in the sky (check the Celestial Calendar at the beginning of this manual)*
Ecliptic or Zodiac	*trace its path across sky*
Celestial Equator	*trace its path across the sky*
Great Andromeda Galaxy *(M31)*	*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*

The Boulder night sky

10 p.m. October 15

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 observing telescopes (the 16-inch and 18-inch) 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.

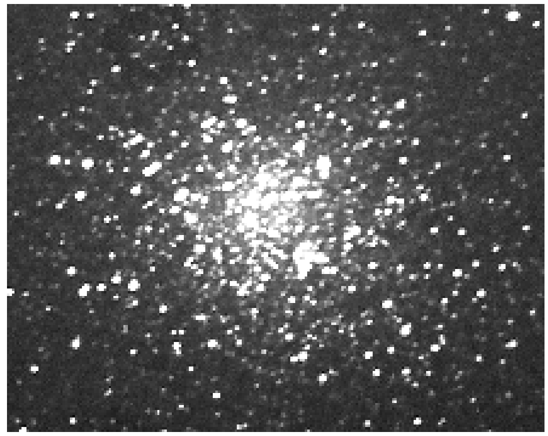
- **Double or multiple stars**. *Separation of the stars, relative brightness, orientation, and color of each component*.
- **Open clusters**. *Distribution, concentration, and relative brightness and color of the stars*.
- **Globular clusters**. *Shape, symmetry, and central condensation of stars*.
- **Diffuse nebulae**. *Shape, intensity, color, possible association with stars or clusters*.
- **Planetary nebulae**. *Shape (ring, circular, oblong, etc.), size, possible central star visible*.
- **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.



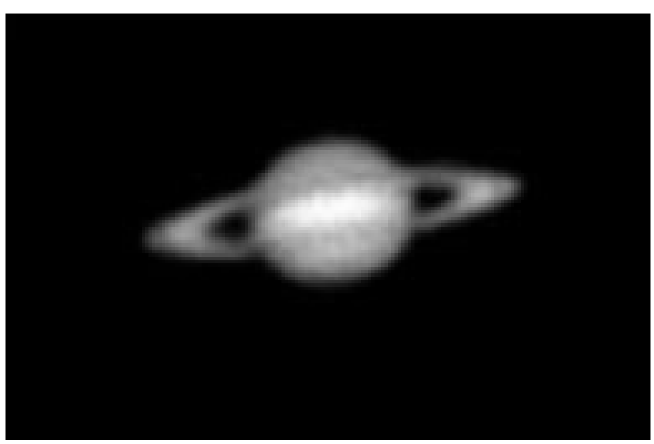
I.4 Include an "eyepiece impression" of what you observed: a brief statement of your impressions and interpretation. Feel free to draw upon comparisons (for example, "like a smoke ring," or "a little cotton ball," etc.). Express your own enthusiasm or disappointment in the view!

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
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Constellation
R.A.
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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)

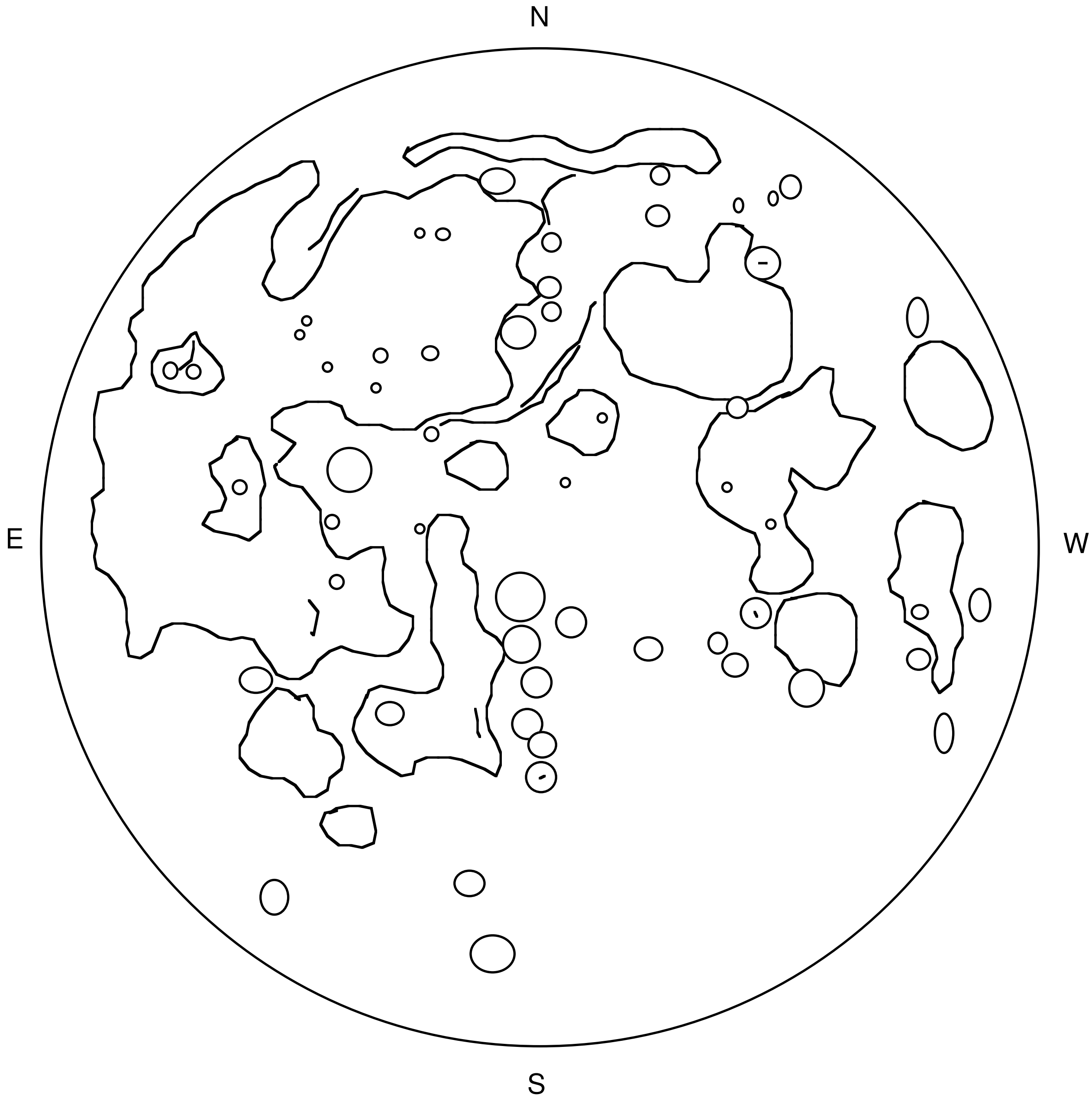
II.3 If you were standing on the Moon at the terminator, describe what event you would be experiencing.

Part III. Lunar Details

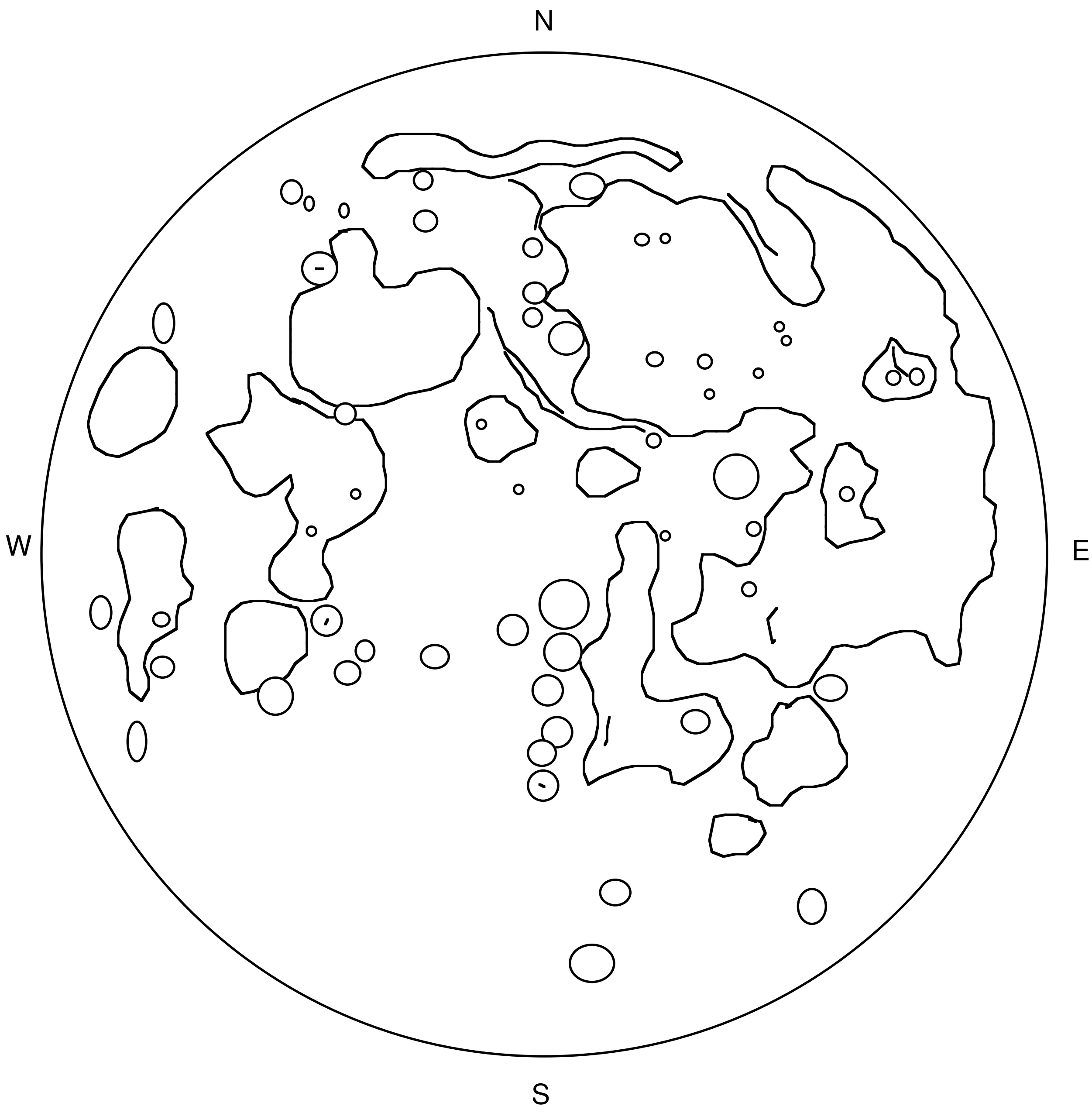
III.1 Select two lunar features of particular interest to you. Use the attached lunar sketch sheet to make a detailed pencil sketch of their telescopic appearance. Be sure to indicate their locations on an outline chart, so that you can later identify the features. (T)

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

NAME:

Object Name
Object Type
Comments

Object Name
Object Type
Comments

NAME:

Object Name
Object Type
Comments

Object Name
Object Type
Comments

INFORMATION

NAME:

ADDRESS:

TELEPHONE:

COURSE TITLE: ***ASTR 1010 - Introduction to Astronomy I***

LECTURE

Class Time:	**9:00AM Mon/Wed/Fri**
Location:	**Duane Physics G1B20**
Instructor:	**Dr. Seth Hornstein**
Office Location:	**Duane F927**
Office Hours:	**See syllabus (or course webpage)**
E-mail:	**seth.hornstein@colorado.edu**
Telephone:	**(303) 492-5631**

Lecture Teaching Assistant:	**Edward Barratt**
Office Location:	**Duane E122**
Office Hours:	**See syllabus (or course webpage)**
E-mail:	**edward.barratt@colorado.edu**
Telephone:	**(303) 492-7902**

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: