ASTRO 1030
Astronomy Lab Manual

Name: ____________________

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University of Colorado, Boulder, CO 80309

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General Information

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

Your lecture section will be held in the 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).

Your laboratory section will meet once per week in 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 Observatory telescopes to view and study the constellations, the moon, planets, stars, and other celestial objects.

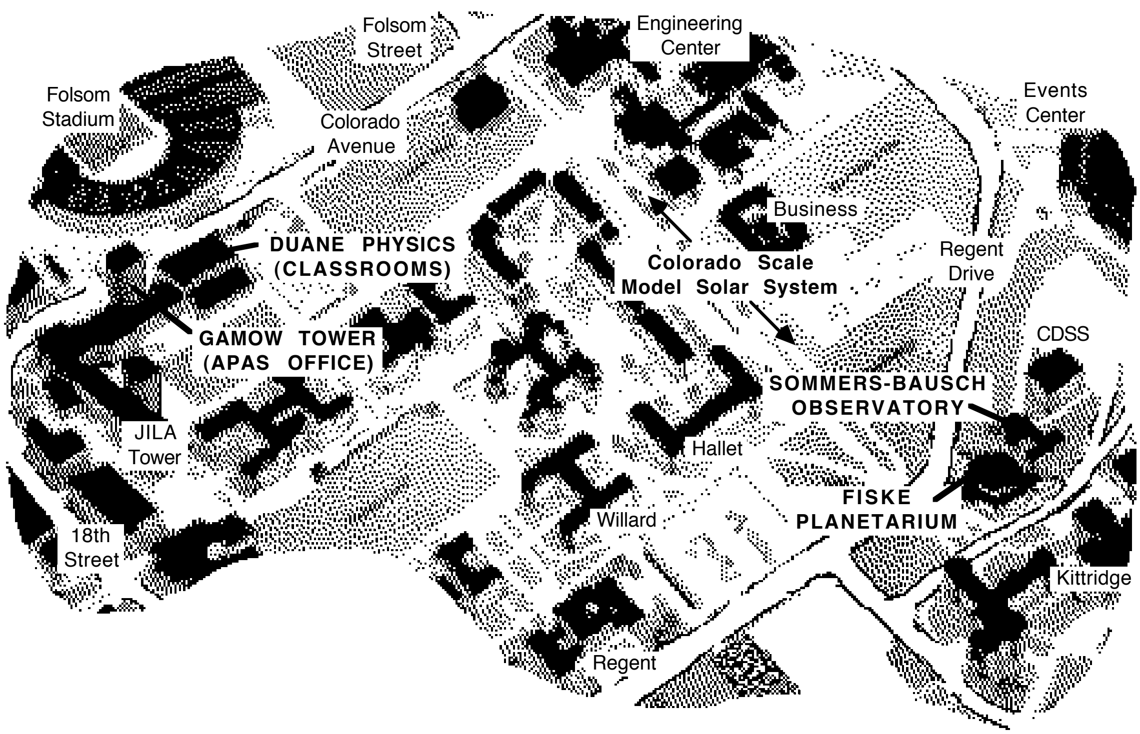


Figure 1: Map of the University.

Materials

The following materials are needed:

- APS 1030 Astronomy Lab Manual (this document). Replacement copies are available in Ac-

robat PDF format downloadable from the SBO web site (lyra.colorado.edu/sbo/manuals/manuals.html).
- Calculator. All students should have access to a scientific calculator which can perform scientific notation, exponentials, and trig functions (sines, cosines, etc.).
- A 3-ring binder to hold this lab manual and your lab notes.
- A lab notebook for your lab write-ups.
- Recommended: a planisphere, or rotating star map (available at Fiske Planetarium, the CU bookstore, other bookshops, etc.).

The Laboratory Sections

Your laboratory session will meet for one hour and fifty 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 a score 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. Rather, we concentrate on how we know what we know, and thus 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, with satellite data, or with computer images. In our laboratory we will explore both 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. Thus, 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, then you cannot complete these either.

Nighttime Observations

You are expected to attend nighttime observing labs. These are held approximately every third week at the Sommers-Bausch Observatory. 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. 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. Nighttime sessions are not necessarily cancelled if it is cloudy; an indoor exercise may be done rather than observing - check with your instructor. The telescopes are not in a heated area, so dress warmly for the night observing sessions.

Academic Dishonesty

We expect students in our classes to hold to a high ethical standard. In general we expect you, as college students, to be able to differentiate on your own between what is honest and dishonest. Nevertheless, we point out the following guideline regarding laboratory assignments:

All work turned in must be your own. You should understand all work that you write on your paper. While you will work in groups if it is helpful, you must not copy the work of someone else. We have no objection to your consulting friends for help in understanding problems. If you copy answers without understanding, however, it will be considered academic dishonesty.

Helping You Help Yourself

Astronomy uses the laws of nature that govern the universe: i.e., physics. We will cover the physics that is needed as we go along. To move beyond just the "ooooh and aaaah" of stargazing, we also need to use mathematics. We are also aware that most of you may not be particularly fond of math. You are expected, however, to be able to apply certain aspects of high school algebra and trigonometry. This manual includes a summary of the mathematics you will need. We recommend that you review it 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 outside lectures and labs for each unit of credit. Thus, for a 4-unit class, you should expect to spend an additional 8 to 12 hours per week studying. In general, if you are spending less time than this on a class, then it is either too easy for you, or you are not learning as much as you could. If you are spending more time than this, you may be studying inefficiently.

We recommend the following strategies for efficient use of your lab time:

- Review the accompanying material on units and conversions, scientific notation, math, and calculator usage. Discuss with your lab instructor any problems you have with these concepts before you need to use them. Use these sections as a reference in case you are having difficulties.
- Read the appropriate lab manual exercise before you come to lab.
- Read any background material in the textbook before you come to lab.
- Complete the whole of the lab exercise before the end of the lab period. Avoid the temptation to "wrap it up later."

Sommers-Bausch Observatory

Sommers-Bausch Observatory (SBO), on the University of Colorado campus, is operated by the Department of Astrophysical and Planetary Sciences to provide 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 would otherwise only be seen on the pages of a textbook or discussed in classroom lectures. The 16- and 18-inch telescopes on the observing deck are both under computer control, with objects selected from a library that includes double stars, star clusters, nebulae, and galaxies. In addition to the standard laboratory room, the Observatory recently added a computer lab.

The 16 and 18-inch telescopes have an additional computer interface for planetarium-style "click-and-go" pointing, and the 18-inch a charge-coupled device (CCD) electronic camera so that students can image celestial objects through an 8-inch piggyback telescope.

The 10.5-inch aperture heliostat is equipped for viewing sunspots, measuring the solar rotation, solar photography, and for studies of the solar spectrum.

The 24-inch telescope is primarily used for upper-division astronomy, graduate student training, and for research projects not feasible with larger telescopes because of time constraints or scheduling limitations. An easy-to-operate, large-format SBIG ST-8 CCD camera with focal reducer assembly is currently used for graduate and advanced undergraduate work on the 24-inch telescope.

Free Open Houses for public viewing through the 16-and 18-inch telescopes are held every Friday evening that school is in session. Students are welcome to attend. Call 492-5002 for starting times and reservations. Call 492-6732 for general astronomical information.

For additional information about the Observatory, including schedules, information on how to contact your lab instructor, and examples of images taken by other students in the introductory astronomy classes, see our website located at http://cosmos.colorado.edu/sbo/

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.

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 stars at Sommers-Bausch Observatory, weather permitting.

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

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

Alternatively, you can check out the upcoming schedules and events on the Fiske website at http://www.colorado.edu/fiske/

Units and Conversions

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

Most of the world uses a much more rational system known as the metric system (the SI, Systeme International d'Unites, "internationally agreed upon system of units") with the following fundamental units:

- The meter for length. Abbreviated "m".
- The kilogram for mass. Abbreviated "kg". Note: kilogram, not gram, is the standard.
- The second for time. Abbreviated "s".

Since the primary units are meters, kilograms and seconds, this is sometimes called the 'mks system.' Some people also use another metric system based on centimeters, grams and seconds, 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. The SI system uses prefixes to make multiples of the units. All of the prefixes represent powers of 10. Table 1 gives prefixes used in the metric system that we will use in lab, along with their abbreviations and values.

Prefix	Abbreviation	Value
micro	μ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}

Table 1: Metric Prefixes

The United States is one the few countries in the world which has not yet made a complete conversion to the metric system. As a result, you are forced to learn conversions between American and SI units, since all science and international commerce is transacted in SI units. Fortunately, converting units is not difficult. Although you can find tables listing seemingly endless conversions between American and SI units, you can do most of the lab exercises (as well as most conversions you will ever need in science, business, etc.) by using just the four conversions listed in Table 2 (along with your own recollection of the relationships between various American units).

Strictly speaking, the conversion between kilograms and pounds is valid only on the Earth since kilograms measure mass while pounds measure weight. However, since most of you will be re-

American to SI				SI to American		
1 inch	=	2.54 cm		1 m	=	39.37 inches
1 mile	=	1.609 km		1 km	=	0.6214 mile
1 pound	=	0.4536 kg		1 kg	=	2.205 pounds
1 gallon	=	3.785 liters		1 liter	=	0.2642 gallons

Table 2: Units Conversion

maining on the Earth for the foreseeable future, we will not yet worry about such details. The unit of weight in the SI system is the newton, and the unit of mass in the American 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 aren't 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 you need to use intermediate conversions to bridge between two sets of units. We offer a simple and foolproof method for handling the problem, which will always work if you don't take shortcuts.

We all know that any number multiplied by 1 equals itself, and also that the reciprocal of 1 equals 1. We can exploit these rather trivial properties by choosing our 1's carefully so that they will perform a unit conversion for us.

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; 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: 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 both the number and the units will).

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? 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 undesired units will cancel. Hence we have

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

Note that you do not omit the units, but multiply and divide them just like ordinary numbers. If you have selected a "well-chosen 1" for your conversion your units will nicely cancel, which will assure you that the numbers themselves will also have been multiplied or divided properly. That's what makes this method foolproof: if you used a "poorly-chosen 1," the expression itself will immediately let you know about it:

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

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

Example: As a passenger on the Space Shuttle, you note that the inertial navigation system shows your orbital velocity at 7,000 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 that you are no traveling fast enough?

$$7000\frac{\text{m}}{\text{s}} = 7000\frac{\text{m}}{\text{s}} \times \frac{1 \text{ km}}{1000 \text{ m}} \times \frac{1 \text{ mile}}{1.609 \text{ km}} \times \frac{60 \text{ s}}{1 \text{ min}} \times \frac{60 \text{ min}}{1 \text{ hr}}$$

$$7000\frac{\text{m}}{\text{s}} = \frac{7000 \times 1 \times 1 \times 60 \times 60}{1000 \times 1.609 \times 1 \times 1} \times \frac{\text{m} \times \text{km} \times \text{mile} \times \text{s} \times \text{min}}{\text{m} \times \text{km} \times \text{s} \times \text{min} \times \text{hr}}$$

$$7000\frac{\text{m}}{\text{s}} = 15,662\frac{\text{miles}}{\text{hour}}$$

Because of your careful analysis using "well-chosen 1's," you can conclude that you will probably not survive long enough to have to do any more unit conversions.

Temperature Scales

Scales of temperature measurement are tagged by the freezing point and boiling point of water. In the U.S., the Fahrenheit (F) system is the one commonly used: water freezes at $32°$ F and boils at $212°$ F ($180°$ F hotter). In Europe, the Celsius (C) 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 (K). The Kelvin degree is exactly the same "size" as the Celsius degree, but is based on the idea of absolute zero, the temperature at which all random molecular motions cease. 0 K is absolute zero, water freezes at 273 K and boils at 373 K. Note that the degree mark is not used with Kelvin temperatures, and the word "degree" is often not even mentioned: we say that "water boils at 373 kelvins."

To convert between these three systems, recognize that $0 \text{ K} = -273°\text{C} = -459°\text{F}$ 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:

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

Energy and Power: Joules and Watts

The SI unit of energy is called the joule. Although you may not have heard of joules before, they are simply related to other units of energy with which you probably are familiar. For example, 1 food Calorie (which actually is 1000 "normal" calories) is 4,186 joules. House furnaces are rated in btus (British thermal units), indicating how much heat energy they can produce: 1 btu = 1,054 joules. Thus, a single potato chip (having an energy content of about 9 Calories) could also be said to possess 37,674 joules or 35.7 btu's of energy.

The SI unit of power is called the watt. 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:

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

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. One potato chip contains enough energy to operate a 100-watt light bulb for over 6 minutes.

Another common unit of power is the horsepower. One hp equals 746 watts, which means that energy is consumed or produced at the rate of 746 joules per second. (In case you're curious, you can calculate (using unit conversions) that if your car has fifty "horses" 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), Table 3 contains some comparative energy outputs:

Energy Source	Energy (joules)
Big Bang	$\sim 10^{68}$
Radio Galaxy	$\sim 10^{55}$
Supernova	$\sim 10^{43}$
Sun's Radiation over 1 year	$\sim 10^{34}$
Volcanic Explosion	$\sim 10^{19}$
H-Bomb	$\sim 10^{17}$
Thunderstorm	$\sim 10^{15}$
Lightening Flash	$\sim 10^{10}$
Baseball Pitch	$\sim 10^{2}$
Hitting Keyboard Key	$\sim 10^{-2}$
Hop of a Flea	$\sim 10^{-7}$

Table 3: Examples of Energy

Scientific Notation

Scientific Notation: What is it?

Astronomers deal with quantities ranging from the truly microscopic to the macrocosmic. It is 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. To save effort, powers-of-ten notation is used. For example, $10 = 10^1$. The exponent tells you how many times to multiply by 10. As another example, $10^{-2} = 1/100 = 0.01$. 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 $10^0 = 1$. 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 $x \times 10^n$, where x must be between 1 and 10, and n must be an integer. Thus, for example, these are not in scientific notation: 34×10^5 or 4.8×100.5.
- If the number 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.
- If the number is a power of 10, then it is not necessary to write that it is multiplied by 1. For example, the number 100 is written in scientific notation as 10^2, and not 1×10^2.

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 $\$3 \times 10^{12}$ rather than as \$3,000,000,000,000.
- 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. 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 convert 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 in 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: $(9 \times 10^8)/(3 \times 10^6) = (9/3) \times (10^8/10^6) = 3 \times 10^{8-6} = 3 \times 10^2$.

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 5795×326. 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 see immediately 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 problem 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 will change anyway 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 can't 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: $C = (2 \times \pi \times R)$. Since the value of pi stored in your calculator is probably 3.141592654, the numerical solution will be $(2 \times 3.141592654 \times 5.23$ cm$) = 32.86105916 = 3.286105916 \times 10^1$ cm.

If you simply write down all 10 digits as your answer, you are implying that you know, with absolute certainty, the circles circumference to an accuracy of one part in 10 billion! That would mean that your measurement of the radius was in error by no more than 0.000000001 cm; that is, its true value was at least 5.229999999 cm, but no more than 5.230000001 cm (otherwise, your calculator would have shown a different number for the circumference).

In reality, since your measurement of the radius was known to only three decimal places, the circles 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 its an honest representation of what you know about the figure.

Since the value of "2" was used in the formula, you may wonder why we're 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, we could have represented the number as 2.0000000000000000000, but merely used the shorthand "2" for simplicity - so we really didn't 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 equals 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 ('): we can write 3 arcminutes as 3'. Therefore there are $360 \times 60 = 21,600$ arcminutes in a full circle.
- There are 60 seconds of arc in one arcminute. The shorthand for arcsecond is the double prime ("): we can write 3 arcseconds as 3". Therefore there are 21,600 $\times 60$ $=$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 subtended by that radius is defined to be an angle of one radian.

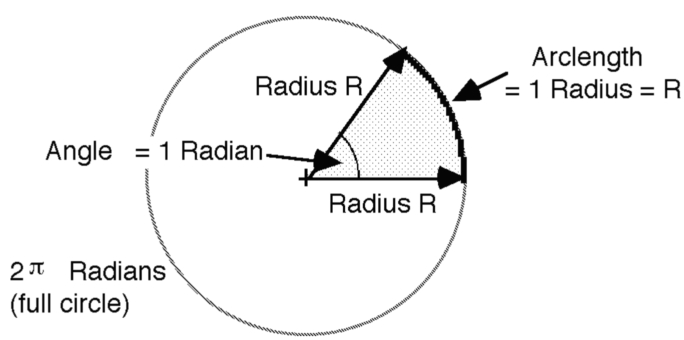


Figure 2: Relation of a radian to an arclength.

Since the circumference of a circle has a total length of 2πR, we can fit exactly 2π radii (6 full lengths plus a little over 1/4 of an additional) 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 subtended arclength of a circle 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 numerically equals the actual curved distance along the portion of its circumference cut by the angle.

The conversion between radians and degrees is

$$1 \text{ radian} = \frac{360}{2\pi} \text{ degrees} = 57.3^\circ \qquad 1^\circ = \frac{2\pi}{360} \text{ radians } = 0.017453 \text{ radians}$$

Trigonometric Functions: In this course we will make occasional use of the basic trigonometric functions: sine, cosine, and tangent. Here is a quick review of the basic concepts.

In any right triangle (one angle is 90°), the longest side is called the hypotenuse and 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 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."

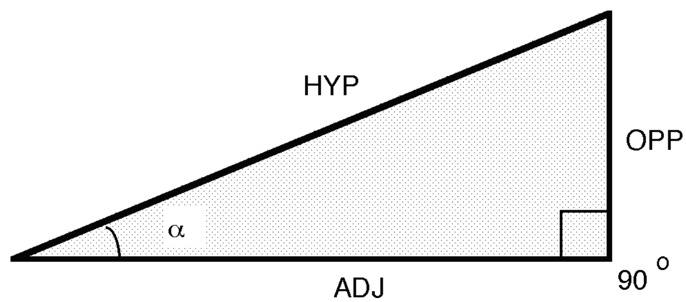


Figure 3: Right Triangle.

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

$$(opp)^2 + (adj)^2 = (hyp)^2$$

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

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

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 field of view, and as you back away from the building it will occupy a smaller and smaller angular size, even though the buildings 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 10 km away. How can we determine the actual physical size (height) of the building?

We imagine we are standing with our eye at the apex of a triangle, from which point the building subtends an angle α = 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.

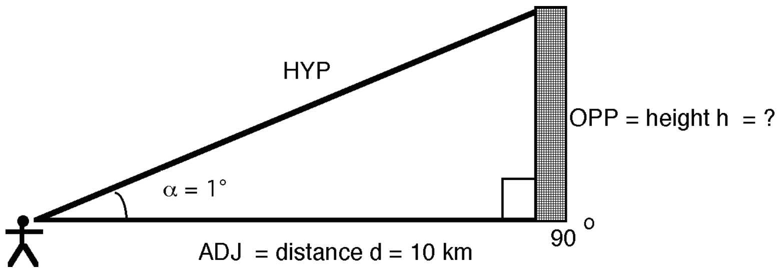


Figure 4: Diagram of a man and a wall.

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

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

which we can reorganize to give

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

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 us and the building. It should be apparent, however, that since we are 10 km away, the distance to the top of the building will only be 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.

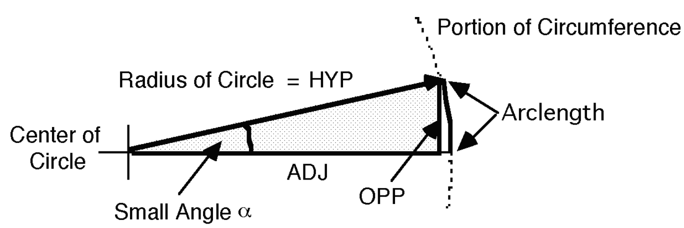


Figure 5

Now imagine that the apex of a small angle α is located at the center of a circle whose radius is equal to the hypotenuse of the triangle, as shown above. The arclength of the circumference subtended 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 subtending angle is small.

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

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

Since the angle is small, the opposite side is approximately equal to the "arclength" subtended 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:

$$h = d \times \frac{(arclength)}{(radius)}$$

But remember that the ratio (arclength)/(radius) is the definition of an angle expressed in radian units rather than degrees - so we 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

$$h = d \times (\text{angular size in radians})$$

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

$$h = d \times \frac{2\pi}{360^\circ} \times \alpha$$

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 didnt require trigonometry, just multiplication and division.

When can the approximation be used? Surprisingly, the angles dont 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: We say that b^n is the "nth power of b," or "b to the n (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, as you know, 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 Experiment**: 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: $4^{-2} = 1/42 = 1/16$; $10^{-3} = 1/10^3 = 1/1000$; $3/2^{-2} = 3 \times 2^2 = 12$
- **Fractional Exponent**: A fractioanl 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: $8^{1/3} = \sqrt[3]{8} = 2$; $8^{2/3} = \left(\sqrt[3]{8}\right)^2 = 2^2 = 4$; $2^{4/2} = \sqrt{2^4} = \sqrt{16} = 4$; $x^{1/4} = \left(x^{1/2}\right)^{1/2} = \sqrt{\sqrt{x}}$

Celestial Coordinates

Geographic Coordinates: The Earth's geographic coordinate system is familiar to everyone - the north and south poles are defined by the Earth's axis of rotation; equidistant between them is the equator. North-south latitude is measured in degrees from the equator, ranging from $-90°$ at the south pole, $0°$ at the equator, to $+90°$ at the north pole. East-west distances are also measured in degrees, but there is no "naturally-defined" starting point - all longitudes are equivalent to all others. Humanity has arbitrarily defined the prime meridian ($0°$ longitude) to be that of the Royal Observatory at Greenwich, England (alternately called the Greenwich meridian).

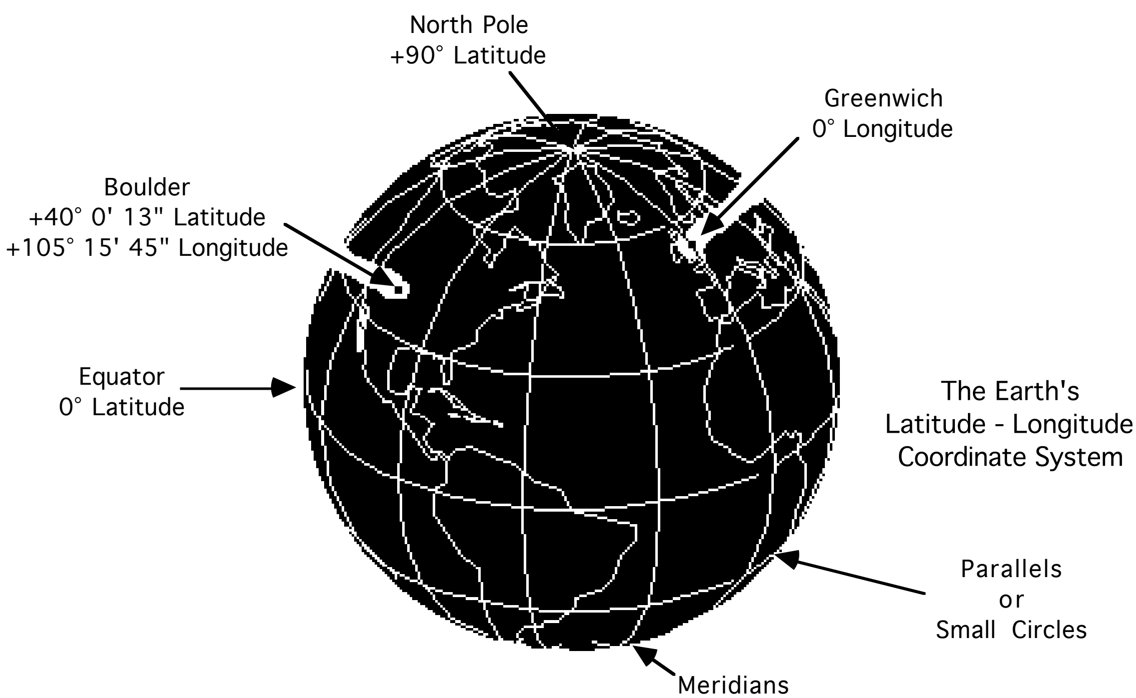


Figure 6: Geographic Coordinates of the Earth.

Each degree (°) of a $360°$ circle can be further subdivided into 60 equal minutes of arc ($'$), and each arc-minute may be divided into 60 seconds of arc ($''$). The 24-inch telescope at Sommers-Bausch Observatory is located at a latitude $40°0'13''$ North of the equator and at a longitude $105°15'45''$ West of the Greenwich meridian.

Alt-azimuth Coordinates: The alt-azimuth (altitude - azimuth) coordinate system, also called the horizon system, is a useful and convenient system for pointing out a celestial object.

One first specifies the azimuth angle, which is the compass heading towards the horizon point lying directly below the object. Azimuth angles are measured eastward from North ($0°$ azimuth) to East ($90°$), South ($180°$), West ($270°$), and back to North again ($360° = 0°$). The four principle directions are called the cardinal directions.

Next, the altitude is measured in degrees upward from the horizon to the object. The point directly overhead at $90°$ altitude is called the zenith. The nadir is "down," or opposite the zenith. We sometimes use zenith distance instead of altitude, which is $90°$ - altitude.

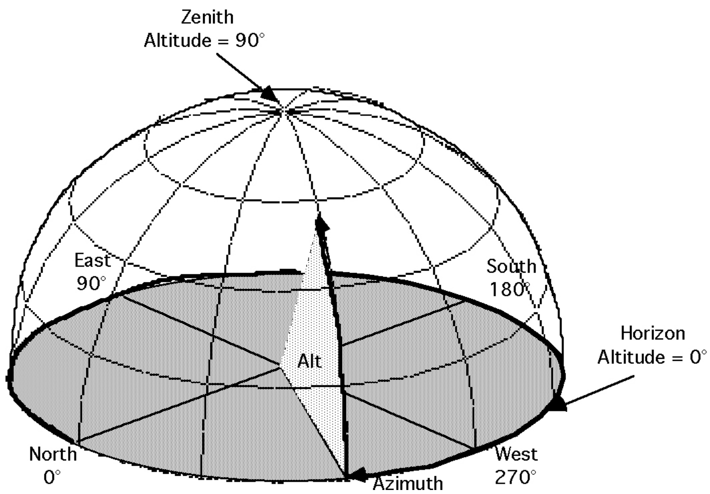


Figure 7: Alt-azimuth Coordinates.

Every observer on Earth has his own separate alt-azimuth system. Thus, the coordinates of the same object will differ for two different observers. Furthermore, because the Earth rotates, the altitude and azimuth of an object are constantly changing with time as seen from a given location. Hence, this system can identify celestial objects at a given time and location, but is not useful for specifying their permanent (more or less) direction in space.

In order to specify a direction by angular measure, you need to know just how "big" angles are. Here's a convenient "yardstick" to use that you carry with you at all times: the hand, held at arm's length, is a convenient tool for estimating angles subtended at the eye:

Equatorial Coordinates Standing outside on a clear night, it appears that the sky is a giant celestial sphere of indefinite radius with us at its center, and upon which stars are affixed to its inner surface. It is extremely useful for us to treat this imaginary sphere as an actual, tangible surface, and to attach a coordinate system to it.

The system used is based on an extension of the Earth's axis of rotation, hence the name equatorial coordinate system. If we extend the Earth's axis outward into space, its intersection with the celestial sphere defines the north and south celestial poles. Equidistant between them, and lying directly over the Earth's equator, is the celestial equator. Measurement of "celestial latitude" is given the name declination (DEC), but is otherwise identical to the measurement of latitude on the Earth: the declination at the celestial equator is $0°$ and extends to $\pm 90°$ at the celestial poles.

The east-west measure is called right ascension (RA) rather than "celestial longitude," and differs from geographic longitude in two respects. First, the longitude lines, or hour circles, remain fixed with respect to the sky and do not rotate with the Earth. Second, the right ascension circle is divided into time units of 24 hours rather than in degrees; each hour of angle is equivalent to $15°$

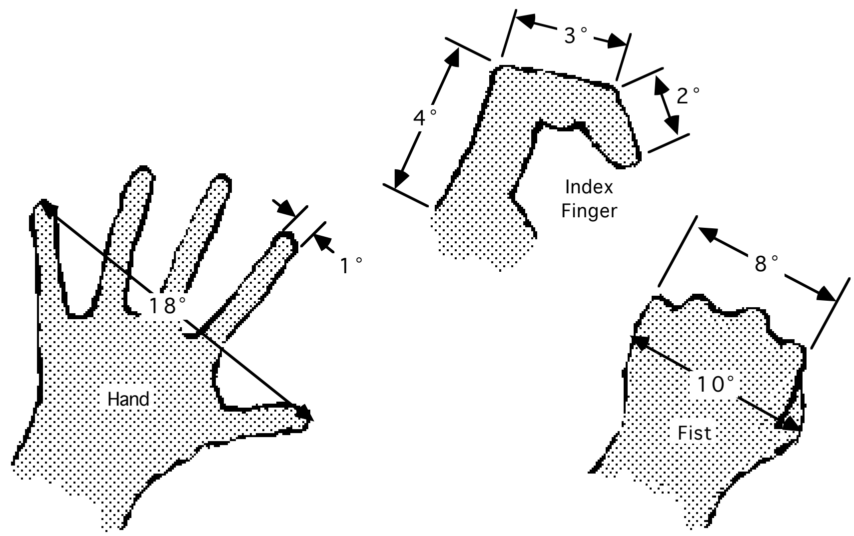


Figure 8: Measuring angles with your hands at arms length.

of arc. The following conversions are useful:

$$\begin{array}{rl} 24\text{ h} = 360^\circ & \quad 1\text{ m} = 15' \\ 1\text{ h} = 15^\circ & \quad 4\text{ s} = 1' \\ 4\text{ m} = 1^\circ & \quad 1\text{ s} = 15'' \end{array}$$

The Earth orbits the Sun in a plane called the ecliptic. From our vantage point, however, it appears that the Sun circles us once a year in that same plane; hence, the ecliptic may be alternately defined as ”the apparent path of the Sun on the celestial sphere”.

The Earth's equator is tilted 23.5° from the plane of its orbital motion, or in terms of the celestial sphere, the ecliptic is inclined 23.5° from the celestial equator. The ecliptic crosses the equator at two points; the first, called the vernal (spring) equinox, is crossed by the Sun moving from south to north on about March 21st, and sets the moment when spring begins. The second crossing is from north to south, and marks the autumnal equinox six months later. Halfway between these two points, the ecliptic rises to its maximum declination of +23.5° (summer solstice), or drops to a minimum declination of -23.5° (winter solstice).

As with longitude, there is no obvious starting point for right ascension, so astronomers have assigned one: the point of the vernal equinox. Starting from the vernal equinox, right ascension increases in an eastward direction until it returns to the vernal equinox again at 24 h = 0 h. The Earth precesses, or wobbles on its axis, once every 26,000 years. Unfortunately, this means that the Sun crosses the celestial equator at a slightly different point every year, so that our “fixed” starting point changes slowly - about 40 arc-seconds per year. Although small, the shift is cumulative, so that it is important when referring to the right ascension and declination of an object to also specify the epoch, or year in which the coordinates are valid.

Time and Hour Angle: The fundamental purpose of all timekeeping is, very simply, to enable us to keep track of certain objects in the sky. Our foremost interest, of course, is with the location of the Sun, which is the basis for the various types of solar time by which we schedule our lives.

Time is determined by the hour angle of the celestial object of interest, which is the angular distance

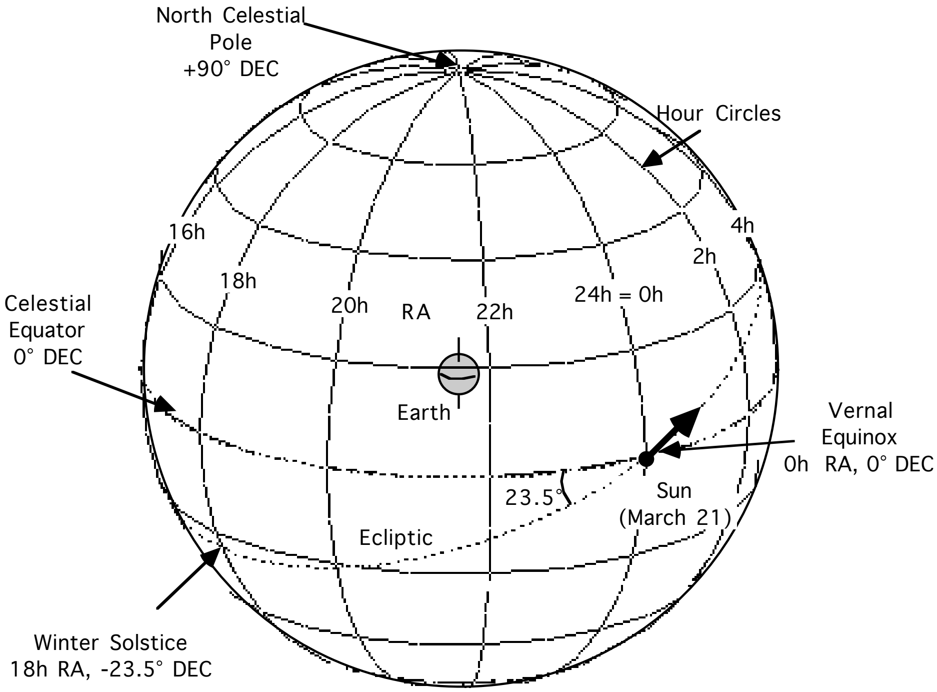


Figure 9: Equatorial Coordinates.

from the observer's meridian (north-south line passing overhead) to the object, measured in time units east or west along the equatorial grid. The hour angle is negative if we measure from the meridian eastward to the object, and positive if the object is west of the meridian.

For example, our local apparent solar time is determined by the hour angle of the Sun, which tells us how long it has been since the Sun was last on the meridian (positive hour angle), or how long we must wait until noon occurs again (negative hour angle).

If solar time gives us the hour angle of the Sun, then sidereal time (literally, "star time") must be related to the hour angles of the stars: the general expression for sidereal time is

$$\text{Sidereal Time} = \text{Right Ascension} + \text{Hour Angle}$$

which holds true for any object or point on the celestial sphere. Its important to realize that if the hour angle is negative, we add this negative number, which is equivalent to subtracting the positive number.

For example, the vernal equinox is defined to have a right ascension of 0 hours. Thus the equation becomes

$$\text{Sidereal time} = \text{Hour angle of the vernal equinox}$$

Another special case is that for an object on the meridian, for which the hour angle is zero by definition. Hence the equation states that

$$\text{Sidereal time} = \text{Right ascension crossing the meridian}$$

Your current sidereal time, coupled with a knowledge of your latitude, uniquely defines the appearance of the celestial sphere. Furthermore, if you know any two of the variables in the expression ST = RA + HA, you can determine the third.

Figure 10 shows the appearance of the southern sky as seen from Boulder at a particular instant in time. Note how the sky serves as a clock - except that the clock face (celestial sphere) moves while the clock "hand" (meridian) stays fixed. The clock face numbering increases towards the east, while the sky rotates towards the west; hence, sidereal time always increases, just as we would expect. Since the left side of the ST equation increases with time, then so must the right side; thus, if we follow an object at a given right ascension (such Saturn or Uranus), its hour angle must constantly increase (or become less negative).

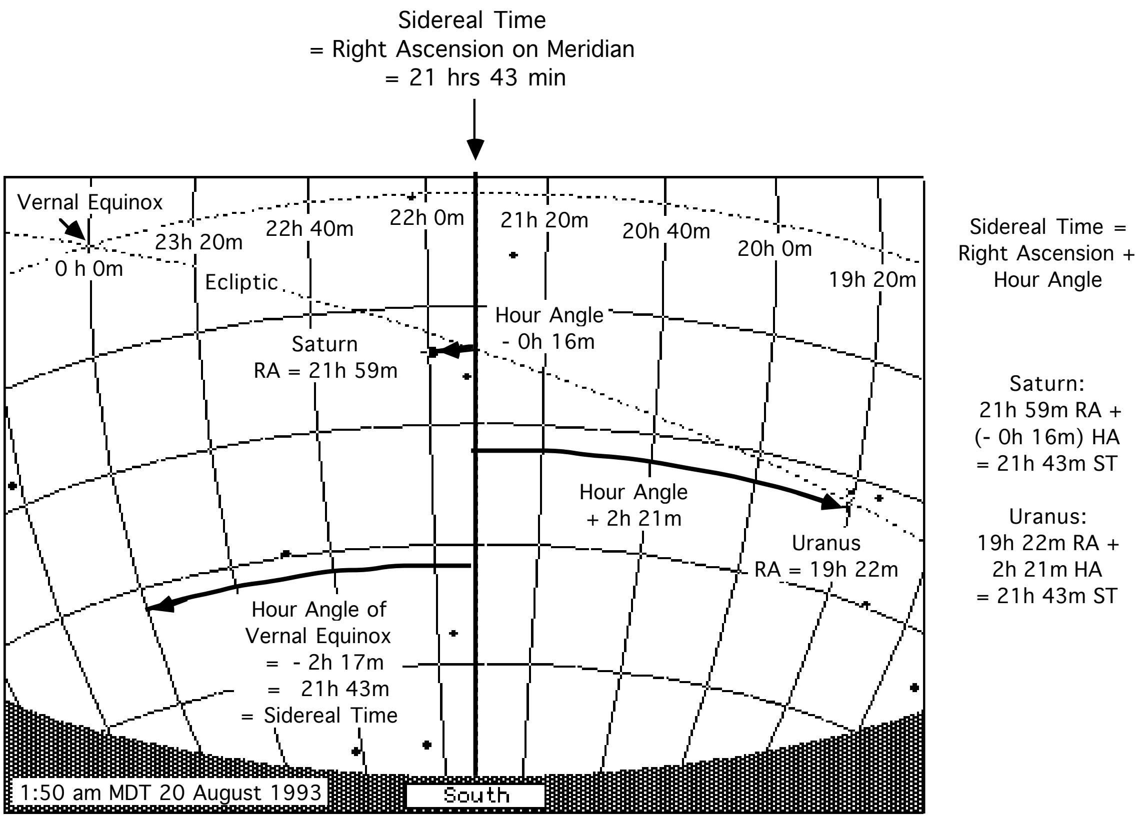


Figure 10: Demonstration of hour angles.

Solar Versus Sidereal Time: Every year the Earth actually makes $366\ 1/4$ complete rotations with respect to the stars (sidereal days). Each day the Earth also revolves about $1°$ about the Sun, so that after one year, it has "unwound" one of those rotations with respect to the Sun. On the average, we observe $365\ 1/4$ solar passages across the meridian (solar days) in a year. Since both sidereal and solar time use 24-hour days, the two clocks must run at different rates. The following compares (approximate) time measures in each system:

Solar	Sidereal	Solar	Sidereal
365.25 days	366.25 days	24 hours	24h 3m 56s
1 day	1.00274 d	23 h 56m 4s	24 hours
0.99727 d	1 day	6 minutes	6m 1s

The difference between solar and sidereal time is one way of expressing the fact that we observe different stars in the evening sky during the course of a year. The easiest way to predict what the sky will look like (i.e., determine the sidereal time) at a given date and time is to use a planisphere, or star wheel. However, it is possible to estimate the sidereal time to within a half-hour or so with just a little mental arithmetic.

At noontime on the date of the vernal equinox, the solar time is 12h (since we begin our solar day at midnight) while the sidereal time is 0h (since the Sun is at 0h RA, and is on our meridian). Hence, the two clocks are exactly 12 hours out of synchronization (for the moment, we will ignore the complication of "daylight savings"). Six months later, on the date of the autumnal equinox (about September 22) the two clocks will agree exactly for a brief instant before beginning to drift apart, with sidereal time gaining about 1 second every six minutes.

For every month since the last fall equinox, sidereal time gains 2 hours over solar time. We simply count the number of elapsed months, multiply by 2, and add the time to our watch (converting to a 24-hour system as needed). If daylight savings time is in effect, we subtract 1 hour from the result to get the sidereal time.

For example, suppose we wish to estimate the sidereal time at 10:50 p.m. Mountain Daylight Time on August the 19th. About 11 months have elapsed since fall began, so sidereal time is ahead of standard solar time by 22 hours - or 21 hours ahead of daylight savings time. Equivalently, we can say that sidereal time lags behind daylight time by 3 hours. 10:50 p.m. on our watch is 22h 50 m on a 24-hour clock, so the sidereal time is 3 hours less: ST = 19h 50m (approximately).

Envisioning the Celestial Sphere: With time and practice, you will begin to "see" the imaginary grid lines of the alt-azimuth and equatorial coordinate systems in the sky. Such an ability is very useful in planning observing sessions and in understanding the apparent motions of the sky. To help you in this quest, we've included four scenes of the celestial sphere showing both alt-azimuth and equatorial coordinates. Each view is from the same location (Boulder) and at the same time and date used above (10:50 p.m. MDT on August 19th, 1993). As we comment on each, we'll mention some important relationships between the coordinate systems and the observer's latitude.

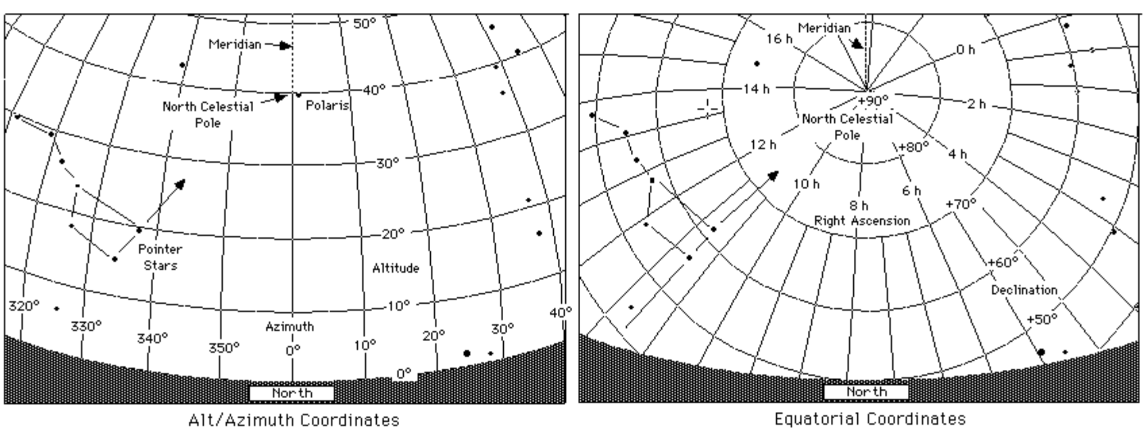


Figure 11: Looking at the northern sky.

Looking North: From Boulder, the altitude of the north celestial pole directly above the North cardinal point is $40°$, exactly equal to Boulder's latitude. This is true for all observing locations:

$$\text{Altitude of the pole} = \text{Latitude of observer}$$

The $+50°$ declination circle just touches our northern horizon. Any star more northerly than this will be circumpolar - that is, it will never set below the horizon.

$$\text{Declination of northern circumpolar stars} > 90° - \text{Latitude}$$

Most of the Big Dipper is circumpolar. The two pointer stars of the dipper are useful in finding Polaris, which lies only about 1/2 from the north celestial pole. Because these two stars always point towards the pole, they must both lie approximately on the same hour circle, or equivalently, both must have approximately the same right ascension (11 hours RA).

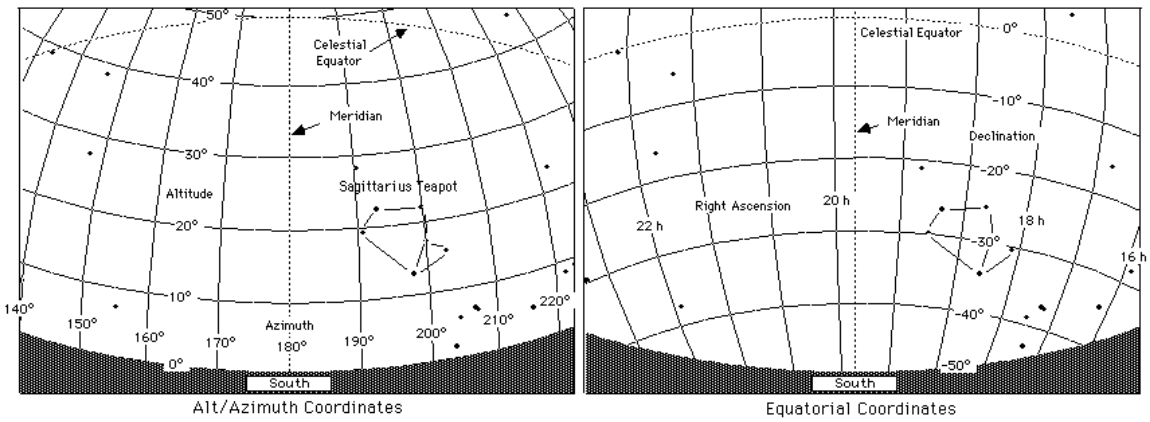


Figure 12: Looking at the southern sky.

Looking South: If you were standing at the north pole, the celestial equator would coincide with your local horizon. As you travel the 50° southward to Boulder, the celestial equator will appear to tilt up by an identical angle; that is, the altitude of the celestial equator above the South cardinal point is 50° from the latitude of Boulder. Your local meridian is the line passing directly overhead from the north to south celestial poles, and hence coincides with 180° azimuth. Generally speaking, then,

$$\text{Altitude of the intersection of the celestial equator with the meridian} = 90^\circ - \text{Latitude}$$

Since the celestial equator is 50° above our southern horizon, any star with a declination less than -50° is circumpolar around the south pole, and will never be seen from Boulder.

$$\text{Declination of southern circumpolar stars} = \text{Latitude} - 90^\circ$$

The sidereal time (right ascension on the meridian) is 19h 43m - only 7 minutes different from our estimate.

Looking East: The celestial equator meets the observer's local horizon exactly at an azimuth of 90°. This is always true, regardless of the observer's latitude:

The celestial equator always intersects the east and west cardinal points

At the intersection point, the celestial equator makes an angle of 50° with the local horizon. In general,

$$\text{The intersection angle between celestial equator and horizon} = 90^\circ - \text{Latitude}$$

Our view of the eastern horizon at this particular time includes the Great Square of Pegasus, which is useful for locating the point of the vernal equinox. The two easternmost stars of the Great Square both lie on approximately 0 hours of right ascension. The vernal equinox lies in the constellation of Pisces about 15° south of the Square.

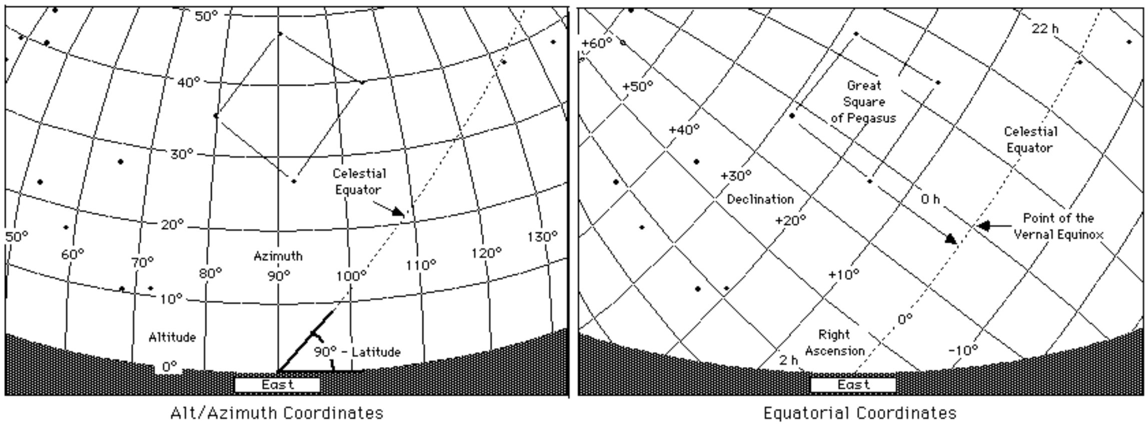


Figure 13: Looking at the eastern sky.

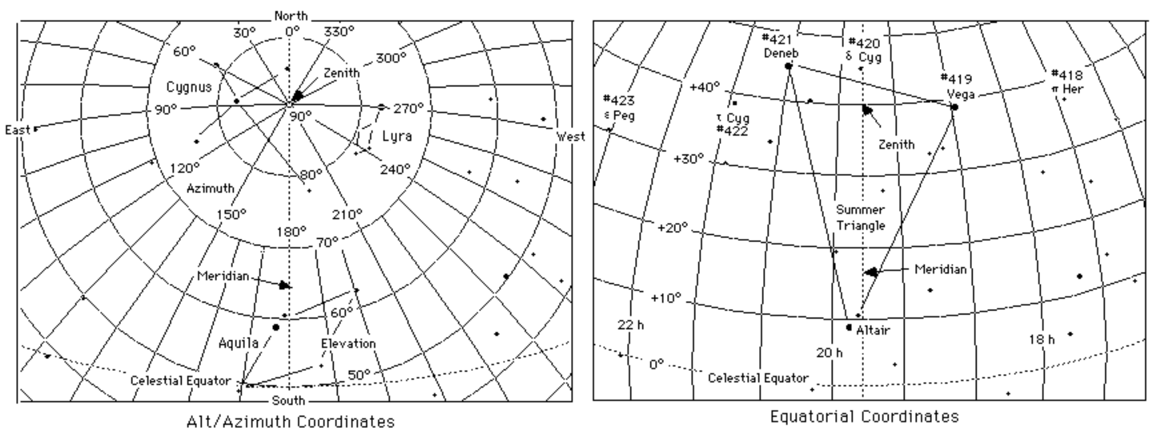


Figure 14: Looking at the zenith sky.

Looking Up: From a latitude of 40°, an object with a declination of +40° will, at some point in time during the day or night, pass directly overhead through the zenith. In general

$$\text{Declination at zenith} = \text{Latitude of observer}$$

The 24 Ephemeris Stars in the SBO Catalog of Astronomical Objects have Object Numbers ranging from #401 to #424. Each of these moderately-bright stars passes near the zenith (within 10 or so) over the course of 24 hours. At any time, the ephemeris star nearest the zenith will usually be the star whose last two digits equals the sidereal time (rounded to the nearest hour). For example, at the current sidereal time (19h 43m), the zenith ephemeris star is #420 (δ Cygni).

At the time of the year assumed in this example (late summer), and at this time of night (mid-evening), the three prominent stars of the Summer Triangle are high in the sky: Vega (in Lyra the lyre), Deneb (at the tail of Cygnus the swan), and Altair (in Aquila the eagle). However, the Summer Triangle is not only high in the sky in summer, but at any period during the year when the sidereal time equals roughly 20 hours: just after sunset in October, just before sunrise in May, and even around noontime in January (though it won't be visible because of the Sun).

Telescopes & Observing

Telescope Types: Telescopes come in two basic types: the refractor, which uses a lens as its primary or objective optical element, and the reflector, which uses a mirror. In either case, light originating from an object (usually at infinity) is brought to a focus within the telescope to form an image of the object. The size of a telescope refers to the diameter its primary lens or mirror, rather than its length.

By placing photographic film at the focal plane, the objective lens or mirror forms a camera system. If instead, we position an eyepiece lens at an appropriate distance behind the focal plane, we form an optical telescope.

The optical arrangement of a refracting telescope is shown below. The image is formed by the refraction of light through the lens. The refractor has an advantage over reflectors in that there is no central obscuration to produce diffraction patterns, and therefore yields crisper images. However, refraction introduces chromatic aberration, which is corrected by using two-element (doublet or achromat) or three-element (apochromat) lenses. The lens complexity makes the refractor very expensive. Hence, refractors are much smaller in diameter than comparably-priced reflectors. All of the Sommers-Bausch Observatory (SBO) finder telescopes are of the refractor type.

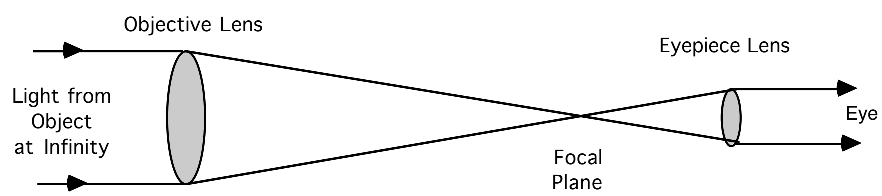


Figure 15: Refractor telescope.

A reflecting telescope focusses and redirects light back towards the incident direction, and therefore requires additional optics to get the image "out of the way". This central obscuration reduces the amount of light reaching the primary, and adds diffraction patterns that degrade the resolution. However, the telescope does not suffer from chromatic aberration, since only mirrors are used. Reflectors can be built much larger since the mirror is supported from behind (while a lens is mounted only at its edges). Furthermore, only one objective surface must be ground and polished, making the reflector much less expensive. As a result, virtually all large telescopes are of the reflector type.

The Newtonian (invented by Sir Isaac Newton) is the simplest form of reflector. It uses a diagonal mirror (a plane mirror tilted at a 45° angle) to re-direct the light out the side of the telescope to the eyepiece. The placement of the eyepiece at the "wrong" end of the telescope limits it practical size, and its asymmetric design precludes the use of heavy instrumentation. The Newtonian is used primarily by amateur astronomers since it is the "cleanest" as well as least expensive reflector.

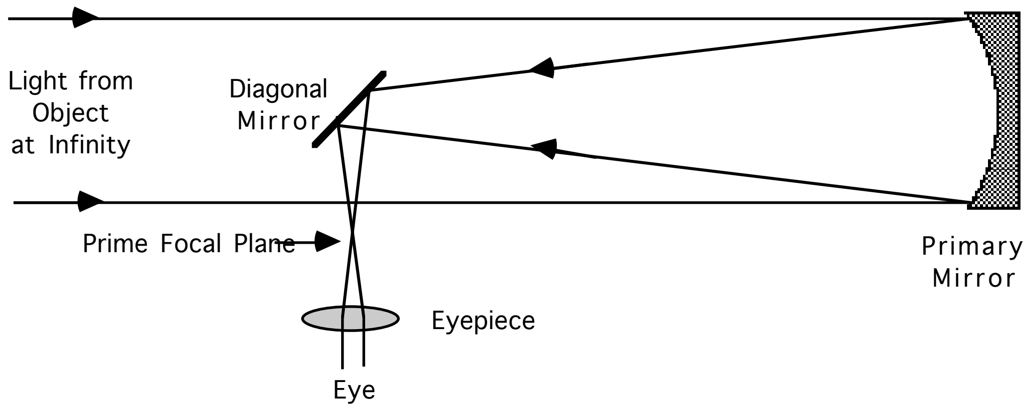


Figure 16: Newtonian telescope.

In the Cassegrain reflector, a convex secondary mirror intercepts the light from the primary and reflects it back again, reducing the convergence angle in the process. The light passes through a central hole in the primary and comes to a focus at the back of the telescope. The location of the Cassegrain focus makes it easy to mount instrumentation, and the folded optical design permits larger diameter telescopes to be houses within smaller domes; hence this design is most widely-used at professional observatories. All three of the permanently-mounted SBO telescopes (16", 18", 24") are Cassegrain reflectors.

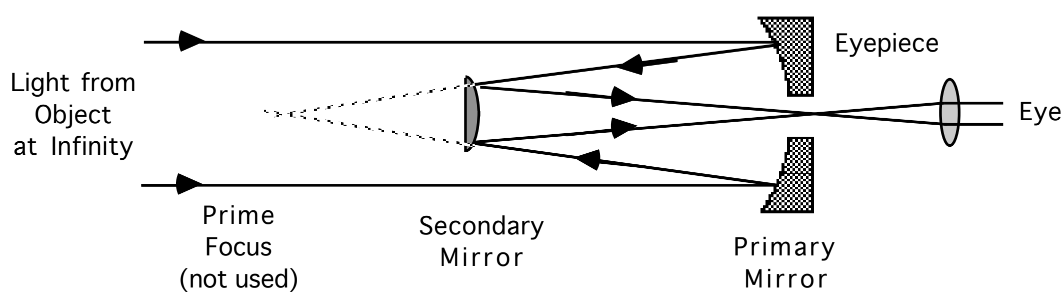


Figure 17: Cassegrain telescope.

Telescopes that use a combination of lenses and mirrors to form images are called catadioptric. One form is the Schmidt camera, which uses a weak lens-like corrector plate at the entrance to the telescope to correct for off-axis image aberrations. This specialized telescope can't be used for viewing but does produce panoramic sky photographs. SBO has an 8" Schmidt for astrophotography.

One of the most popular, albeit expensive, telescope designs is the Schmidt-Cassegrain. As the name suggests, it looks like the Cassegrain telescope but with the addition of a Schmidt corrector plate. SBO has seven of these smaller, portable telescopes: an 8" Meade, two 5" Celestrons, two 5" Meades, and two 3.5" Questars.

The fundamental optical properties of any telescope are described by three parameters: the focal length, the aperture, and the focal ratio (f/ratio). The focal length (f) is the distance from the objective where the image of an infinitely-distant object is formed. The aperture (A) of a telescope

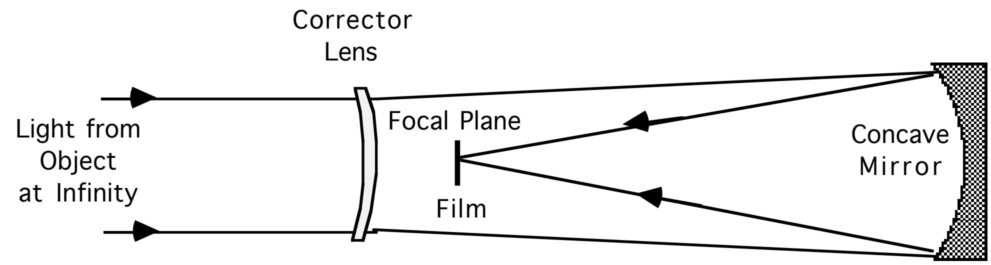


Figure 18: Catadioptric telescope.

is simply the diameter of its light-collecting lens (or mirror). The f/ratio is defined to be the ratio of the focal length of the lens or mirror to its aperture:

$$\text{f/ratio} = \frac{f}{A}$$

Obviously, if you know any two of the three fundamental parameters, you can calculate the third.

Focal Length: As shown in the diagram below, an object that subtends an angular size θ in the sky will form an image of linear size h given by $\theta \approx \tan\theta = h/f$. Therefore

$$h = \theta_{\text{radians}} f = \frac{\theta_{\text{degrees}}}{57.3^\circ} f$$

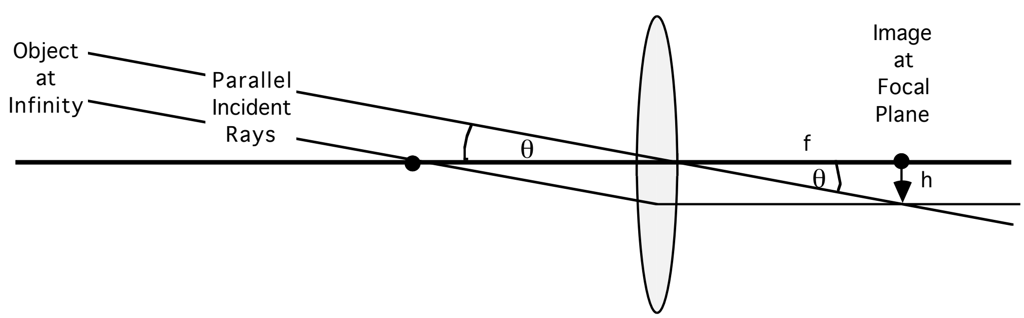


Figure 19: Diagram of the focal length.

The image scale is the ratio of linear image size to its actual angular size:

$$\text{Image Scale} = \frac{h}{\theta} = \frac{f}{57.3^\circ}$$

Thus, the scale of the image of any object depends only upon the focal length of the telescope, not on any other property. Two telescopes with identical focal lengths will produce identically-sized images of the same object, regardless of any other physical differences. Furthermore, the image scale is directly proportional to f, doubling the focal length will produce an image twice the linear size (and four times the area).

The plate scale (used in photography) is usually expressed as the inverse of the above - the angular size of the object (usually in arc-seconds) corresponding to a linear size (usually in millimeters) in the focal plane.

For a compound telescope (with more than one active optical element), we refer to the effective focal length (EFL) of the entire optical system, and treat it as a simple telescope with single lens or mirror of focal length f = EFL.

Aperture: The aperture A of a telescope is the diameter of the principle light-gathering optical element. The light-gathering ability, or light grasp, of the telescope is proportional to the area of the objective element, or A^2. For point sources such as stars, all of the collected light will (to a first approximation) converge to form a point-like image. Hence, stars appear brighter, and fainter stars can be detected, with telescopes of larger aperture. Telescope aperture is the principle criteria for determining the limiting visible stellar magnitude.

The resolving power (ability to resolve adjacent features in an image) of an optical telescope is also chiefly a function of aperture. The larger the aperture, the smaller the diffraction pattern formed by each point source, and therefore the better the resolution. The theoretical diffraction-limited resolution of a telescope is given by

$$\theta_{diff} \geq \frac{1.2\lambda}{A} = \frac{5 \text{ arc-sec}}{\text{Inches of Aperture}}$$

where λ is the wavelength of the light used, assumed to be 5500 Å.

Focal Ratio: Although the amount of light gathered by a telescope is proportional to A^2, the collected light is spread out over an area at the focal plane that is proportional to h^2, and therefore proportional to f^2; hence, the image brightness of an extended (not point-like) object will scale linearly with the ratio $(A/f)^2$, or inversely with the square of the f/ratio = f/A of the telescope:

$$\text{Brightness} \propto \frac{1}{\text{f/ratio}^2}$$

The f/ratio of a telescope is therefore the only factor that determines the image brightness of an extended object. For example, if one telescope has twice the aperture and twice the focal length of another, both telescopes are geometrically similar and would use exactly the same photographic exposure to produce identically-bright images of, say, the Moon. Of course, the first telescope would produce an image twice the linear size (and four times the area) as the latter, but both would have the same photographic "speed." Note that the smaller the f/ratio, the brighter the image and the faster the speed: a 35mm camera using an f/ratio of f/2 will photograph the Milky Way in less than 5 minutes, while the same film on an f/15 telescope will require an hour or more to capture the diffuse glow. On the other hand, individual stars will record much better using the telescope.

The optical speed of a compound telescope is simply the ratio of its effective focal length to its aperture. Both effective or actual f/ratios are a measure of the final angle of convergence angle of the cone of light before it forms the image; the smaller the f/ratio, the greater the convergence, and the more critical the focus. This is why "slow" optics, with a slowly-converging beam, exhibit a larger "depth-of-field."

Seeing and Clarity: The diffraction equation gives the theoretical limit to the angular size that can be resolved by a telescope. This limit is almost never achieved in practice, since atmospheric turbulence is always present to blur our image of the object. The quality of the seeing is measured by the angular separation needed between two stars for their images to just be resolved. Average seeing in the Boulder area is about 2 arc-seconds, making it a marginal task to "split" the 2 arc-sec pairs of the "double-double" star Epsilon Lyrae. Good seeing in Boulder is when the atmosphere is stable enough to resolve 1" separations. Poor seeing conditions can be as bad as 5" or even worse. By comparison, half-arc-second seeing occurs routinely at several carefully located major observatories, but it is rare for any ground-based telescope to experience 0.2" conditions.

One can estimate the seeing of a night simply by glancing up. If the stars glow solidly, the seeing is probably "good." If they twinkle, the seeing is "average." If bright stars dance and planets flash with color, the seeing is "poor." Another measure is to look towards Denver - if there are lots of particulates in the air, and Denver is on smog alert, you will see a bright horizon glow. In this situation, you can usually count on good seeing. These conditions are created by an inversion layer of stagnant air, which permits rock-solid astronomical viewing.

The best conditions for good seeing are the worst for sky clarity. Good clarity implies dark skies due to a lack of light-scattering dust particles, and an absence of water-vapor haze. Clarity usually improves in Boulder after the passage of a thunderstorm, which clears out the dust. Of course, the conditions that improve clarity usually destroy seeing.

Since ideal nights of good clarity and seeing are rare, an observer must be prepared to take advantage of the best properties of the night, if any. Lunar and planetary observing requires good seeing conditions, since planetary disks are small, only 2-40 arc-seconds in diameter. Poor clarity is not a major problem for bright solar system objects, although low-contrast features may be washed out. On the other hand, good clarity (and the absence of strong moonlight) is essential to observe galaxies and diffuse nebulae, since the light from these objects is faint and dark skies are needed for contrast. Seeing is not critical, since these objects are fuzzy patches to begin with. When both seeing and clarity are poor, it's best to focus your attention on bright star clusters and widely-spaced double stars.

Eyepieces and Magnification: An eyepiece or ocular is simply a magnifier that allows you to inspect the image formed by the objective from a very short distance away. The eyepiece is placed so that its focal plane coincides with the focal plane of the objective, so that the rays from the image emerge parallel from the eyepiece. As a result, the telescope never forms a final image - the lens of your eye does that.

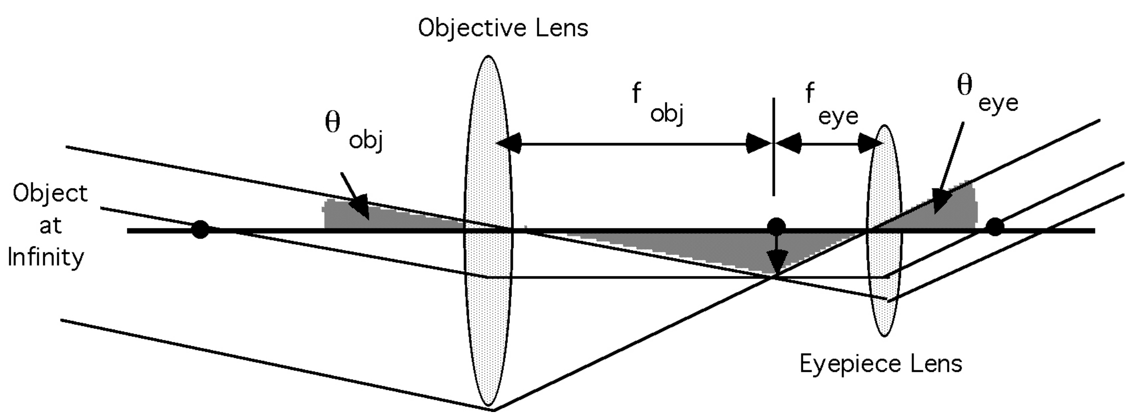


Figure 20

By selecting appropriate rays for both the objective lens (obj) and the eyepiece lens (eye), we can see that rays incident at the telescope at an angle θ_{obj} will emerge from the eyepiece at a larger angle θ_{eye}. The observer perceives that the object subtends a much larger angle than is actually the case. A little geometry gives the angular magnification M_θ produced by the arrangement:

$$M_\theta = \frac{\theta_{obj}}{\theta_{eye}} \approx \frac{f_{obj}}{f_{eye}}$$

That is, magnification is the ratio of the objective focal length divided by the eyepiece focal length. For example, the 16-inch f/12 telescope has a focal length of 192 inches, or 4877 mm. If we use an eyepiece with a focal length of 45 mm (engraved on its barrel), the "power" of the telescope will be about 108 X; by switching to an 18 mm eyepiece, we will have 271 X. The answer to the question "what is the power of this telescope?" is "whatever you want - within the range of the available eyepiece assortment."

Eyepieces come in a variety of designs, each representing a different trade-off between performance and cost, ranging from the inexpensive short-focal-length two-element Ramsden (R) to the 6-element triple-doublet Erfle (Er). Other types include: the Kellner (K), an improved Ramsden; orthoscopic (Or), good at moderate focal lengths at reasonable cost; and the expensive low-power wide-field designs - the Plossl (including Clave), the Konig, and the Televue.

Besides focal length (and image quality), the other important characteristic of an eyepiece is its field-of-view - the size of the solid angle viewable through the ocular, or when used on a particular telescope, the actual angular size of the observable sky field. The field available with a given telescope-eyepiece combination can be measured directly by positioning a bright star just at the northern edge of the field; after noting the declination, you move the telescope northward until the star is at the southern boundary of the field, note the declination again, and calculate the difference in angle.

The Barlow is a telecompressor (concave or negative) lens that can be installed in front of the eyepiece. It reduces the angle of convergence of the objective light cone and hence increases the f/ratio and the EFL of the telescope, thus increasing the magnification (by a factor of 2 to 3) from a given eyepiece. It helps achieve high magnification without sacrificing eye relief (see below).

Selecting an Eyepiece: The choice of eyepiece is one of the few factors that an observer may control to enhance the visibility of astronomical objects.

The Observatory's eyepieces range from focal lengths of 70 mm down to 4 mm. The longer focal lengths are in the 2"-diameter format, which fit directly into the large telescope tubes; the shorter (higher magnification) eyepieces have 1-1/4" diameter barrels, but can be used in the 2" tube using an eyepiece adapter plug.

Although the magnification equation implies that it's possible to have any magnification one desires, there are practical limits. The entrance pupil of the human eye (the diameter of the iris opening) is about 7 mm for a fully dark-adapted eye (5 mm for older individuals). The exit pupil of an telescope (diameter of the bundle of light rays exiting the eyepiece) can be shown to be

$$\text{Exit Pupil} = \frac{A}{M_\theta} = \frac{f_\text{eye}}{\text{f/ratio}}$$

If the exit pupil is larger than the entrance pupil of the eye, the eye can't intercept it all and some of the light is wasted. This occurs if the magnification is too low. If the exit pupil just matches the eye pupil, all of the light is utilized and we have the brightest-possible, or "richest-field" arrangement. This is why 7×50 (7 power, 50 mm aperture) and 11×80 (11 power, 80 mm aperture) binoculars are excellent for night observing - their exit pupils optimally match the dark-adapted human eye. At higher magnifications, all of the light enters the eye but is spread over a larger solid angle, dimming the field.

The average human eye can just barely resolve two objects separated by about 1 arc-minute, although a separation of about 4' (240") is much more comfortably perceived (about 50 such 4 arc-minute "pixels" comprise the face of "the man in the Moon"). Hence, one criterion for a telescope's maximum useful power Mmax is "that magnification that matches a 250 arc-second visual separation to the diffraction limit of the telescope"; from equation (4) this equates to

$$M_{max} = 50 \times \text{Aperture of Telescope in Inches}$$

By this "rule of thumb," the 16-inch telescope has a maximum useful magnification of 800 X on a night of perfect seeing, which would be achieved with a 6 mm eyepiece. Any greater magnification will be "empty" - that is, the image will become larger, but the enlargement will contain only "blur," not additional detail. (Note: poor-quality 2.4"-refractors are provided with 4 mm eyepieces plus a cheap 2.5X Barlow lens so that the manufacturer can advertise "600 power" - 5 times beyond any useful application.)

The above magnification limit is somewhat optimistic for telescopes of moderate-to-large aperture, since detail is almost invariably limited by atmospheric seeing rather than by telescope resolution. For example, if the seeing is about 1", a 250" perceived separation implies a useful maximum magnification of about 250 X - or an eyepiece in the 18 - 24 mm range for the 16-inch telescope. For 2" seeing, a reasonable choice is about 125 power, or eyepieces in the 32 - 45 mm range.

There are several additional considerations related to high magnification. On the negative side, short-focal-length eyepieces require critical focussing and eye placement, making them difficult for inexperienced observers to use. In addition, they exhibit short eye relief - the distance behind the lens where the eye is positioned to see the entire field-of-view. In particular, eyepieces shorter than about 12 mm focal length are problematic for eye-glass wearers, since glasses prevent the eye from being placed close enough to avoid "tunnel vision."

On the positive side, high magnification reveals fainter stars. Remember that stars are unresolved point sources whose light is concentrated (to a first approximation) at a single point in the image regardless of magnification. The glow of the background sky is a diffuse source, which will be spread out by higher magnification, reducing its brightness. Although high magnification doesn't increase the brightness of faint stars, it improves their contrast against the sky, making them more visible. By this same token, high magnification helps diminish the intense glare from bright solar system objects, making the Moon less painful to look at, and the bands of Jupiter easier to see.

Finally, there is the consideration of the type and angular extent of the object being viewed. High magnification certainly helps resolve fine planetary detail and separates close double stars, provided that seeing conditions permit. Open clusters usually extend over a large patch of the sky, and hence need low power (a wide field-of-view) to encompass them - in fact, the small finder scopes may present a more pleasing view than the main telescope. High power won't help the contrast between sky background and diffuse nebulae (since both are extended sources), and in fact may keep the observer from seeing the glow since all aspects of the image are dimmer. Low power is essential for extremely large nebulae, since these objects can fill the field-of-view - creating a situation where "you can't see the forest for the trees." Globular clusters can be appreciated at a variety of magnifications: low power creates an impression of a "cotton-ball" floating in space, while high magnification shows a magnificent sparkling array of bright points reminiscent of distant city lights. In the end, your personal experience and judgement should be your guide.

Observing Technique: Observing through an eyepiece is an unnatural experience; good observing techniques come with time and experience. Here are some hints to help you get the most out of your telescope time:

- Let your eyes become fully dark-adapted before doing "serious" observing. This can take 20-30 minutes.
- "Gaze," don't "glimpse." It takes a few moments to mentally and optically adjust to the scene in an eyepiece. Continued observation also improves the chances for brief periods of atmospheric stability when new details may appear.

- Don't stare fixedly through the eyepiece. Let your eye wander. The human eye is much more sensitive to changes in brightness than to constant light levels. By looking around, you'll see fainter detail.
- Use averted vision to help bring out dim features. The color-sensitive cone cells concentrated near the center of the eye's retina don't respond to low light levels. If you look out of the "corner of your eye," you'll utilize the much more sensitive black-and-white rod cell receptors that are used for peripheral vision.
- Finally, don't expect to see the colors that appear in photographs; for the reason just mentioned, most faint objects appear greenish to whitish because they are too faint to stimulate the color receptors in your eye.

Solar Observing at SBO

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

The heliostat (solar telescope) on the deck of Sommers-Bausch Observatory is used to bring an image of the Sun directly into the laboratory. This is one of the few facilities in the country that permits students to continuously monitor real-time solar activity - without ever having to leave their seats! Detailed information about the heliostat, and the various ways it can observe the Sun, can be found at the Sommers-Bausch Observatory website:

http://cosmos.Colorado.EDU/sbo/telescopes/heliostat/heliostat.html

The instrument is used in portions of several different ASTR 1010 and ASTR 1030 laboratory exercises: to keep track of the changing distance of the Earth from the Sun (Seasons); to determine the temperature of sunspots (Temperature of the Sun); and to look at the spectrum of light coming from our star (Spectroscopy).

However, the heliostat can be used for much, much more but unfortunately, solar activity is somewhat unpredictable as is, of course, the local weather. It is difficult to design and plan laboratory exercises around a star and a planet that may not cooperate on a particular day.

As a result, we're going to take the approach that "if something really interesting is happening, we'll stop whatever we're doing and take a look". The following pages will help guide you through some of the interesting possibilities.

Sketching Sunspots: The "Large White Light" heliostat mode projects an image of the solar photosphere onto the laboratory wall, making it easy to see and study details in the solar photosphere. The most prominent features you'll see, of course, are the dark areas known as sunspots.

It's easy to sketch details of sunspots - simply hold a sheet of white paper against the wall and directly trace, with a pencil, all of the details of the spot that you can see. Be sure to appropriately shade the dark central umbra of the spots, and the surrounding lighter penumbra regions. You might also wish to add a scale to your drawing at this projection, each millimeter corresponds approximately to 1,100 miles on the "surface" of the Sun!

Note that spots tend to appear in sunspot groups. Some of the bigger, complex, and more "gnarly-looking" of these regions are the most likely to be active regions giving rise to flares and other interesting features in the overlying solar chromosphere and corona.

Sunsets: An enjoyable pastime is to watch a sunset behind Green Mountain, three miles to the west, using the Large White Light mode of the heliostat. We can observe sunsets daily at high magnification from September through March, weather permitting. Each evening's sunset is unique as the Sun disappears behind different trees or rocky crags of the foothills.

The actual time of sunset depends on a number of factors: the date (which sets the declination of the Sun); the shape of the mountain profile as seen from the Observatory; the "equation of time"

Figure 21: Sunset over Bear Peak through the heliostat.

which records whether the Sun is running "fast" or "slow" compared to our watches; and of course, daylight savings time.

Sunsets can occur as early as 3:20 p.m. in November and December, as the Sun reaches its lowest declination and passes behind the peak of Green Mountain or as late as 6:30 Daylight Savings Time in September, when it sets behind Flagstaff Mountain instead.

So that you can plan ahead, the heliostat manual includes a timetable of when and where a sunset will occur for any day of the year.

Sunspot Temperatures The Sun radiates energy in accordance with the Stefan-Boltzmann Law, which states that the intensity I (power emitted per unit area of the radiating body) is proportional to the fourth power of the temperature T (in Kelvin). For example, if the Sun's temperature were to suddenly double, it would emit $2^4 = 16$ times as much energy as before!

Obviously, then, if a region of the Sun appears darker than its surroundings - like a sunspot - we can infer that the area is "cooler" than the rest of the Sun (relatively speaking, of course!).

The Stefan-Boltzmann Law gives us a quantitative way to measure the relative temperatures of the Sun from the observed intensity of the light coming from it:

$$T_{spot} = T_{sun} \left(\frac{I_{spot}}{I_{sun}} \right)^{1/4}$$

To measure the temperature of a spot, use the Observatory's pinhole lightmeter to measure the intensity I_{spot} of the light coming from a sunspot, and also the intensity I_{sun} from the brighter surrounding region. Substitute these measurements into the equation, and use the average overall temperature of the Sun, 5800 K, for the value of T_{sun}. You'll find that sunspots are, in fact, anything but "cool"!

Sunspot Latitude and Longitude: The "Small White Light" mode of the heliostat permits you to map the location of sunspots. Position a sunspot record form in the holder so that the Sun's image is centered on the circle. Carefully trace with a pencil all of the sunspots that are visible.

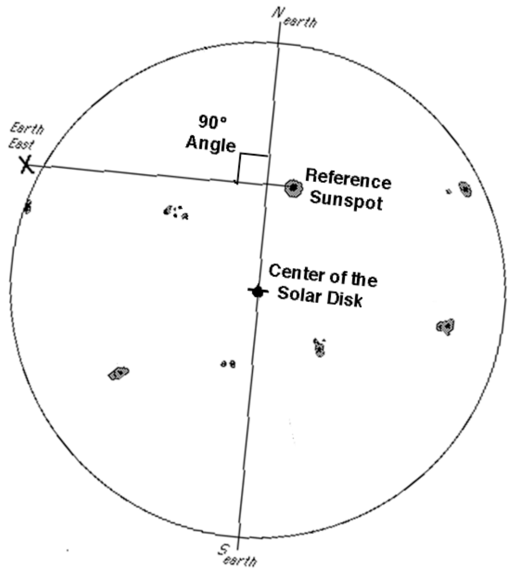


Figure 22

North is not necessarily at the top of the image. You determine direction by noting which way the image shifts when the heliostat is driven in a known direction: without disturbing your drawing, drive the heliostat briefly in the west direction, using the direction toggle on the heliostat control box. Since the field of view is now westward of its original position, the solar image appears to have shifted to the east. Follow the motion of a single sunspot. When the spot clears the disk circle, make an "X" at its new position and label it "earth east".

Next, map out the directions from Earth's point of view. Draw a line from the original position of the selected sunspot to its final location. This line is parallel to the Earth's equator. Use a protractor to draw a second line perpendicular (90°) to the equatorial line and through the center of the solar disk. The new line marks the projection of the Earth's axis of rotation onto the disk of the Sun. Label the upper end of the line Nearth (for "Earth north") and the lower end Searth (for "Earth south").

The Earth's and the Sun's axes of rotation are not aligned with each other: the Earth's north pole is aimed approximately towards the star Polaris in Ursa Minor, while the Sun's north pole is oriented about 26° away towards the star Delta Draconis. As a result, when we view the Sun from the Earth at different times during the year, the Sun's north pole may appear tilted eastward or westward of the Earth's north pole, and may be tipped either towards or away from us as well.

The number of angular degrees of tilt and tip are defined by two angles, P and B_0; these values can be found in the Astronomical Almanac for the current day.

The angle P describes how much the north pole of the Sun is tilted, in the plane of the sky (or the plane of your paper), towards the east (or west) from Earth north. A positive angle P means the Sun's north pole lies to the east of N_{earth}.

The angle B_0 describes how much the north pole of the Sun is tipped towards (or away from) you, the observer on Earth. A positive angle B_0 means that the north pole of the Sun is tipped towards the Earth (so that the north pole of the Sun would, at least theoretically, appear on your drawing).

Use a protractor to draw a line through the center of the solar image at an angle P from the N_{earth}-

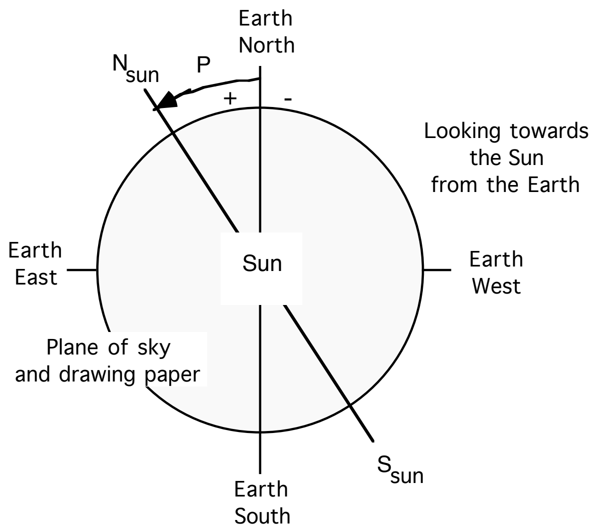


Figure 23

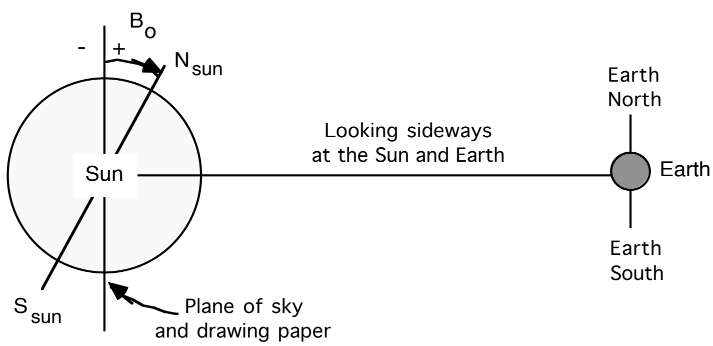


Figure 24

S_{earth} line; remember, the line should lie to the east (left) of Earth north if P is positive, and to the west (right) if negative. This line marks the solar meridian, the north-south line dividing our view of the Sun into eastern and western hemispheres. Mark the upper end of the solar meridian N_{sun} (solar north) and the lower end S_{sun} (solar south).

A transparent overlay, known as a Stonyhurst disk, will help you find the latitude and longitude of the sunspots. The grid is marked every 10° in latitude north and south of the solar equator, and every 10° east or west of the solar meridian line. Choose the Stonyhurst overlay with a B_0 closest to the actual value corresponding to your observation. Center the circle of the overlay on top of your circular drawing, with the axis aligned with the solar meridian. Be sure that the correct sign (+ or -) for B_0 appears at the top of the overlay.

Finally, number the prominent sunspots and estimate, to the nearest degree, the solar latitude (N or S of the solar equator) and solar longitude (E or W of the solar meridian) of every numbered spot.

The Sunspot Cycle The number of sunspots is observed to grow and decline over a period of approximately 11 years; this phenomenon is known as the sunspot cycle.

At the beginning of a new 11-year cycle, sunspots first appear at high latitudes (approximately 40° north and south of the solar equator). As the cycle progresses, the average latitude of the sunspots shifts to lower latitudes, so that near the end of the cycle the majority of the sunspots appear

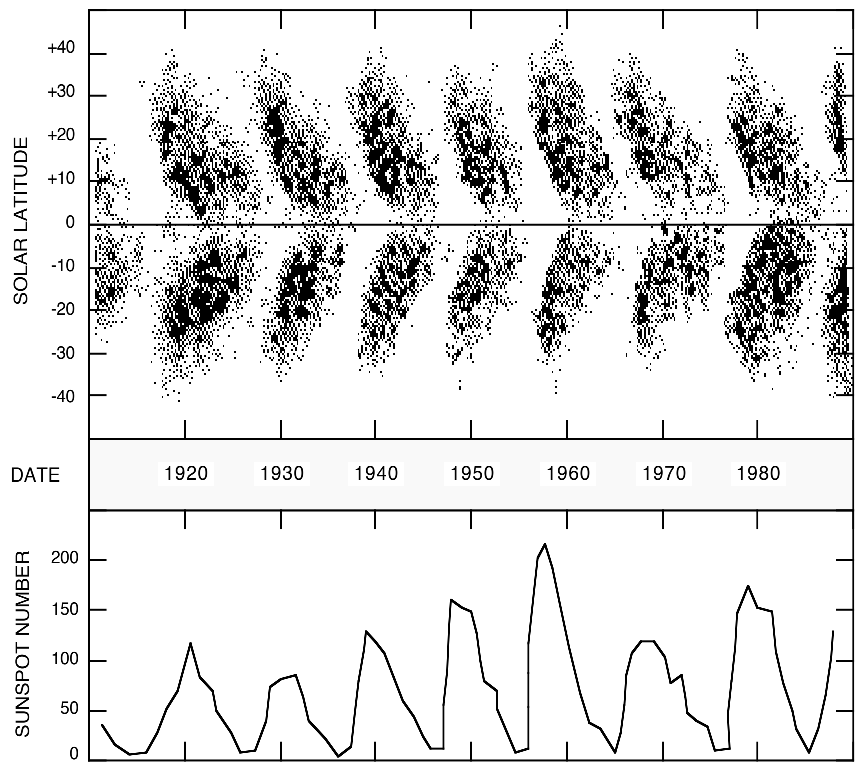


Figure 25: The sunspot cycle

around 10° north or south of the equator. The upper chart shows the latitudes at which sunspots have occurred over the past 80 years. Although spots can appear at nearly any latitude, note the trend from high to low latitudes in each cycle. The pattern of the distribution has given the chart its name: the butterfly diagram.

The lower chart shows the annual average sunspot number; it clearly illustrates the cyclical nature of solar activity. The number is computed as follows:

$$\{(\text{Number of Spots}) + (\text{Number of Groups})\} \times \text{Correction Factor} = \text{Sunspot Number}$$

Count every visible spot, including each tiny individual spot as well as those appearing in groups. To this is added the number of distinct sunspot groups, which count as an additional 10 spots each. The sum is then multiplied by a correction factor (we use a value of 2.0) which takes into account the size of the solar telescope, the location, and the experience of the observer.

You can compare your determination of the sunspot number with the official daily count found at www.sunspotcycle.com/.

It is frequently possible to get a rough estimate of the current phase of the sunspot cycle from a single day's observation. Simply compare your sunspot count with the chart above, and figure in the average latitude of the spots to deduce whether we're in the early or late stages of the current 11-year cycle.

Solar Rotation: Sunspots are observed to shift their positions across the solar disk due to the rotation of the Sun. By using two separate latitude/longitude sunspot drawings made from one or more days apart, you can measure the solar rotation rate.

Identify one or more spots that are common to both drawings. Appearance, relative position to other spots, and the measured latitude are all clues in making the identifications.

Use the difference in the measurements of spot longitude to determine the size of the angle through which the spot has rotated. Divide the observed rotation angle by the elapsed time in fractional days to determine the apparent solar rotation rate in degrees per day.

Your measurement was made from a moving platform: the Earth, which orbits around the Sun at a rate of 360° in one year (365 days), or an average motion of almost exactly 1° per day. (This is probably not a coincidence; it is generally assumed that ancient astronomers/mathematicians divided the circle into 360 parts for just this reason!)

We orbit the Sun in the same direction that it rotates so that our motion "chases after" the sunspots. Therefore, the apparent movement of spots is less than their actual rotation by about 1 per day. You'll need to compensate for the orbital motion of the Earth by adding 1 to your computed apparent daily rotation to get the Sun's true rate of rotation.

Photosphere (White-Light Image) The photosphere (literally, "sphere of light") is the visible layer of the solar atmosphere, about 500 km (300 miles) thick, from which we receive most of the Sun's light. This layer of the Sun may be observed either using the "Large White Light" mode of the heliostat, or with the SCRIBES camera imaging system.

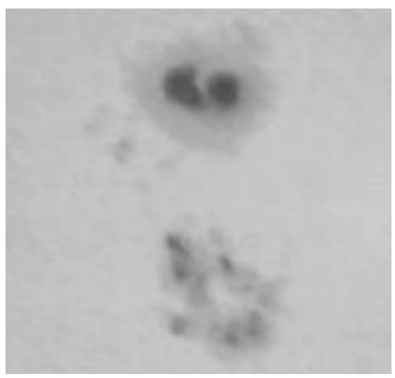


Figure 26: A sunspot.

The most prominent features are sunspots (with the dark umbra and surrounding semi-dark penumbra regions). You may also notice the brightness mottling (called faculae) that occurs over the entire disk. And on an exceptionally good day you can just pick out granulation cells (convection cells about 1000 km (600 miles) across, similar in nature to earthly cumulus clouds) which deliver thermal energy from the solar interior to the photosphere.

Lower Chromosphere (Calcium-K Filter) The region of the solar atmosphere about 500 km (300 miles) above the photosphere can be observed using the ultraviolet light emitted by calcium atoms present in the Sun; a calcium-K filter and SCRIBES camera system is used to make this layer visible.

Look for the bright patches, called plages ("PLA-juhs") that tend to surround sunspots. These regions delineate the "active region" where the magnetic fields associated with sunspots are the strongest. Essentially, these bright regions mark the strength, location, and extent of strong solar magnetic fields - and prove that seemingly isolated sunspots are actually just pieces of a much larger, complex, and dynamic grouping. Far away from the spots, look for large, ill-defined circlets of bright emission, which are the boundaries of super-granulation convection cells. These regions

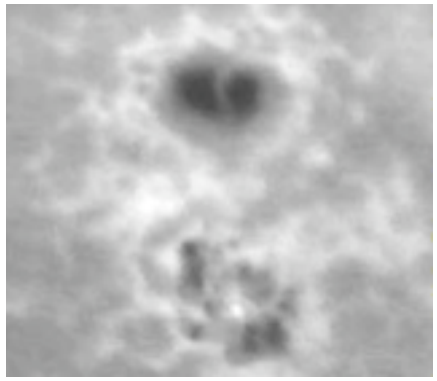


Figure 27: A solar plages.

are thought to deliver energy from very deep in the solar interior up to the surface.

Upper Chromosphere (Hydrogen-alpha Filter) Several thousand kilometers above the photosphere (and sometimes extending outward to several tens of thousands of kilometers) is the chromosphere, or "sphere of color." The layer is named for the pink light (a combination of red and blue) emitted from this layer by hydrogen gas. The chromosphere is a thousand times dimmer than the photosphere, but can be observed on any clear day using a special hydrogen-alpha (Hα) filter. The filter permits you to see only the red light emitted at a wavelength of 6563 Ångstroms by hydrogen atoms in the solar atmosphere.

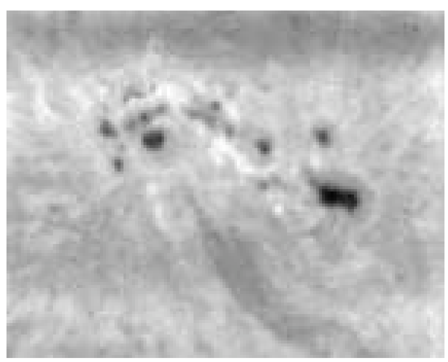


Figure 28: A solar fibril.

In this view, one can see how the tenuous solar gasses of the outer atmosphere are forced to conform to the magnetic fields of the Sun. Finger-like fibril structures produce a "picture" of the lines of magnetic force (just as iron filings line up with the magnetic field of a bar magnet). If viewed near the limb, the fibrils may be seen to extend outwards to form flame-like or bush-like structures known as spicules. Dark patches or long string-like structures called filaments are frequently apparent, particularly in the vicinity of sunspot groups. These are clouds of hydrogen gas that extend far above the surrounding region, and which tend to form in, and delineate the areas of, magnetically neutral zones.

If a sunspot group is quite active, you may also be able to observe a flare in progress - a region of intense brightening where the solar temperature has abruptly risen from several thousands of degrees to several millions of degrees! Flares can change dramatically in appearance from one minute to the next, and rarely last for more than an hour or two. Also look for surges and sprays that rise high into the chromosphere around such regions.

Or, if you look towards the edge (limb) of the Sun, you're almost certain to see numerous bright regions of glowing hydrogen gas that extend far out into space into the solar corona. These features, which may form loops, or arrange themselves into Prussian helmet-shaped structures, or hedgerow-like patterns, are called prominences. Generally, a prominence will just hang quietly in space, but may occasionally erupt outward, or even "rain" back upon the lower photosphere. In fact, a prominence is the same thing as a filament - except that it is seen in profile against the blackness of space, rather than from the top against the bright disk of the photosphere.

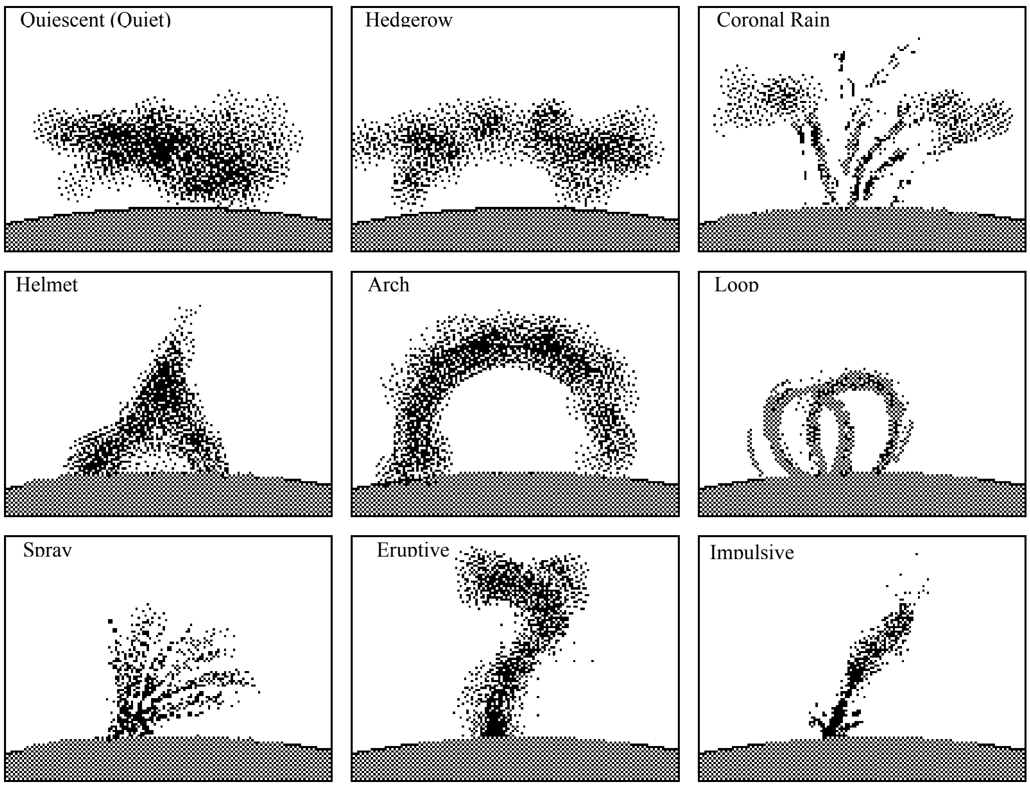


Figure 29: A solar prominence.

Watching for Flares Because of their high temperatures, solar flares produce enormous amounts of X-rays. Although these X-rays can't penetrate our atmosphere to reach the Earth's surface (fortunately for us), they are detected from space by Earth-orbiting GOES satellites - the same satellites that give us those familiar views of cloud cover on the evening television weather segments.

The satellites are continuously sending X-ray reports down to the Space Environment Center (SEC) of the National Oceanic and Atmospheric Administration (NOAA) here in Boulder. And once a minute, every minute, SEC updates a graph showing the latest change and publishes it on the web. You can use the SBO Laboratory computer to keep a constant eye on this activity (and that of the last 6 hours) by monitoring the following site: www.sel.noaa.gov/rt_plots/xray_1m.cgi

A flare will show itself as an abrupt and dramatic rise in the plots, indicating an increase in X-rays from the Sun. Note that the graph is logarithmic, so that even a small rise in the curve represents a large change in the X-ray output. Flares are broken down into several classes: moderate ("C-class"), large ("M") or huge ("X") outbursts.

If an M or X flare comes along, you certainly don't want to miss it. Assuming it's sunny, use the heliostat in hydrogen-alpha mode to inspect each of the sunspot groups currently on the disk of the Sun - one of them will show an intensely bright patch, which will likely change in appearance from minute-to-minute - the solar eruption responsible for all those X-rays.

For more information about flares, you may wish to consult NASA's Solar Flares page: science.msfc.nasa.gov/ssl/pad/solar/flares.htm

Solar Forecasts Even if a flare isn't happening at the moment, you can find out the likelihood that one may come along. SEC also maintains an extremely informative site, called Today's Space Weather, at www.sel.noaa.gov/today.html.

Here you'll find summaries of what the Sun is up to, including:

- A recent image of the solar disk taken in hydrogen-alpha light.
- A three-day forecast of anticipated solar activity, and also a prediction of how recent solar activity may impact the Earth's near-space environment (the geophysical forcast).
- A graphical history of the past three days of solar X-ray activity.
- A three-day record of the space environment in which the satellites find themselves, all due to particles streaming past the Earth from the Sun.
- The K-Index - which gives an excellent "feel" for the strength of geomagnetic disturbances that are occurring in Earth's ionosphere in response to solar activity. The index is a number ranging from 0 to 9: a K-index larger than 7 means there's a fair chance that we in Boulder might be able to observe an aurora.

The Aurora The energy to power flares comes from a reconfiguration of the Sun's magnetic field. Major large-scale changes in the field are caused by expulsion of material from the solar corona, called a coronal mass ejection or CME. For movie sequences of coronal mass ejections , see sohowww.nascom.nasa.gov/gallery/LASCO/. If such material reaches the Earth, it can significantly perturb the Earth's magnetosphere, causing wild swings in magnetic field strengths and directions (Hp-index).

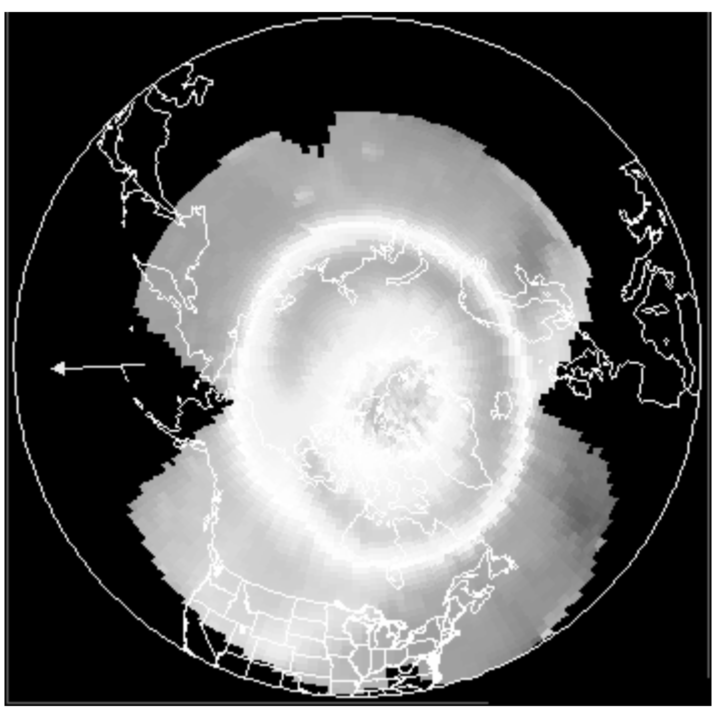


Figure 30: The aurora.

Ejected solar material takes about 36 to 72 hours to reach the Earth, arriving as the solar wind. Under certain circumstances, the solar particles can enter the Earth's ionosphere near the poles and give rise to the Aurora Borealis (the "northern lights"). The aurora is the glow of gasses in the Earth's upper atmosphere, which are excited to emit light by the passage of the high-speed charged particles.

Aurorae generally appear in the shape of oval rings encircling the Earth's magnetic poles; the ovals shift in intensity and position in response to changes in the direction and strength of the solar wind. The stronger the perturbations (higher K-index), the farther the oval will expand from the poles, extending down to lower latitudes. The oval also tends to skew away from the direction of the Sun - and so as the Earth turns, the aurora generally shifts closer to us here in Boulder around local midnight.

NOAA's Polar Orbiter Earth Satellite (POES) is constantly monitoring the Earth's auroral arcs, and publishes the latest image extrapolations on the web: www.sel.noaa.gov/pmap/

If the Kp-index becomes large, and if the polar image suggest that the northern oval may be extending southward towards Colorado, you might wish to make an attempt to observe it. Although Colorado aurorae are fairly rare, they do happen once or twice a year on the average.

You should observe from a dark site (away from city lights) with a clear view to the north. Displays tend to be more probable within a couple of hours before or after midnight. The "northern lights" may appear as luminous patches in the northern sky, or may develop into vertical rays and curtains. Colors can vary from a ghostly pale-white glow to bright greens and vivid reds, depending upon the altitude and intensity of the aurora.

For more information regarding the direct effects of solar activity on human activities, see

www.sec.noaa.gov/primer/primer.html

The Solar Corona Above the chromosphere of the Sun lies the corona, the extremely tenuous but very hot outermost atmosphere of the Sun. Since the corona glows a thousand times dimmer than the chromosphere (and hence a million times dimmer than the photosphere), it can only be seen during a total solar eclipse, or with a very specialized ground-based telescopes, or from satellite ultraviolet and X-ray images of the Sun.

A number of exquisite, daily satellite images of the outer layers of the Sun, primarily from the SOHO and YOHKOH spacecraft, can be found at umbra.nascom.nasa.gov/images/latest.html

The site also includes recent ground-based magnetograms (which depict the strength and polarity (North or South) of the magnetic fields surrounding sunspots), doppler images (representing velocities of gas flows), coronograph images, and others from Kitt Peak, Sacramento Peak, Mauna Loa, Stanford, and Big Bear solar observatories.s

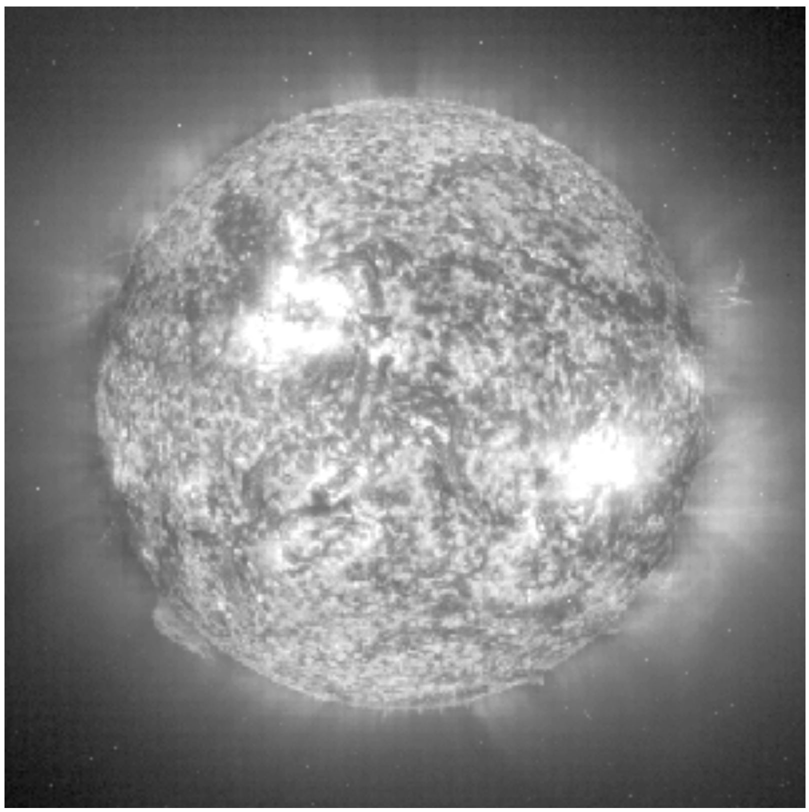


Figure 31: The solar corona.

Lab 0

Example Lab

Purpose: The educational goals of the lab are stated here.

Equipment: Any equipment needed is stated here. The student is always expected to bring their lab book and a writing utensil.

Pre-lab Questions

1 These directions and questions are to be completed before the student arrives for lab. The student should have his/her answers recorded on a separate sheet of paper to be turned in at the beginning of lab.

2 All of the answers to the pre-lab questions can be found in the lab manual either within that lab or in the preface material.

Introduction: Any background information directly needed for the lab exercise will be provided here. The class textbook will provide more detailed explanations of key concepts and is an important resource, but it is not necessary for the labs.

I Organization of Each Lab

The lab will be broken up into three or four sections. The lab instructor will announce when students should be progressing to the next section.

I.1 Sections will consist of directions to be followed or questions to be answered. It is expected that lab groups will always stay together, so that no member gets ahead or falls behind.

I.2 The lab manual does not provide space for recording your answers to questions. You must bring a lab notebook to lab, in order to record your work. After lab, you will type up your responses to the questions and return them the next week to your lab instructor.

II Post-lab Questions

II.1 These questions are to be answered individually after the student has completed the lab. If there is time remaining, the student may answer them in the lab, so that the instructor is present to assist her/him. Otherwise he/she must do them before the labs are due utilizing the instructor's office hours as necessary.

Lab 1

The Colorado Model Solar System

Purpose: To understand the layout and composition of the solar system and get an appreciation for astronomical distances and measurements including the Astronomical Unit and the light-second.

Equipment: Scale model solar system.

Pre-Lab Questions

1 In your own words, describe what an astronomical unit represents. Give an example of something measured in an astronomical unit.

2 In your own words, describe what a light-minute represents. Give an example of something measured in a light-minute.

3 Explain what angular size represents, and how two things of the same angular size could be very different in actual size.

4 Write down the scientific notation for 1 thousand, 1 million, and 1 billion.

Introduction: 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 as shown in Figure 1.1. 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}). This means that for every meter (or foot) in the scale model, there are 10 billion meters (or feet) in the real solar system.

All of the distances between the objects within the solar system, as well as the sizes of the objects within the solar system (where possible), have been reduced by this same scale factor ($1{:}10^{10}$). As a result, the angular sizes and relative separations of objects in the model are accurate representations of how things truly appear in the real solar system.

The scale model arranges all the planets in a straight line on the same side of the Sun. This is a rare alignment and the last time all nine planets were lined up was in the year 1596 BC. This representation reduces the separation from one planet to the next. If the planets in the scale model were instead arranged as the planets might be today, 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 in the Police Building, and Pluto in Folsom Stadium.

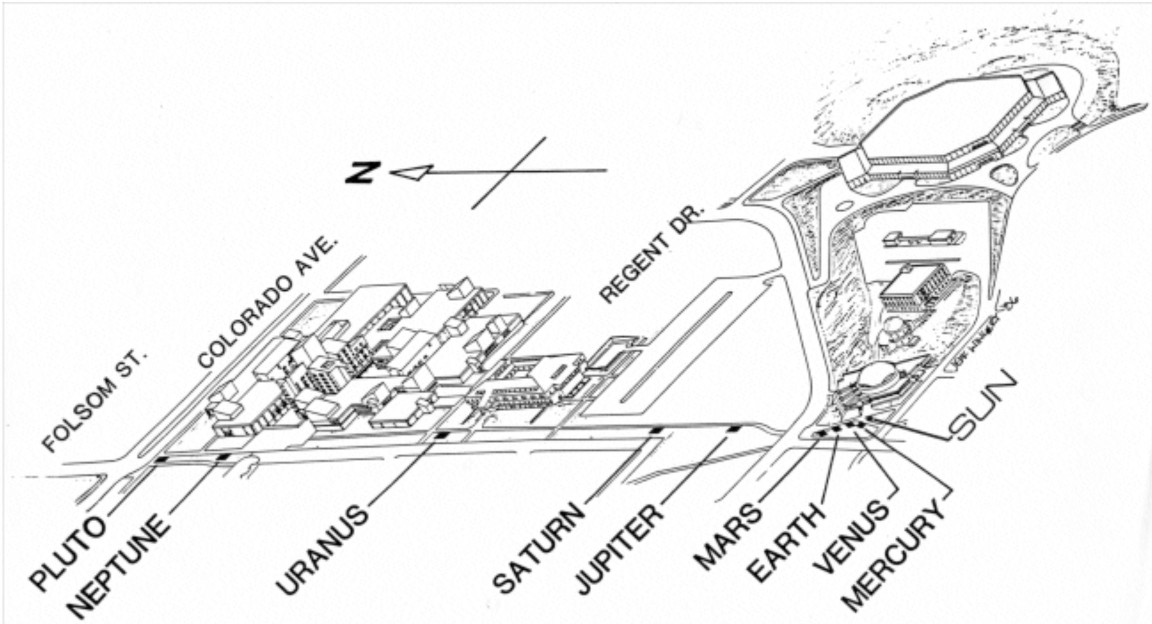


Figure 1.1: Map of CU's scale model solar system.

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 of the Sun.

Before you begin, take a look at Table 1.1 at the end of the lab. As you walk through the model solar system you will need to fill in the table, in addition to answering the questions below. Instructions for how fill out the table will be given below.

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 its only 14 cm (5.5 inches) across.

I.1 Measure the size of the orbit of each of the four inner planets by counting the number of paces (single steps, using your normal walking stride) from the model Sun to each planet. Record this distance in column 1 of Table 1.1.

I.2 Use the information given on the plaques to fill in columns 5-11 of Table 1.1. Leave columns 2-4 empty for now.

Already, you should notice the diversity of the planets. Examining their similarities and difference, jot down the answers to the following questions:

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 Earths?

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

The Earth orbits about 150 million km (93 million miles) from the Sun. This distance is 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 distance as a "yardstick."

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

I.5 For the remainder of the lab you will use the fraction you calculated for the previous step to determine the distance in AU between the Sun and each planet from your measured distance in paces. Do so now for the inner planets recording your result in column 2.

I.6 Convert your measured values for the distance to each planet from AU to km and record them in column 4 of Table 1. You can check your work by comparing to the actual distance in column 5. Show your conversion in your lab report for one of the values in this column.

Another way to describe distance is to use "light-time." The time it takes light, traveling at 300,000 km/second (670 million mph) to get from one object to another. Since light travels at the fastest speed possible in the universe, light-time represents the shortest time-interval in which information can be sent from one location to another. We can measure large distances such as those between the planets in units of light-seconds or light-minutes. We can also consider the distance between stars in units of light-years.

I.7 How many seconds does it take 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. Show your work.

I.8 (a) What is the distance in AU from the Earth to Mars as they are aligned in the model?

(b) What is this distance expressed in light-seconds? Show your work.

(c) NASA has sent rovers to the surface of Mars. Instead of being steered remotely by an operator back on the Earth, each of theses vehicles is equipped with a camera and an on-board computer that enables it to recognize obstacles and to drive around them. Explain why this is necessary.

Take a closer look at Earth's own satellite, the Moon. The furthest object to which mankind has traveled "in person." It took three days for Apollo astronauts to cross this vast gulf of empty space between the Earth and the Moon.

I.9 (a) At the scale of this model, estimate how far (in cm or inches) mankind has ventured into space.

(b) How far away is the moon in AU? in light-seconds?

(d) Just like we constructed a measure of distance from the time it took light to travel one minute, construct a measure of distance from how far an astronaut can travel in one day. How many AU are there in one "astronaut-day?" How many km?

(c) What is the distance to Mars at its closest approach in "astronaut-days?" Show your work.

II The View from the Earth

Stand next to the model Earth and take a look at how the rest of the solar system appears from our vantage point.

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

(b) The width of you index finger at arm's length has an angular size of about one degree. Estimate the angle, in degrees, of the diameter of the model Sun as seen from the model

Earth.

II.2 (a) If its not cloudy, use the same technique to cover the real Sun with your outstretched index finger. Be sure to cover the disk of the Sun, looking directly into the Sun can injure your eyes. Is the angular size of the Sun as seen from the Earth the same as the angular size of the model Sun as seen from the model Earth?

(b) Compare angular size and separation distance in the model to reality. How much does each one change?

Off in the distance to the north, along the walkway leading to the Engineering Center, you can see the pedestals for Jupiter.

II.3 (a) Use your hand to measure the angle between Jupiter and Mars, as seen from the model Earth. (Remember, if this were the real solar system, 10 billion times bigger in all directions, the angle between them would still be the same!)

(b) If the solar system were aligned tonite as it is in the model, how far apart in degrees would Jupiter and Mars be in the night sky? Explain your reasoning.

III Journey through the Outer Planets

It will not be necessary to pace from the Sun to each planet, only to keep track of the cumulative distance traveled in a straight line (i.e. after pacing from the Sun to Mars, pace from Mars to Jupiter and add the two values together to get the proper distance).

III.1 Keep recording the distance to each planet in paces in Table 1.1, as well as filling out the rest of the table from the important information on each plaque.

As you cross under Regent Drive heading for Jupiter, you'll also be crossing the region of the asteroid belt, where a few "minor planets" and millions of asteroids can be found crossing your path. The very largest of these is Ceres, which is 760 km (450 miles) in diameter.

III.2 If the asteroids are scaled like the rest of the solar system model, would you be able to see Ceres as you passed by it? Show a calculation to support your answer.

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

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

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

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

III.4 (a) Earlier you found that Jupiter and Saturn appeared to be very close to each other as seen from Earth. What is their separation distance in AU?

(b) What is the relationship between angular separation of two objects and their separation distance? What is the missing information?

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.5 (a) How do you expect the angular size of the Sun as seen from Jupiter to change compared with your earlier measurement of the Sun from the Earth. Be quantitative.

(b) Measure and record the angular size of the Sun from Jupiter.

(c) Does this angular size agree with your prediction? If not, why?

(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. The most distant object in the solar system that you can see from Earth without a telescope.

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.

III.7 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. Give your answer as a ratio.

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

III.8 (a) Count the number of paces (steps) between Uranus and Saturn: ____________ and also count the number of seconds it takes for you to walk from the orbit of Saturn out to the orbit of Uranus: ____________

(b) What is the distance between the orbits of Saturn and Uranus as measured in light-seconds?

(c) Now compare your answers to parts (a) and (b). 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.9 (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?

(d) What is the distance between the orbits of Earth and Neptune in astronaut-days? Is this a good estimate for how long it would take a team of astronauts to get to Neptune? Explain your reasoning.

IV Pluto and Beyond

Now begin the final walk to Pluto. When you get there, youll be standing three-tenths of a mile, or one-half of a kilometer, from where you started your journey. Youll 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, estimate the angular size of the Sun. Use your knowledge of the distance to Pluto in AU, and the angular size of the Sun as seen from Earth.

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

Although we've reached the edge of the solar system visible through a telescope, that doesnt mean that the solar system actually ends here - nor does it mean that mankinds 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 traveling outwards towards the stars, and still sending back data to Earth.

IV.3 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 will reach its furthest distance from the Sun (aphelion), just north of the city of Boulder at our scale. Comet Hyakutake, the Great Comet of 1996, will require 23,000 years more to reach its aphelion distance - 15 miles to the north near the town of Lyons.

Beyond Hyakutakes 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 over the space between Wyoming and the Canadian border. Each of these is slowly orbiting our grapefruit-sized model of the Sun, waiting for a passing star to jog it into a million-year plunge into the inner solar system.

And there is where our solar system really ends. Beyond that, youll 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 the size and brightness of the Sun and the other only half as big (the size of an orange) and one-fourth as bright. The two scale model stars of Alpha Centauri orbit each other at a distance of only 1000 feet (0.3 km).

IV.4 At the scale of the model solar system, where on Earth would you find Proxima Centauri?

IV.5 How does the distance between the two stars called Alpha Centauri compare to the size of our solar system? Calculate. How do you think our solar system would be different if the sun had a companion at this distance?

V Post-lab Questions

V.1 We are going to examine the data you recorded in Table 1.1.

(a) What planetary properties are directly related to the distance from the Sun? Do any properties increase/decrease as you travel further from the Sun?

(b) Are there any properties where this is almost true? Why are there exceptions?

(c) What properties divide the outer planets from the inner planets?

(d) Would you group the planets differently? If so, how? Explain your reasoning.

V.2 In your opinion, should Pluto have remained classified as a planet? Why or why not?

V.3 Now think about the largest galaxy in our Local Group, the Andromeda galaxy, located at a distance of about 2.4 million light-years from the Milky Way galaxy. Roughly where would we need to locate the plaque for the Andromeda galaxy at the scale of our model solar system? Since the Andromeda galaxy has a diameter of about 100,000 light-years, how big would the plaque need to be?

V.4 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.

	Paces	Measured Distance (AU)	Measured Distance (light min.)	Measured Distance (km)	Actual Distance (km)	Rotation Period (hours)	Orbital Period (years)	Surface Temp. (Kelvin)	Radius (km)	Mass (kg)
Mercury										
Venus										
Earth										
Mars										
Jupiter										
Saturn										
Uranus										
Neptune										
Pluto										

Table 1.1: Data from each of the planetary plaques.

Lab 2

Motions of the Earth and Sun

Purpose: To understand the motions of the Earth and Sun, their relative orientations, and the path of the Sun and planets through the night sky.

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

Pre-Lab Questions

1 The Earth rotates 360° in 24 hours. How many 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?

Introduction: Humanity has been studying the motion of the Earth and Sun for many millenia. Their motions have determined how humans measure time defining the day and the year. The orientation of the Earth relative to the Sun determines the seasons, and the path of the Sun through the Zodiac defines its own coordinate system in the sky.

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 in Figure 2.1 shows an overhead view of the Earth and Sun:

I.1 Indicate the direction of the Earth's rotation, and label the time of day at points A, B, C, and D. Explain your reasoning. (Hint: In what direction does the Sun rise?)

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

I.2 Position the globe so that the light source is illuminating it from a distance. Find Colorado on the globe, and position the globe such that Boulder (latitude 40°, longitude 105°) is facing the light source in the noon position. Orient the globe so that the tilt of the Earth's axis is pointing veritcal–perpendicular to the light source.

This orientation represents Boulder, CO at noon during either one of the equinoxes and only occurs twice a year. One these days, the Northern and Southern Hemispheres each receive 12 hours of

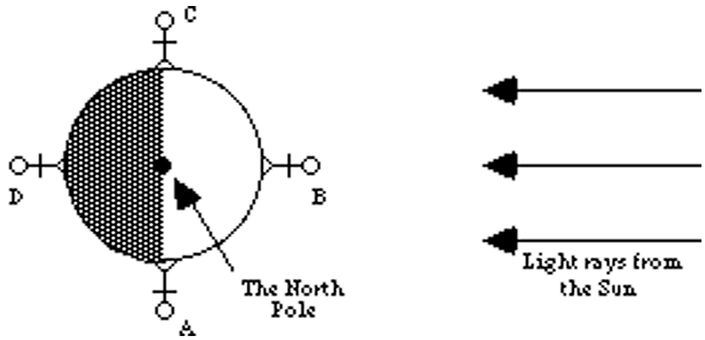


Figure 2.1: View of the northern pole of the Earth.

sunlight.

I.3 (a) What fraction of the Earth is illuminated?

(b) What major cities are experiencing sunrise and sunset?

(c) What is on the opposite side of the globe from Boulder?

(d) What time is it in Bhutan?

(e) What time is it on Easter Island?

(f) Will the banks be open in Tokyo?

(g) What do you think noon at either of the Poles (North or South) is like? What is the Sun doing throughout the day?

Rotate the globe, so Boulder is at sunset.

I.4 (a) How much of the globe is illuminated now?

(b) What time is it in Boulder?

(c) What time is it in Bhutan?

(d) What time is it on Easter Island?

The axis of the Earth is not always perpendicular to the Sun. The orientation changes over the course of the year and is responsible for the seasons. We will discuss this in the next section, but for now let's pretend the Earth is another planet that we are exploring for the first time. This pseudo-Earth has all the same geographic features and political boundaries, but it's rotation axis might have a different orientation.

I.5 Let's say we have two explorers, one in Colorado and one in Bhutan, and they are both experiencing the same time of day. Where is the rotation axis pointing? Explain your reasoning.

What if instead of the orientation of the rotation axis changing, the geographic location of the poles changes, so that the new North and South Poles are now located somewhere else on the globe but the rotation axis is still perpendicular to the Sun.

I.6 Our explorers are still in Colorado and Bhutan, and still experiencing the same time of day. Where are the new North and South Poles? Explain your reasoning.

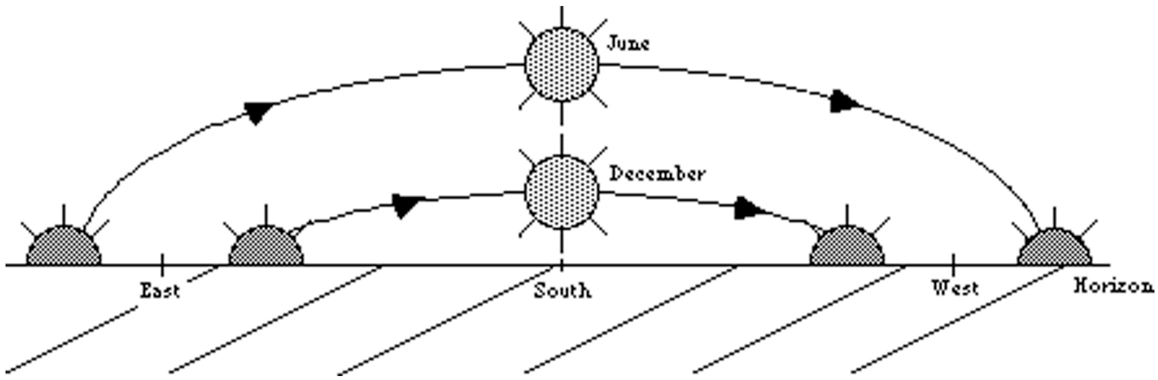


Figure 2.2: Position of the Sun throughout the day in June and December. Note that the winter Sun does not rise as high, nor is it up for as long.

II Annual Motion of the Sun

The position of the Sun in the sky also changes as the Earth orbits around the Sun as shown in Figure 2.2. This motion is not to be confused with the daily motion of the Sun described above, which only moves the Sun from east to west. The Earth's axis is tilted $23.5°$ with respect to the perpendicular of its orbital plane (see Figure 2.3). As a consequence different parts of the Earth receive different amounts of sunlight depending on where the Earth is in its orbit.

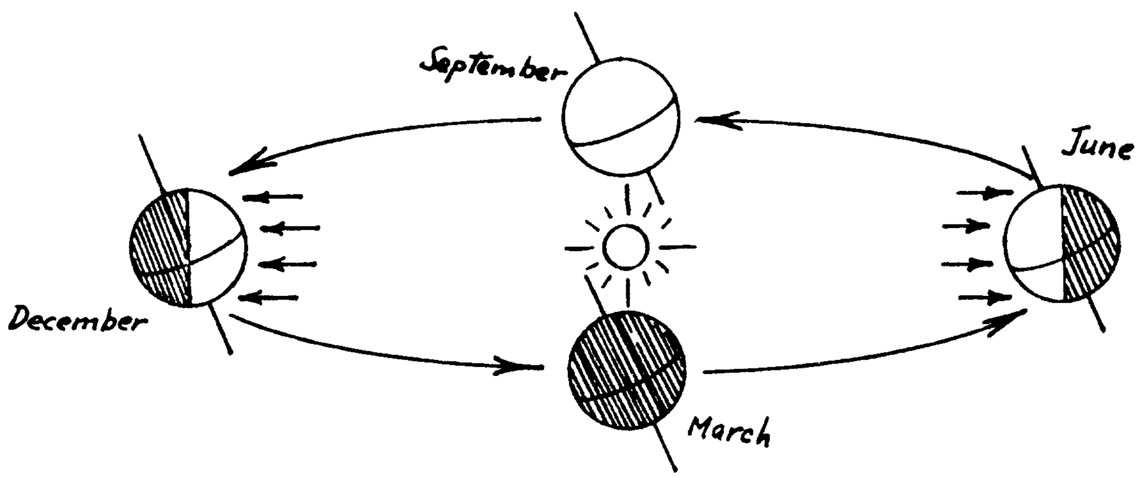


Figure 2.3: Tilt of the Earth's axis is responsible for alternating seasons in the northern and southern hemispheres. Note: the orbit is circular, but it is shown here in projection

Due to the Earth's tilt the northern hemisphere receives more light during the summer months and less light during the winter. The Sun also rises higher in the sky during the summer and this direct sunlight is more warming. These two effects cause the summer to be warmer than the winter. The summer is not warmer than the winter because the Earth is closer to the Sun. In fact, the Earth is slightly closer to the Sun during the northern hemisphere's winter.

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 up and down 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 changes the direction of its seasonal movement. On the Summer solstice the Sun stops moving to the North and starts to descend to the South; the opposite happens when the Sun's motion stands still on the winter solstice.

Figure 2.4 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.

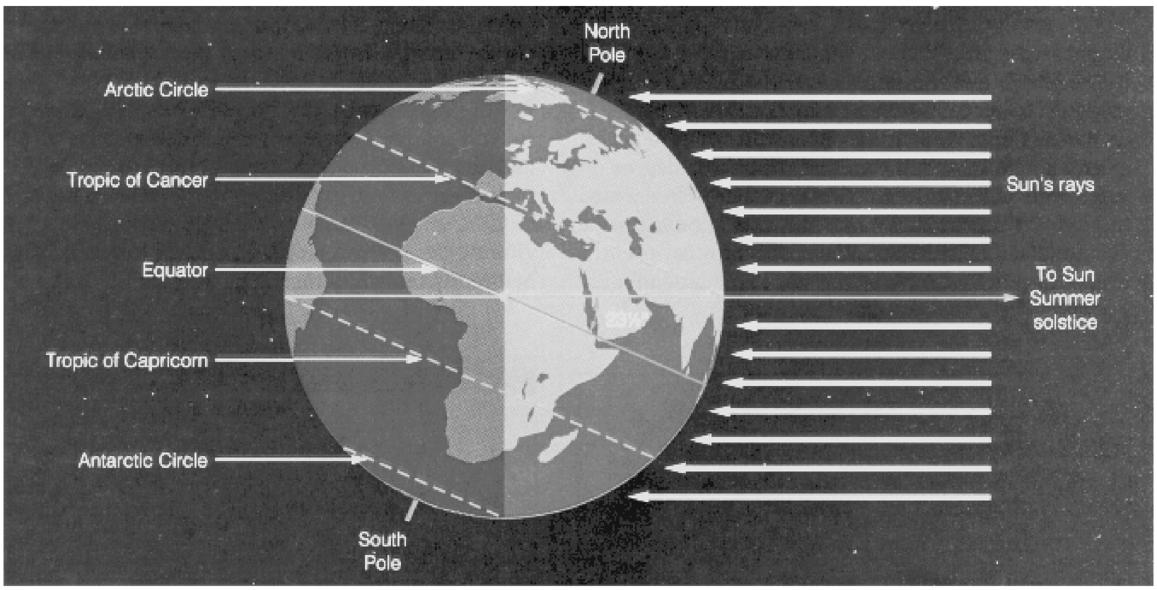


Figure 2.4: The Earth at the summer solstice

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, South, East or West.

Rotate the globe so that the stars are rising to answer the next question.

II.2 What direction do the stars rotate around Polaris, the "North Star," as seen from (the ground) here in Boulder. Do they go appear to move clockwise or counter-clockwise? (Hint: It can be helpful to imagine looking up at the night sky as well.)

II.3 (a) What season is Bhutan experiencing?

(b) How about Easter Island?

(c) Do locations at the equator experience seasons? Do the poles? Explain your reasoning.

The Tropic of Cancer (23.5° N latitude) marks the latitude where the Sun can be seen at the zenith (i.e. directly overhead) on the summer solstice.

II.4 (a) Can the Sun ever be at at zenith in Boulder? If so, when? If not, why not? Use your globe to confirm your answer.

(b) Is there anywhere in all of the fifty United States where you could see the Sun at the zenith? If so, where?

The Arctic Circle lies at a latitude of 66.5° N. 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.

II.5 (a) Find the town of Barrow, Alaska on your globe. On the summer solstice at what times will the Sun rise and set in Barrow?

(b) How high is the sun in the sky on the summer solstice in Barrow?

(b) If the sun spends half the year continuously up in the North pole, why doesn't it become really hot there?

Without changing the orientation of the globe, study what is happening down under in Australia.

II.6 (a) On the Northern hemisphere's Summer solstice is the Sun to the North or South?

(b) What season is Australia experiencing?

(c) Is the whole southern hemisphere experiencing the same season? Explain your reasoning.

The Tropic of Capricorn (23.5° S latitude) marks the southernmost point at which the Sun can be seen at zenith.

II.7 (a) Does Easter Island ever experience the Sun at zenith?

(b) Find the town of Alice Springs in the center of Australia. Is the sun ever directly overhead in Alice Springs? If so, when? (Refer to the dot marking the town.)

The Antarctic Circle (66.5° S) is the southern equivalent of the Arctic Circle.

II.8 (a) On our summer solstice what time does the Sun rise at the South Pole?

II.9 (a) In Australia, do the stars rise in the east and set in the west?

(b) Which way do the stars appear to revolve around the south celestial pole?

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 (a) 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.)

(b) Three months later it is the time of the Autumnal Equinox. Which Zodiac constellation is now on the meridan at midnight?

(c) 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.2 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.

IV Post-lab Questions

IV.1 You may have noticed (and most certainly will by the end of the semester) that the peak altitude of the sun changes throughout the year. We know that the Earth rotates around the Sun in a flat plane and that the Sun is in the center of our solar system so why does its altitude change. Explain. Would you expect this change to be cyclical or random? Explain.

IV.2 NASA has considered building a moon base at the southern pole of the moon. The moon has almost no axial tilt. Using what you've learned in this lab regarding the effects of axial tilt, explain why NASA would choose to put a base on top of a mountain at one of the poles.

IV.3 How does a planet's rotation and axial tilt effect the way NASA plans long-term expeditions to a planet? How does NASA power its missions? How does NASA communicate with them? What do remote sensing instruments often need?

Lab 3

Motions of the Moon and Planets

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, a light box, styrofoam ball, pinhole camera tube.

Pre-Lab Questions

1 The Moon completes one rotation around the Earth every 27.3 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 27.3 days, why does each cycle of phases take about 29.5 days?

3 Describe how using the two similar triangles relationship can allow you to solve for the size of the Sun and the size of the Moon.

Introduction: The orbit of the moon is responsible for determining the original length of the month. The phases of the moon allow us to estimate the time at night, and understanding and predicting eclipses was a major accomplishment in early astronomy.

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 in Figure 3.1 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 shown in Figure 3.2. 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

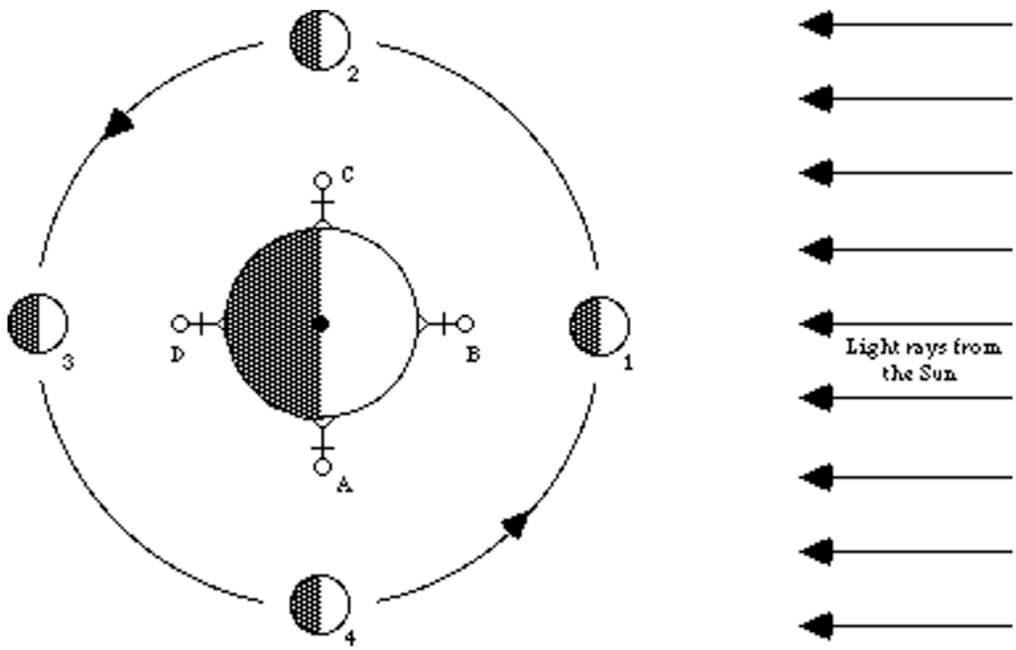


Figure 3.1: Diagram of the orbit of the Moon.

Figure 3.2: The first half of the Moon's phases.

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 as shown in Figure 3.3.

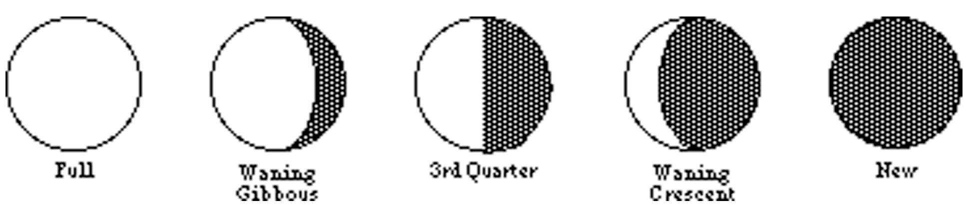


Figure 3.3: The second half of the Moon's phases.

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 Boulder is on the end of your nose. Position yourself in front of the light-box such that Boulder (your nose) is at noon. 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 Moon (foam ball) such that it appears in front of the Sun (the light box). This is the new Moon. You should only see the dark side of the Moon. Is it easy to see the Moon next to the bright light?

I.2 While holding the Moon at arm's length rotate counter-clockwise (i.e. to your left). Keep your eyes on the Moon the entire time. Watch the phase of the Moon change as you move. You should begin to see the illuminated half of the Moon come into view. Stop turning when you can see exactly half of the Moon illuminated (i.e. 1st quarter). Which side of the Moon is being illuminated?

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

What time is it for you on Earth?

I.3 Continue to turn slowly to your left until the Moon 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'll probably move it behind the shadow of your head. This is lunar eclipse - when the shadow of the Earth covers the Moon.

I.4 Again continue to turn to your left, holding the Moon at arm's length. Which side of the Moon is now illuminated?

Move until the Moon is half illuminated (3rd quarter). What time is it now?

II Moonrise and Moonset:

As you observed in the last exercise, there is a relationship between the position of the Moon in its orbit and the time of day on Earth when you see it. When (i.e. what time of day) you can see the Moon depends on where it is in its orbit; and as you just saw the position of the Moon in its orbit also determines the Moon's phase.

Now use the globe of the Earth and the light-box as you did before, 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's phase is new.

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 so that its phase is 1st Quarter. Where in the sky will the Moon appear to be from Boulder?

Where in the sky does the Moon appear to be in Tibet?

What time will the Moon rise and set?

II.3 Now position the Moon so that its phase is full. At what time will it rise and set?

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

II.4 The Moon completes one lunar orbit in 27.3 days. In this time the moonrise (and moonset) time will have changed by 24 hours - which means it will appear to be right back to where it started. What time does the Moon rise in New York, as compared to Tokyo? How much earlier or later does the Moon rise each night?

II.5 The Moon is not the only Solar System object which shows phases - the planets do as well. You've learned that the Moon shows a crescent phase when it is between the Earth and Sun. Which of the planets can show a crescent phase? Why is this?

II.6 Ask your TA what phase is the Moon today. Estimate (the date) when the Moon will be new. When will it be full? What phase is best viewed during your lab time? If the Moon is visible now go outside and 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! Explain why this is so.

III The Size of the Sun and Moon

Warning! Looking directly at the Sun can 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 the 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?

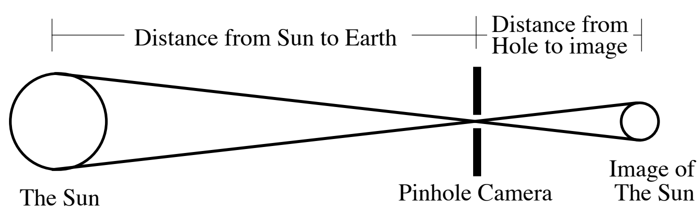


Figure 3.4: Pinhole camera.

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:

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

III.2 Determine the diameter of the Sun and compare this to the true value. Assume that the Earth is located at its average distance from the Sun.

The Moon has roughly the same angular size as the Sun. We can use the similar triangles relationship again to determine the size of the Moon:

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

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, how big is the Moon? How close are you (within 'x' percent) to the true value (which you can look up in the back of your textbook). Check to see if your number makes sense: the Moon's diameter is a little less than the width of the United States.

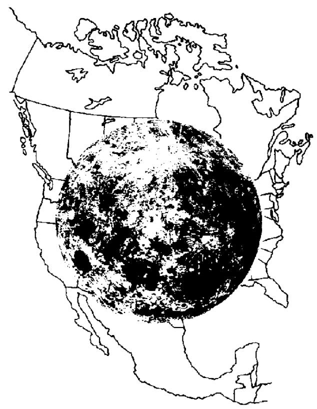


Figure 3.5: The Moon overlayed North America.

IV Solar and Lunar Eclipses

Since 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 exactly matches the Sun's. This produces a very brief total eclipse - perhaps lasting only 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 amount of time that the eclipse could be observed?

If an eclipse occurred 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.

What distance is just right for the Moon's apparent size to exactly match the Sun's? Express your answer in km and in Earth radii.

It's 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 of the Earth (your head) can fall on the Moon, causing a lunar eclipse. What phase is this?

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? (Hint - could anyone standing on your face see the Moon in shadow?)

Many people 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.

IV.4 Hold the styrofoam Moon at its true (properly-scaled) distance from the globe of the Earth. Calculate the size of the Earth's shadow at this distance (Hint: Think about similar triangles).

V Motions of the Planets:

Five planets are easy to find with the naked eye: Mercury, Venus, Mars, Jupiter, and Saturn. Like the Sun and the Moon, the planets appear to move slowly through the constellations of the zodiac. The word planet comes from the Greek for "wandering star."

However, although the Sun and Moon always appear to move eastward relative to the stars, the planets occasionally reverse course and appear to move westward through the zodiac. This is called apparent retrograde motion. This phenomena was a problem for ancient astronomers but today we know it is a consequence of the planets orbiting the Sun (heliocentric solar system).

It wasn't until the 1500s that Copernicus worked out the details of a heliocentric solar system. He was also able to show whether the known planets were closer or further from the Sun than the Earth. Because Venus and Mercury are always observed to be fairly close to the Sun in the sky (i.e. we only see them near sunrise or sunset), they must have orbits interior to the Earth's. We call them inferior planets.

Likewise, because Mars, Jupiter, and Saturn can be seen in the middle of the night, they must be further from the Sun than the Earth. These planets are called superior planets.

We can use geometry to define certain positions for the planets in their orbits. Take a look at the diagram in Figure 3.6. This configuration is called a conjunction, meaning that a planet appears lined up with (i.e., in conjunction with) the Sun as seen from Earth.

Note that the inferior planets have two configurations called conjunction: superior conjunction when the planet is behind the sun as seen from Earth and inferior conjunction when the planet is between the Sun and Earth.

V.1 Although Venus is as close to Earth as possible at inferior conjunction, it would not be a good time to observe the planet. Why not?

V.2 The angle between the Sun and a planet as seen from the Earth is called elongation. So when a planet is at conjunction, its elongation is 0°. When elongation is at its maximum value, we say that the planet is at greatest elongation. What is the greatest elongation for Venus? Refer to the diagram above for help. What assumption did you make in order to do your calculation?

For the superior planets, we can also define a configuration called opposition when the elongation is 180°. The diagram in Figure 3.7 shows Mars at opposition. Note that Mars can also be seen at conjunction (but Venus will never be seen at opposition).

V.3 Sketch the diagram in your lab report, labeling the positions of Mars at conjunction, opposition, and quadrature.

V.4 Which planets can show apparent retrograde motion, superior, inferior, or both? What

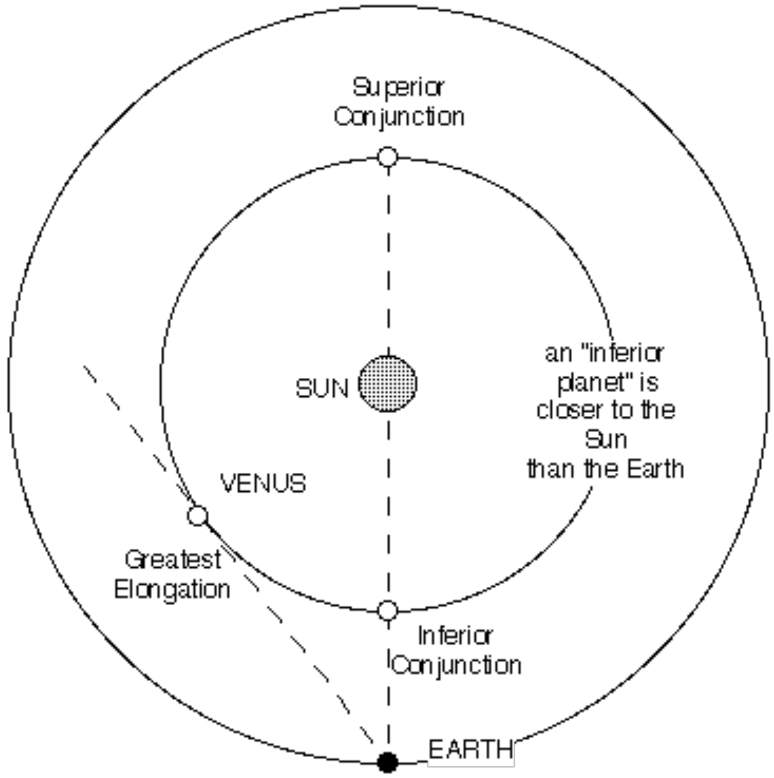


Figure 3.6: Orbit of Venus.

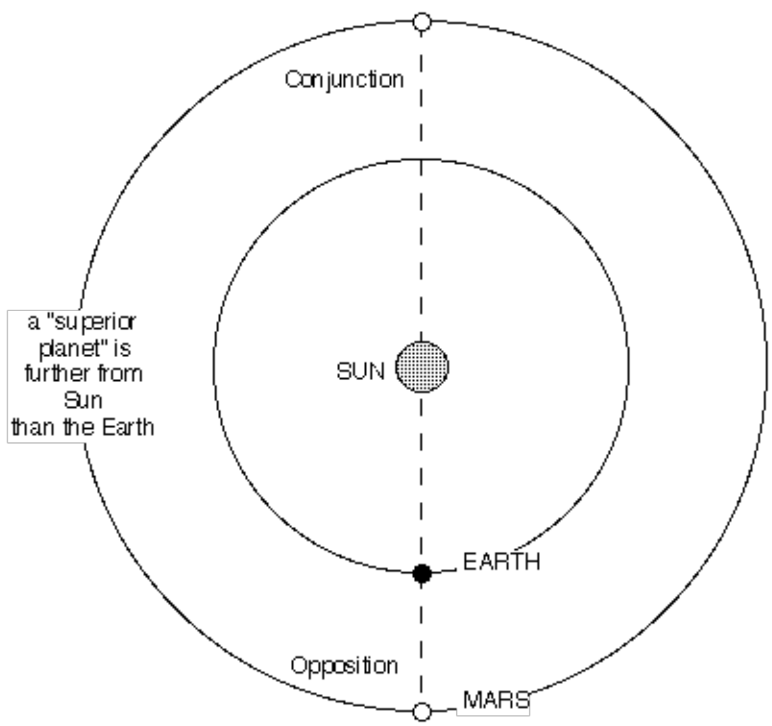


Figure 3.7: Orbit of Mars.

configuration must the planet be near?

VI Motions of the Stars

Now we will consider the "motions" of the stars as seen from Earth. We know now that the variation in the position of stars from month to month is really due to the movement of the Earth around the Sun. However, it is still convenient to use a coordinate system which treats the Earth as stationary to locate the positions of stars. We call this the Celestial Sphere. In this coordinate system the Earth is located at the center of a sphere containing all of the objects in the sky.

Just like longitude and latitude are used to locate your position on the Earth, we can locate any star on the celestial sphere by specifying its Right Ascension (RA) and Declination (dec). Right Ascension is measured in units of time (hours, minutes, seconds) and is defined to be 0h at noon on the vernal equinox (around March 21).

Declination is measured in units of degrees. The celestial equator has a dec of 0° and the north celestial pole has a dec of $90°$.

You may have noticed that the digital clocks on the deck at the observatory do not match the time on your watch. This is because they measure Universal Time (UT) and Local Sidereal Time (LST). UT is the time as kept in Greenwich, England. In Boulder, we are 7 hours behind Greenwich when on Standard Time and 6 hours behind Greenwich when on Daylight Savings Time. Local Sidereal Time literally means "local time according to the stars." LST changes from regular solar time by about 4 minutes each day. LST is very useful because it tells you the RA of the stars which are directly overhead (at your meridian). For example, if you stand outside at night and look up and see the star Vega at the meridian, you know that the LST is 18h 36m, the RA of Vega. Note: Your meridian is a half-circle (not a point) that starts at your horizon due south and ends at your horizon due north. The point on your meridian which is directly overhead is called your zenith.

VI.1 Boulder is located at 40°N Latitude. We can observe stars all the way to the horizon in our eastern sky and to the top of the flatirons ($\sim$10° above the horizon) in our western sky. What is the range of declinations that we can observe on any given night. (Hint: You may find it helpful to draw a diagram here. Remember the north celestial pole is an extension of the Earth's north pole and the celestial equator is an extension of the Earth's equator. If you were standing at the north pole, the celestial equator would be at your horizon. As you walk south, the celestial equator will begin to tilt up so that your horizon is now below it.)

Determining the range of Right Ascensions that we can observe on any given night is a little more complicated. As the Earth orbits the Sun, the range of RAs that we can observe changes. In order to make our lives a little easier we use another term for determining this range at any given location: Hour Angle.

Imagine that the meridian represents 0 HA and that we can see $\sim$6 hours worth of nighttime sky at any given time (3 hours to the left of the meridian and 3 hours to the right). That means if we know the RA of a star on the meridian we can determine the range of RAs that we can observe at that time.

VI.2 Imagine you go to an observing session and Vega is at the meridian. Would you be able to observe the Ring Nebula (RA = 18h 53m 32s, dec = 33° 1' 54")? How about the spiral galaxy M74 (RA = 1h 36m 39s, dec = 15° 47' 36")? If either of the of these objects could not be observed when you arrived, could they be observed later in that night? Explain.

VI.3 At one particular time on one particular day of the year, solar clocks will exactly agree with sidereal clocks. When is this?

Hint: After this time, the sidereal clock will gain about 1 second for every six minutes, or

2 hours for each month.

By how much will the solar and sidereal clocks differ on New Year's Day?

VII Post-lab Questions

VII.1 The lunar month (the time to go from one full moon to the next) is approximately two days longer than the time it takes for the Moon to make one full circle around Earth. Why is this?

VII.2 The same face of the Moon always faces the Earth. Why?

VII.3 Earlier, you calculated the greatest eastern elongation of Venus using the sizes of Venus' and Earth's orbits. Working backwards (i.e. knowing the greatest elongations of the inferior planets) Copernicus was able to calculate the sizes of their orbits relative to the Earth's.

Using what you know about the different configurations of the superior (outer) planets, work out how Copernicus found the sizes of their orbits. Remember, Copernicus thought the planets all had circular orbits, and he knew how long it took them to orbit the Sun (e.g. sidereal period).

VII.4 Imagine you have just been put in charge of tonight's observing session. Your students will begin arriving at 9 pm and you need to have a list of objects for them to observe. The SBO catalog has a listing of observable objects by Right Ascension. Ask your TA for a copy of the catalog and make a list of 5 objects (give object name, type, RA, and dec) for your class to observe. Show all of your calculations in your lab report.

Lab 4

Kepler's Laws

Purpose: The learning goal of this lab is to understand what factors control a planets motion around the Sun.

Equipment: Computer with internet connection to the Nebraska Astronomy Applet Project, stopwatch.

Pre-lab Questions

1 Which law states that planets orbit in an ellipse?

2 What is the semi-major axis of an ellipse?

3 Explain why the following statement is false: The orbital period of Mars is longer than the Earth's orbital period because it is circular.

4 Mathematically, rearrange Kepler's 3rd Law for period.

Introduction: 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.

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

1) Launch an internet browser.
2) Go to the website http://astro.unl.edu/naap/pos/animations/kepler.html

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

I Kepler's First Law:

Kepler's First Law states that a planet moves on an ellipse around the Sun. If you have not already done so, launch the NAAP Planetary Orbit Simulator described in the previous section.

- Click on the Keplers 1st Law tab if it is not already highlighted (its 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 dont 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 planets parameters to those like our solar systems 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?

(c) Does your answer make sense with respect to your answer to I.1? Explain.

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

(b) What happens to an ellipse when the eccentricity becomes zero?

(c) What happens to an ellipse when the eccentricity gets close to one?

I.4 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.5 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.6 (a) Draw an elliptical orbit with non-zero eccentricity. On your ellipse diagram, draw a line from the position of the sun to some point on the ellipse. Label this line r. This will represent the planet-sun distance. Note that the length of r will change as the planet orbits the sun. When r is at its minimum value, we say the planet is at periapsis (this is a generic term used for an object that orbits any other object). Likewise when r is at its maximum value, we say the planet is at apoapsis.

(b) Now use your ellipse diagram to come up with an equation for r at periapsis and an equation for r at apoapsis in terms of the semi-major axis and eccentricity. You know four constraints, what the distance should be if $e \to 0$ and $e \to 1$ for any a, and you know what happens to the periapse and apoapse distance if $a \to 0$ and if $a \to$ very large number.

(c) Use the applet to check your equations: For an ellipse of eccentricity e = 0.9, find the ratio of periapsis to apoapsis. You can use the tick-marks to read distances directly off the screen (to the nearest half-tick).

I.7 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). Show your work.

(b) For e = 0.1?

(c) Without using the simulation applet, come up with an estimate for what the ratio would be for e = 0? What about e = 1? Show your work.

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

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

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

I.9 (a) What is the eccentricity of the Earth? Mars? Venus?

(b) Do you think it would be harder or easier for life to develop on a planet with a high eccentricity? Explain your reasoning.

I.10 (a) What is the eccentricity of the Jupiter? Saturn? Uranus? Neptune?

(b) Asteroids often have eccentricities between 0 and 0.2, Kuiper Belt objects can have eccentricities from 0 to 0.5, and comets can have eccentricities between 0 and 1. Knowing this information and the eccentricity information of the planets, what does this tell us about the solar system? Explain your reasoning.

(c) Can we infer from this anything about how the solar system formed? Explain your reasoning.

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 Keplers 2nd Law tab.

- Important: Use the "clear optional features" button to remove the 1st Law options.
- Press the "start sweeping" button. Adjust the semi-major axis and animation rate so that the planet moves at a reasonable speed.
- Adjust the size of the sweep using the "adjust size" slider.
- Click and drag the sweep segment around. Note how the shape of the sweep segment changes as you move it around.
- Add more sweeps. Erase all sweeps with the "erase sweeps" button.
- The "sweep continuously" check box will cause sweeps to be created continuously when sweeping. Test this option.

II.1 Where (or when) is the sweep segment the "skinniest?" Where is it the "fattest?"

II.2 What eccentricity in the simulator gives the greatest variation of sweep segment shape?

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 (dont 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 (a) Where does a planet spend more of its time: near perihelion or near aphelion?

(b) Where is a planet moving the fastest: near perihelion or near aphelion?

(c) If you were planning a mission to a near-Earth asteroid, where in an asteroid's orbit would you try and land the spacecraft? What would be the biggest orbital challenge? Explain your reasoning.

(d) If you were planning a mission to a comet, where in the comet's orbit would you try and land the spacecraft? What would be the biggest orbital challenge? Explain your reasoning.

II.6 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.)

III Kepler's 3rd 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 Keplers 3rd Law for semi-major axis. 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 6 months each year)?

Click on the Newtonian Features tab.

Click on both show vector boxes to show both the velocity and the acceleration of the planet. Observe the direction and length of the arrows. The length is proportional to the values of the vector in the plot.

III.4 The acceleration vector is always point towards what object?

III.5 Create an ellipse with a = 5 AU and e = 0.5. For each marked location on the diagram in Figure 4.1 indicate a) whether the velocity is increasing or decreasing at the point in the orbit (by circling the appropriate arrow) and b) the angle ? between the velocity and acceleration vectors. Note that one is completed for you.

III.6 Where do the maximum and minimum values of velocity occur in the orbit?

III.7 Can you describe a general rule which identifies where in the orbit velocity is increasing and where it is decreasing? What is the angle between the velocity and acceleration vectors at these times?

IV Galilean Moons

A great laboratory for studying Kepler's laws are the Galilean moons of Jupiter. From simple observations of their orbits and Kepler's laws, we can deduce many facts about the Jupiter system that would otherwise be difficult to deduce.

Figure 4.2 shows depictions of nine observations of Jupiter's moons, each one day apart. All of Jupiter's moons orbit in the same plane, and we are viewing that plane almost edge on. This means that the moons will not move much up and down, only left to right. The simulations earlier in the lab showed a different view, from above.

IV.1 Using what you know about orbits, study these nine days of observations and determine

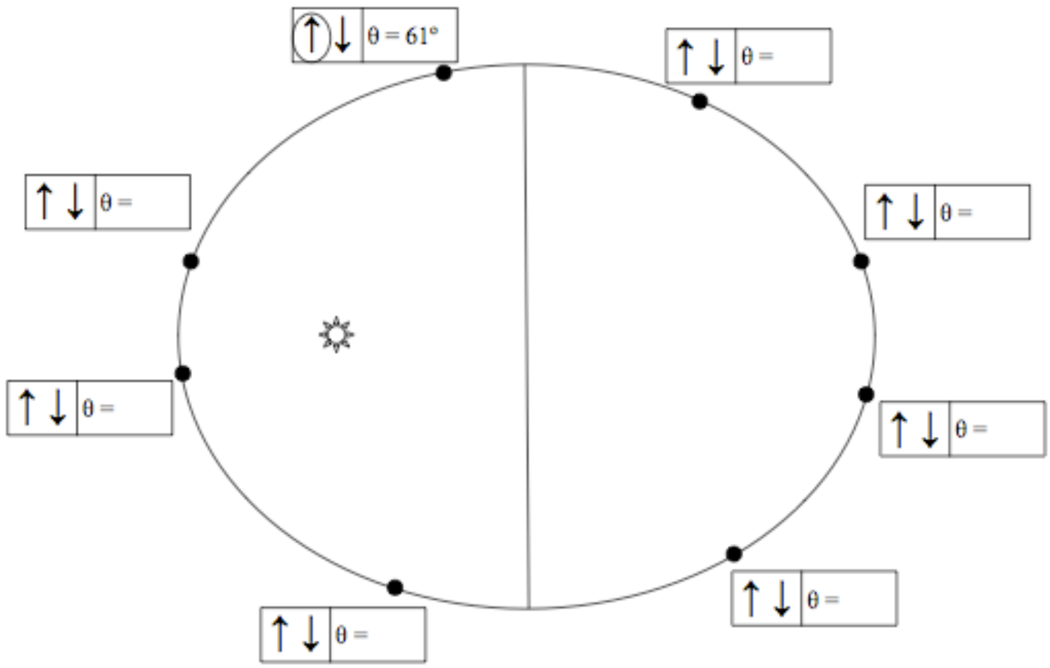


Figure 4.1

the periods of all four moons: Io, Europa, Ganymede, and Callisto.

IV.2 Do you notice a pattern? If so, explain what the pattern is.

This is called an orbital resonance, and is responsible for heating the interiors of the Galilean moons and producing exciting geophysics. Io is covered with volcanoes that constantly spew material. Some of which even enters into orbit; it is expelled with so much energy. Europa and Ganymede may have subsurface oceans because of this resonant heating.

IV.3 Using the above images, measure the semi-major axis of Io and Europa in Jupiter radii. One Jupiter radii is 71,492 km. How can you improve your estimate? Explain what you did and why you did it.

Kepler's 3rd law for the Galilean moons can be written:

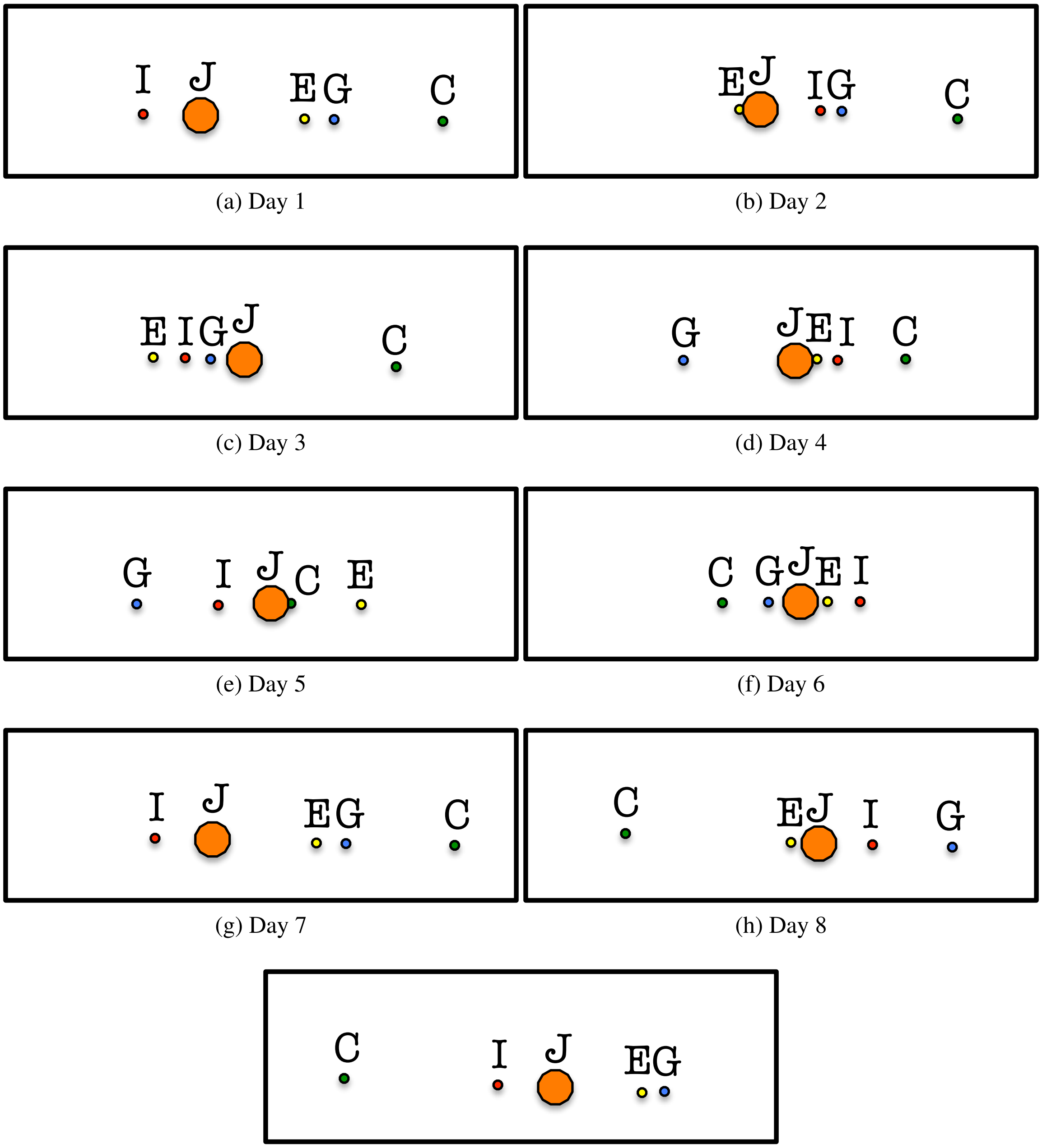
$$a^3/P^2 = GM$$

where a is the semi-major axis, P is the period, G is the gravitational constant (G = 6.673 $\times$ 10^{-11} m^3 $kg^{-}1$ $s^{-}2$), and M is the mass of Jupiter.

IV.4 (a) You now know the period and the semi-major axis of Io and Europa, and so you are able to get two independent mass estimates for Jupiter. You will need to do some unit conversions.

(b) Combine your answers so that you get the most accurate estimate. Explain what you did and why you did it.

IV.5 Now that you know the mass of Jupiter, rearrange the equation so that you solve for the semi-major axis. Then use the equation and the periods of Ganymede and Callisto to solve for their semi-major axes.



(a) Day 1 (b) Day 2 (c) Day 3 (d) Day 4 (e) Day 5 (f) Day 6 (g) Day 7 (h) Day 8 (i) Day 9

Figure 4.2: Cartoons of data that show the orbits of the Galilean moons (I: Io, E: Europa, G: Ganymede, C: Callisto) and Jupiter (J).

With only nine days of observations, we have learned many of the fundamental characteristics of the Jupiter system!

V Post-lab Questions

V.1 (a) What is the rotational period of the Moon? How does this relate to the orbital period of the Moon?

(b) Is the Moon's orbit eccentric? What does this mean about the speed of the Moon through its orbit?

(d) In the Motions of the Moon lab you learned that the same face of the Moon always faces the Earth (i.e. only 50% of the Moons surface can be observed from Earth at any one time). Actually, we have been able to see up to 59% of the Moons surface from Earth. Explain how we can see more than half of the Moons surface using what you know about the Moon's eccentricity.

V.2 Earlier, you compared the average global temperatures of two planets and asked how their eccentricities might differ. What is the eccentricity of Earth? Given that value, should the Earth's average global temperature have more in common with Blip or Blob? Does your answer make sense and if not can you think of another factor that might regulate global temperatures?

Lab 5

The Eratosthenes Challenge

Purpose: The purpose of this observing project is to measure the circumference of the Earth in your paces, 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.

Equipment: Compass, 100-yard tape measure, and ruler.

Pre-lab Questions

1 If the Sun was directly above Syene on the summer solstice, what latitude was Syene at?

2 In your own words, explain the difference between a measurement (random) error and a systematic error?

3 Why must you measure the distance between SBO and baseline road in an exactly north-south direction?

4 Estimate the distance (in either paces or yards) from SBO to the south sidewalk of Baseline Road (you will not be penalized if you are wrong).

Introduction Eratosthenes of Cyrene was born in 276 BC in Cyrene, North Africa (now Shahhat, Libya) and died in 194 BC in Alexandria, Egypt. He was a student of Zeno (founder of the Stoic school of philosophy), created the field of geography, invented a mathematical method for determining prime numbers, and made the first accurate measurement for the circumference of the Earth.

I His Famous Experiment

Details of his famous measurement 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, and describe how Eratosthenes compared the noon shadow on the summer solstice (June 21st) between two Egyptian cities, which were 500 miles apart in the north-south (N-S) direction: Syene (now Aswan) on the banks of the Nile river and Alexandria 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 (5,000 stadia, now thought to be 24% too low), 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, during the Renaissance, the length of a Greek stadium was under-estimated yielding an even smaller circumference for the Earth in Renaissance units of length. 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.

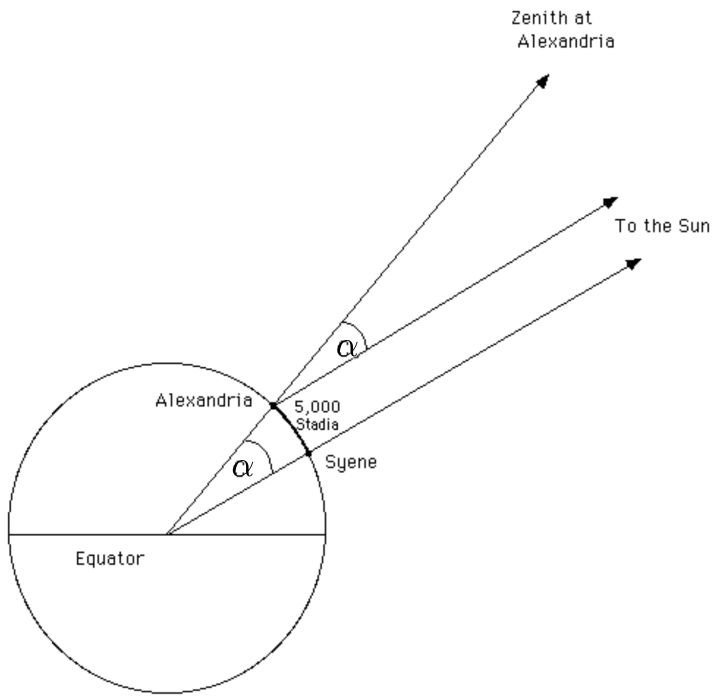


Figure 5.1: Diagram of Eratosthenes experiment. The angle α could be determined from the length of the shadow of a gnomon in Alexandria.

Here is how Eratosthenes made his measurement (see Figure 5.1). He had heard that on the summer solstice the Sun at noon stood directly over Syene, at the zenith. So that on the summer solstice in Syene, the Sun's light would penetrate all the way down to the bottom of a well casting no shadow. Eratosthenes measured the angle of the Sun off the zenith (α in Figure 5.1) in Alexandria on that same day. He measured α to be 7.2°. Unfortunately, this was 6% too small. As shown in the figure, α is also the difference in latitudes of these two locations. This is only true on the summer solstice in the northern hemisphere.

From here on, its all arithmetic. Logically, α is to 360° (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, and a measurement of α of 7.2°. Mathematically:

$$\frac{\alpha}{360^\circ} = \frac{\text{Distance between Syene and Alexandria}}{\text{Circumference of the Earth}} \tag{5.1}$$

and so:

$$\text{Circumference of the Earth} = \frac{360^\circ}{7.2^\circ} \times 5000 \text{ stadia} = 250000 \text{ stadia} \tag{5.2}$$

II Making a Modern "Eratosthenes Measurement"

In order to repeat Eratosthenes' experiment, we need to know the equivalent of the two measurements he had:

1. The difference in latitude between two locations on Earth.
2. The difference in distance between these same two locations in the N-S direction.

Eratosthenes measured #1 and had obtained from others a value for #2. We will measure #2 and obtain a value from others for #1.

Conveniently, we have two nearby locations with well-known latitudes:

Loc. 1: Baseline Road was determined to be at precisely 40° North Latitude when Colorado was surveyed in the 1800s, hence its name.

Loc. 2: Sommers-Bausch Observatory (SBO) has had its latitude determined to be: 40.00372° N by an astronomical measurement.

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 86, 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, someone has painted a red line on the sidewalk near the bus stop in order to mark the exact location of the 40th parallel. (Notice how it splits the rock to the east.)


US 36
SBO
Broadway
Baseline
(40th Parallel)

III The Eratosthenes Challenge:

Repeat the Eratosthenes measurement using your paces and the information about latitude provided above.

We will provide a 100-yard tape measure to convert your paces to 100 yards (length of a modern stadium), and then you can convert yards to miles using the standard conversion (1760 yards = 1 mile).

Each member of your lab group must make these measurements (both pacing between SBO and Baseline and "calibrating" their paces by stepping off the 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, as well as how many modern stadii and then miles in circumference the Earth is.

On the next pages you will find space to record your experiment, and 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.

Remember you must record all measurements and calculations made. 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 and stay safe, especially when crossing Baseline and other streets; the cars do not know that you are conducting an historical reenactment.

IV Understanding Error

Webster's dictionary defines error as "the difference between an observed or calculated value and the true value". When we think of reducing error we often think of using a better measuring device or by repeating measurements several times and averaging, however this may not get us any closer to the "true value". To understand why, we need to understand the distinction between precision and accuracy. Errors in precision are called measurement (random) uncertainties and repeating measurements and averaging or using a ruler with finer ticks can reduce these uncertainties but never eliminate them. However, precise measurements do not yield an accurate result if the experimental setup is inaccurate. Errors with the experimental setup are systematic errors, and reducing these errors make an experiment more accurate. Thus, accuracy is a measure of how closely the results of the experiment are to the true result, and precision is a measure of how closely are measurements agree with each other when we repeat the experiment. This demonstrated well in Figure 5.2. We wish our measurements to be both accurate and precise.

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% 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.

Precision (Measurement Uncertainty) Typically, an experimental result is listed as: [value obtained] +/- [precision], e.g. 25,000 miles +/- 1000 miles for the circumference of the Earth.

IV.1 You can estimate your individual precision just as you might if you were using a ruler. What is your individual value for the circumference of the Earth (in miles) and its estimated precision here:

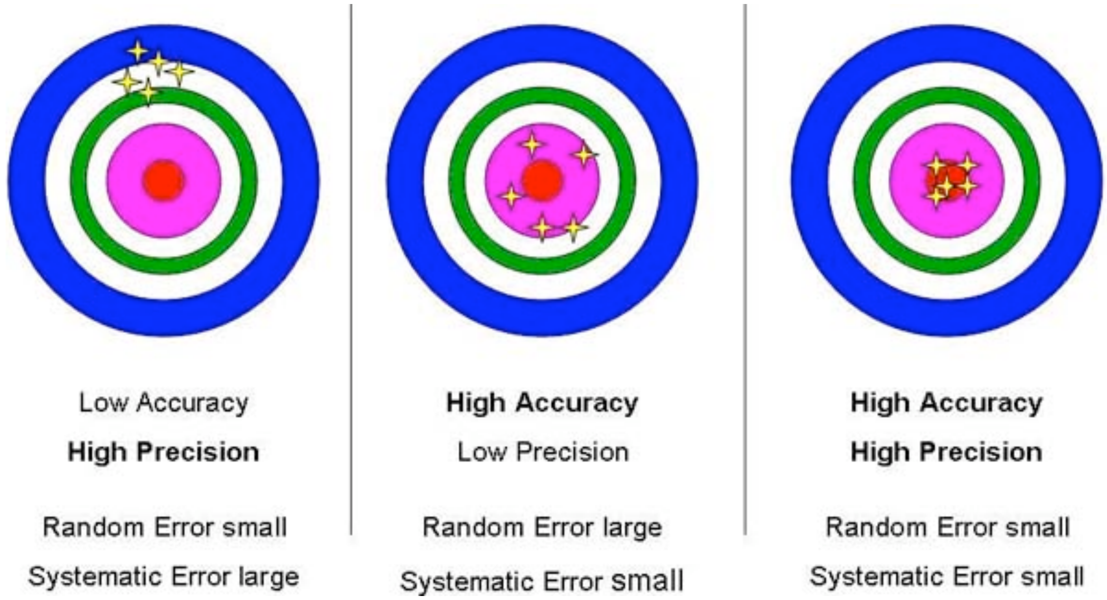


Figure 5.2: Difference between accuracy and precision.

Compare your final results on the circumference of the Earth with the results from the other members of your group.

IV.2 Knowing their measurements, improve your estimate for the value of the circumference of the Earth and your estimate for the precision. Show what you did and explain why.

Accuracy (Systematic Error) 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, assumptions involving using paces as the measuring device, in the "calibration" of your paces, or in the route employed.

IV.3 Fill in Table 5.1. (Note: A listing of "human error" is insufficient, be specific!) The more specific you are in the Table entries, the better your grade for this observing project.

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

Table 5.1: Systematic Errors in Eratosthenes' Experiment

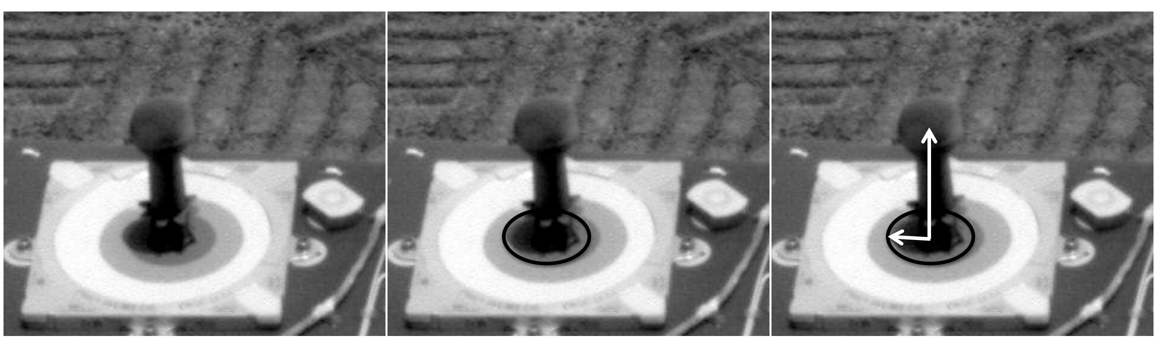
IV.4 Why does averaging many results typically not serve to reduce the systematic errors?

V Post-lab Questions

We can perform the same experiment on Mars that Eratosthenes did on the Earth. The Mars rovers, Spirit and Opportunity, landed on the Martian surface in early 2004. Each rover was built with a Sundial that was used also as a photometric calibration device, but we will use them as gnomons, measure their shadows, and calculate the angle of the Sun at the two locations of the Mars rovers. Spirit is located at 14.57°S 175.48°E and Opportunity at 1.95°S 354.47°E and they are 743.7 km km apart in the N-S direction.

(a) Gnomon (b) Projected ring of constant radius (c) Projected shadow length

Figure 5.3: Sundial on the Spirit rover at 12:45 PM local Mars time on March 31, 2004.



(a) Gnomon (b) Projected ring of constant radius (c) Projected shadow length

Figure 5.4: Sundial on the Opportunity rover at 11:47 AM local Mars time on March 31, 2004.

The images in Figures 5.3 and 5.4 were taken on the same day (March 31, 2004) very close to local noon, so the Sun is near zenith and the shadow from the gnomon is almost completely in the N-S direction. The rovers were not orientated in the N-S direction, so the direction of the shadow in the images is not the same.

V.1 Determine the angle of the Sun from zenith for each rover, α, from the height of the gnomon, h, and the length of the shadow cast, l. This can be done using geometry, as shown in Figure 5.5.

For the Spirit rover:

$$\alpha_{\text{Spirit}} = 90^\circ - \arctan\left(\frac{h_{\text{Spirit}}}{s_{\text{Spirit}}}\right) = \underline{\hspace{3cm}} \tag{5.3}$$

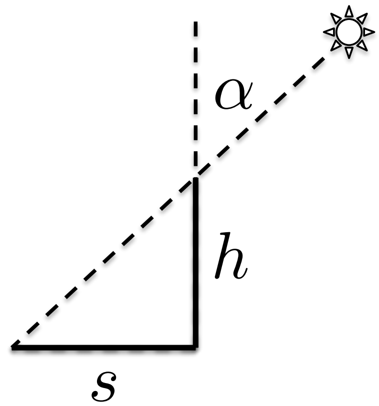


Figure 5.5: Geometry of the Sundial on Mars rover.

For the Opportunity rover:

$$\alpha_{\text{Opportunity}} = 90^\circ - \arctan\left(\frac{h_{\text{Opportunity}}}{s_{\text{Opportunity}}}\right) = \underline{\hspace{3cm}} \tag{5.4}$$

V.2 The difference between α_{Spirit} and $\alpha_{\text{Opportunity}}$ will be equal to the difference in latitude between the two rovers.

$$\text{Difference in latitude} = \alpha_{\text{Spirit}} - \alpha_{\text{Opportunity}} = \underline{\hspace{3cm}} \tag{5.5}$$

V.3 (a) Use Eratosthenes' equation to find the circumference of Mars from the difference in latitude.

(b) Explain how you could reduce random error, while using the Mars rovers to perform Eratosthenes' experiment?

(b) Explain how you could reduce systematic error, while using the Mars rovers to perform Eratosthenes' experiment?

Lab 6

Collisions, Sledgehammers, & Impact Craters

Purpose: 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.

Pre-lab Questions

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 Why should counting a small patch of craters on the moon show the same power law distribution as asteroids in the solar system?

4 In 1998, NASAs Near Earth Asteroid program was established with the goal of locating at least 90 percent of the asteroids and comets that approach the Earth and are larger than 1 kilometer (about 2/3-mile) in diameter, by the end of 2020. (Proposals to extend this search to sizes down to 140 meters are still in debate). In your opinion, is this a useful program? Why or why not?

I Power Law Distributions:

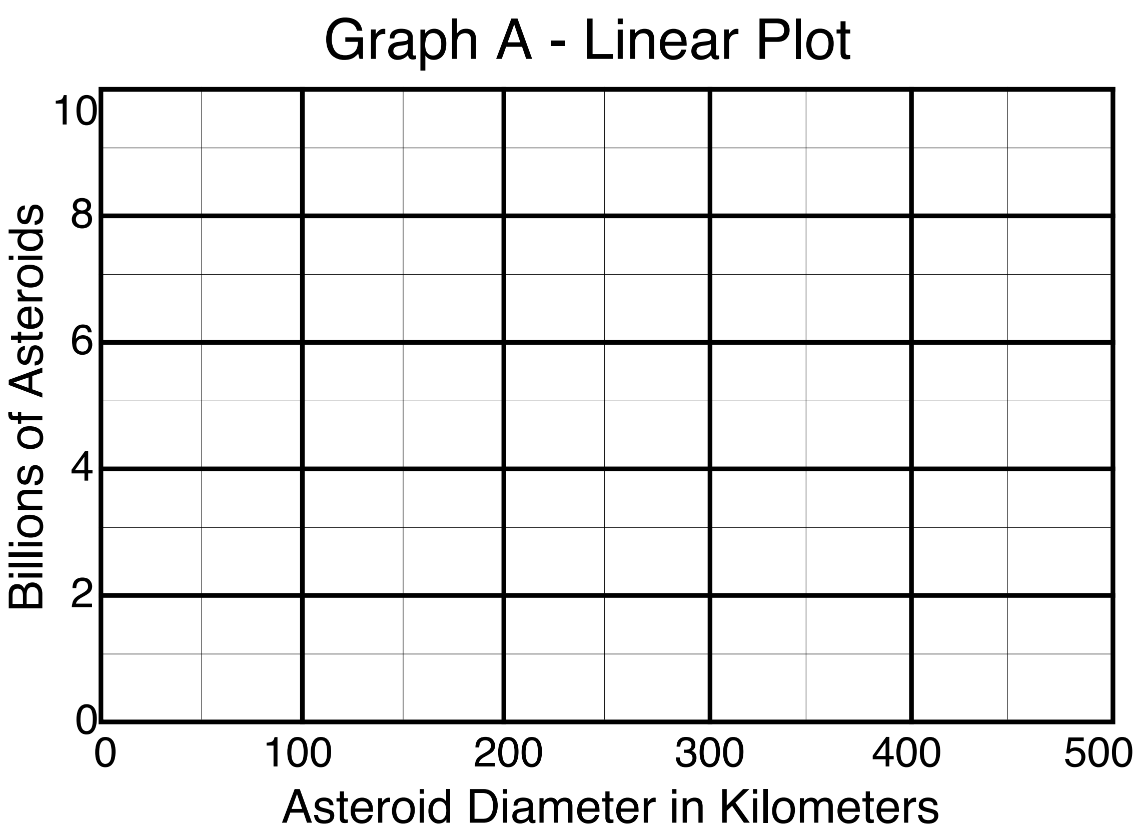
Numbers and sizes of asteroids in the asteroid belt are not random, but rather exhibit a fairly well behaved and predictable pattern. For example, smaller asteroids are much more numerous than larger ones. Only three asteroids in the belt have diameters exceeding 500 km, yet twelve have diameters greater 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.

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

Diameter	Number	Scientific Number
500 km	3	3×10^0
250 km	10	10^1
100 km	130	1.3×10^2
10 km	5,000	5×10^3
1 km	1,000,000	10^6
0.05 km	10,000,000,000	10^{10}

Table 6.1: The size distribution of the asteroids.



in any meaningful manner on a linear 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.

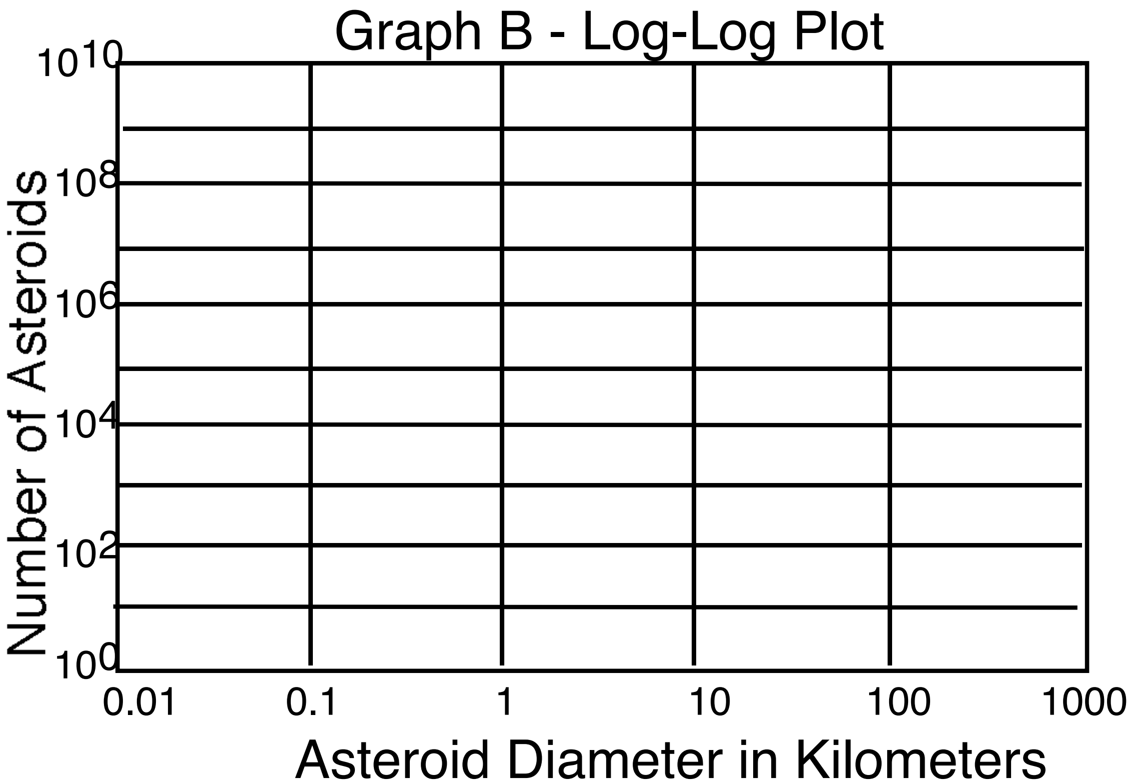
I.2 (a) In Graph B, how many orders of magnitude (powers of 10) are there on the x-axis?

(b) the y-axis?

I.3 Now, plot the same numbers again, but this time using the scale provided with Graph B (a log-log plot).

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

$$N = AR^b$$



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. 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!

Figure 6.1 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. The power law distribution of the sizes of asteroids therefore suggests a collisional fragmentation process, the consequences of which are fascinating. The sizes continue getting smaller and smaller and the numbers continue to become greater and greater.

The equation $N = AR^b$ describes a relationship between the number of objects, N, and their radius, R. But what are the effects of changing the values of the parameters A and b? The left plot in Figure 6.2 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 plot in Figure 6.2 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.

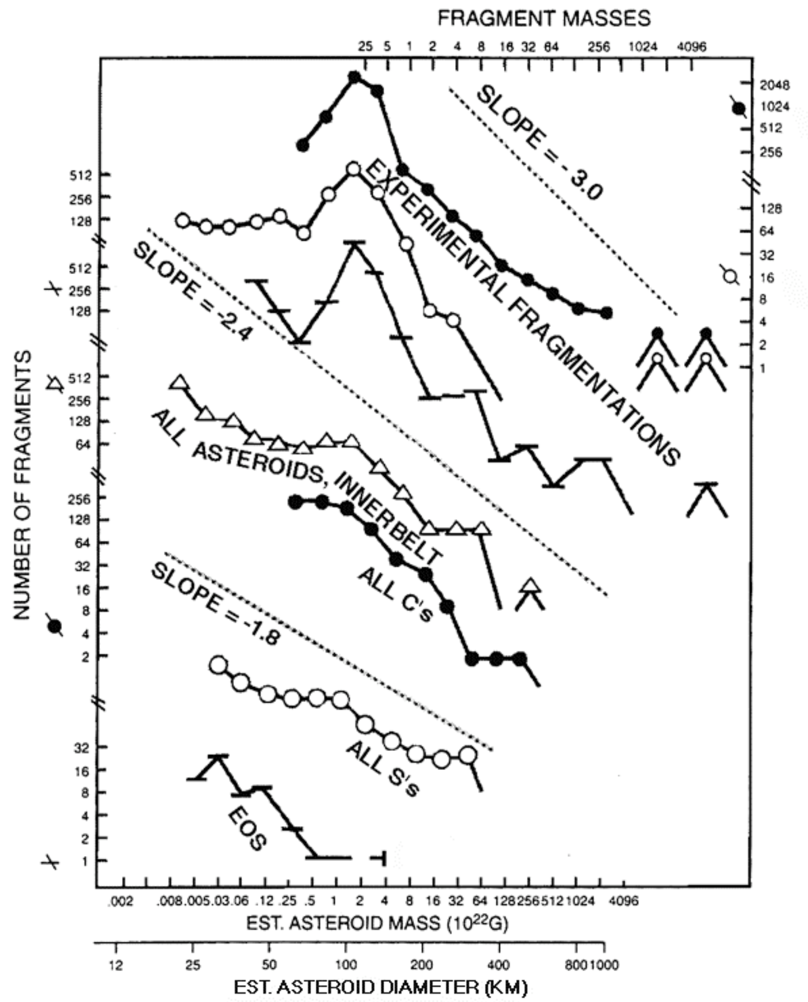


Figure 6.1: Comparison of size distributions of shattered rock fragments and asteroids: The top three curves are fragment distributions of artificial aggregate targets of rock with masses on upper scale. The bottom four curves show actual asteroids in the inner half of the asteroid belt, with masses on the lower scale, including members of the Eos Hirayama familywhich may be fragments of a single asteroid collision event. (From Moons and Planets, W. Hartmann, 4th Ed. 1999)

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?

The diagram in Figure 6.3 was made using a computer simulation of different size distributions for a range in the values from b = 1.5 to 4.0.

I.5 (a) Which of these size distributions has more big particles and fewer small particles? Which has more small particles and fewer large particles?

(b) You will create your own size distribution by pounding on a brick with a sledgehammer. What size distribution do you predict finding afterwards? Explain your reasoning.

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

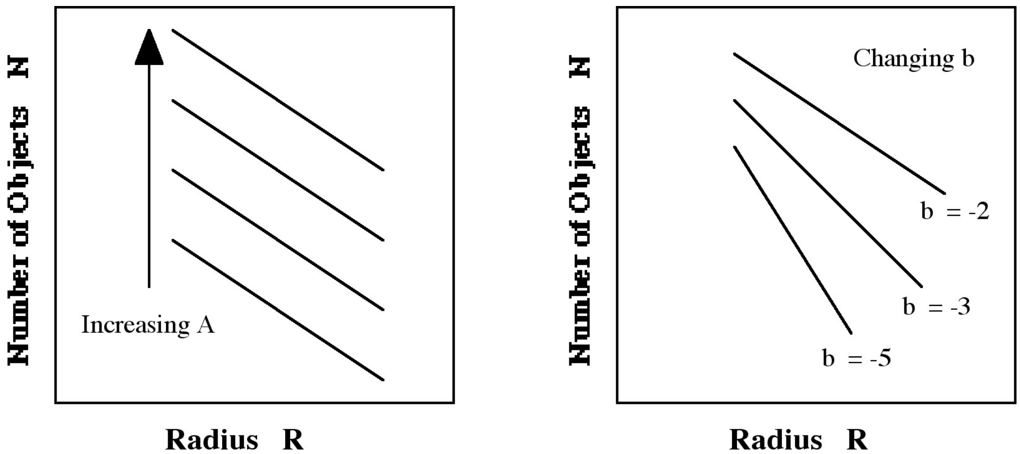


Figure 6.2: How power laws depend on their parts.

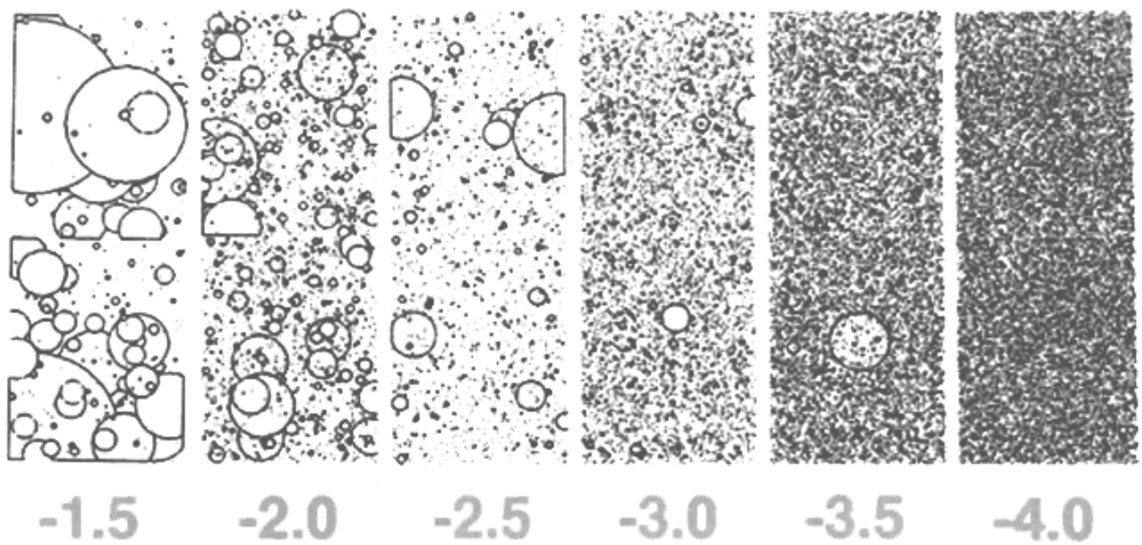


Figure 6.3: A representation of different size distributions changing the exponent, b, from -1.5 to -4.

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 cm3):

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 outside, 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.

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 materialby following the steps belowaccording 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 Table 6.2 on page 97. (Note: You do not need to empty the material onto the scale.

1	2	3	4	5	6	7
Bag #	Former Sieve Size (cm)	Current Sieve Size (cm)	Mean Particle Radius (cm)	Mass of Bits (grams)	Mass of One Particle (grams)	Number of Particles
1	2.54	1.27	0.95			
2	1.27	0.64	0.48			
3	0.64	0.32	0.24			
4	0.32	0.16	0.12			

Table 6.2

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

$$M_1 = Volume \times Density = [(4/3)\pi R^3] \times Density \tag{6.1}$$

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 Table 6.2, 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.

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?

IV Plotting and Analyzing Your Results

IV.1 Using the log-log plot in Figure 6.4, 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 (a) 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?

(b) How does this compare with the value of b for the asteroid power law distributions? Was your prediction correct? 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.

IV.3 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.

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 Table 6.3.

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 km2) 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.

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

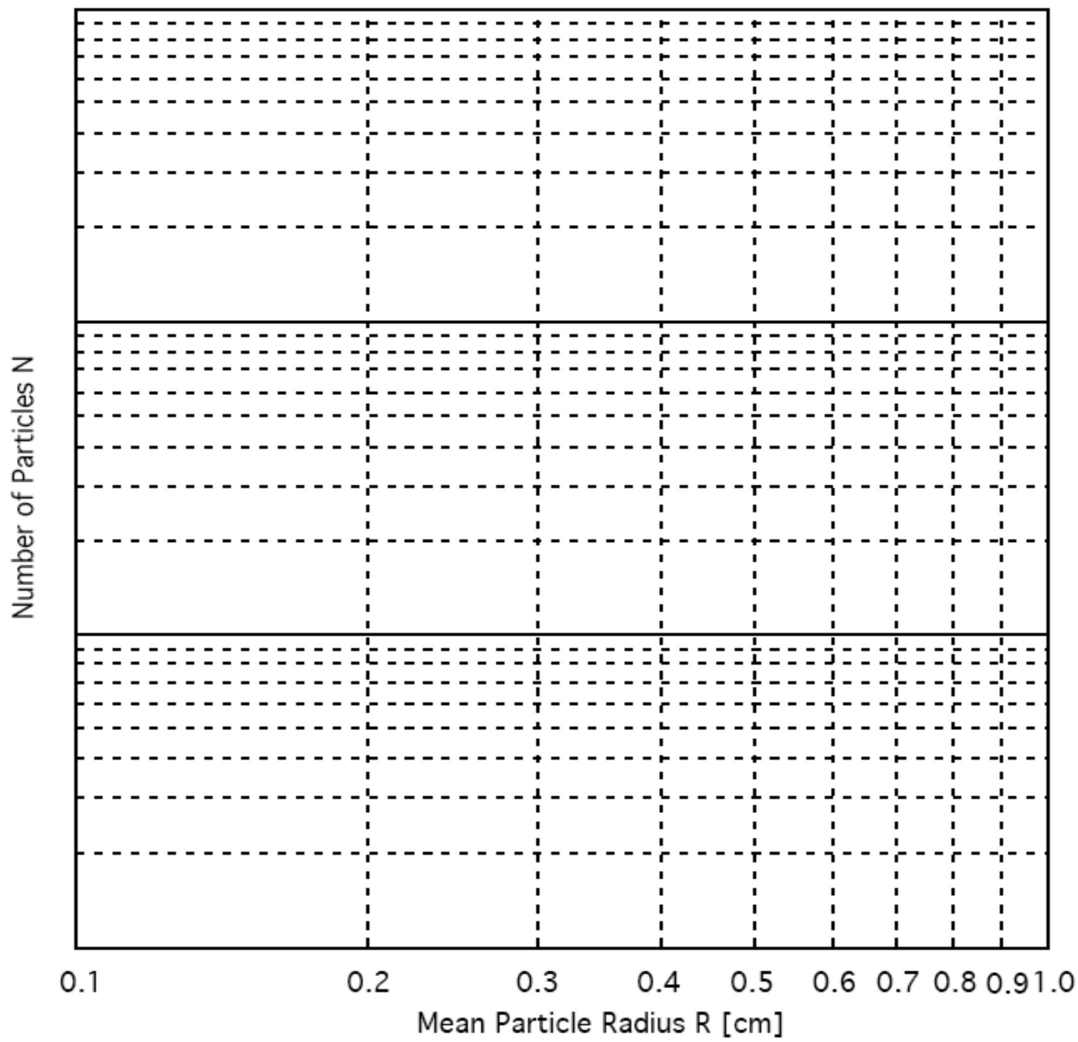


Figure 6.4

graph in Figure 6.5.

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 previous sections, what can you determine about the processes that created this population of impactors?

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.

VI Post-Lab Questions

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,

1	2	3	4	5	6	7
#	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	

Table 6.3

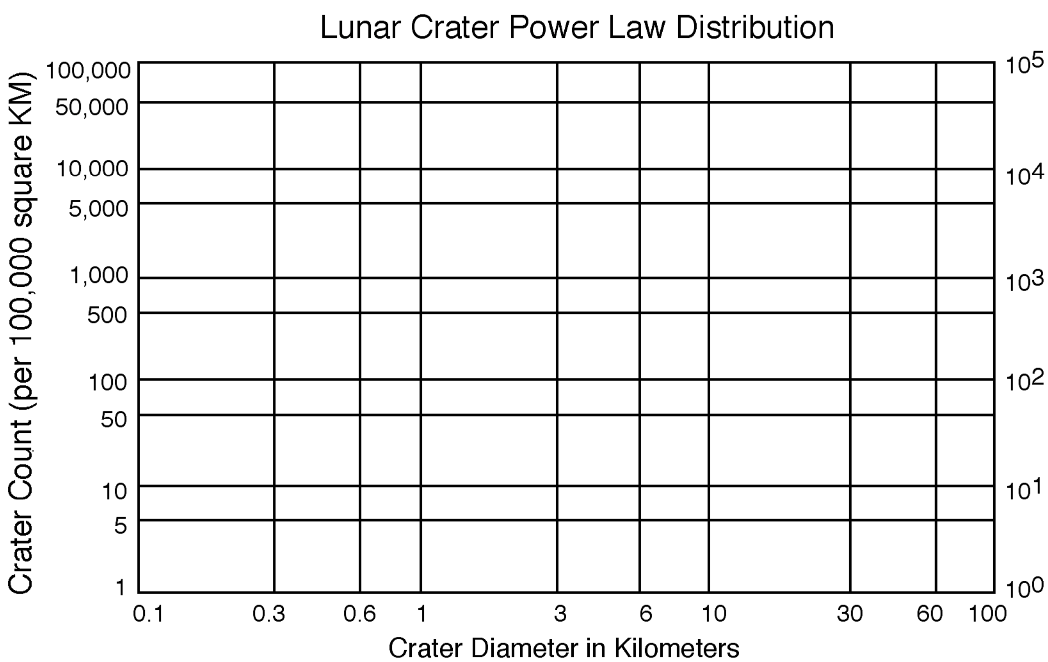


Figure 6.5

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:

$$\text{Surface Area of a Sphere} = 4\pi R^2 \tag{6.2}$$

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

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

(c) 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?

(d) Does this seem right to you? Did you expect a different number?

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 x 10^9) years ago. We expect the Earth to have encountered a similar rate of impacts over that same time period.

VI.3 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.2 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.4 On average, about how frequently do such impacts of this size occur on the Earth? (Hint: Question VI.3 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 thats 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.5 Compare your assessment of typical collision frequency with the estimates shown in Figure **??**. 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.6 Have your opinions changed about the NASA Near Earth Asteroid program? Why or why not?

Figure 6.6

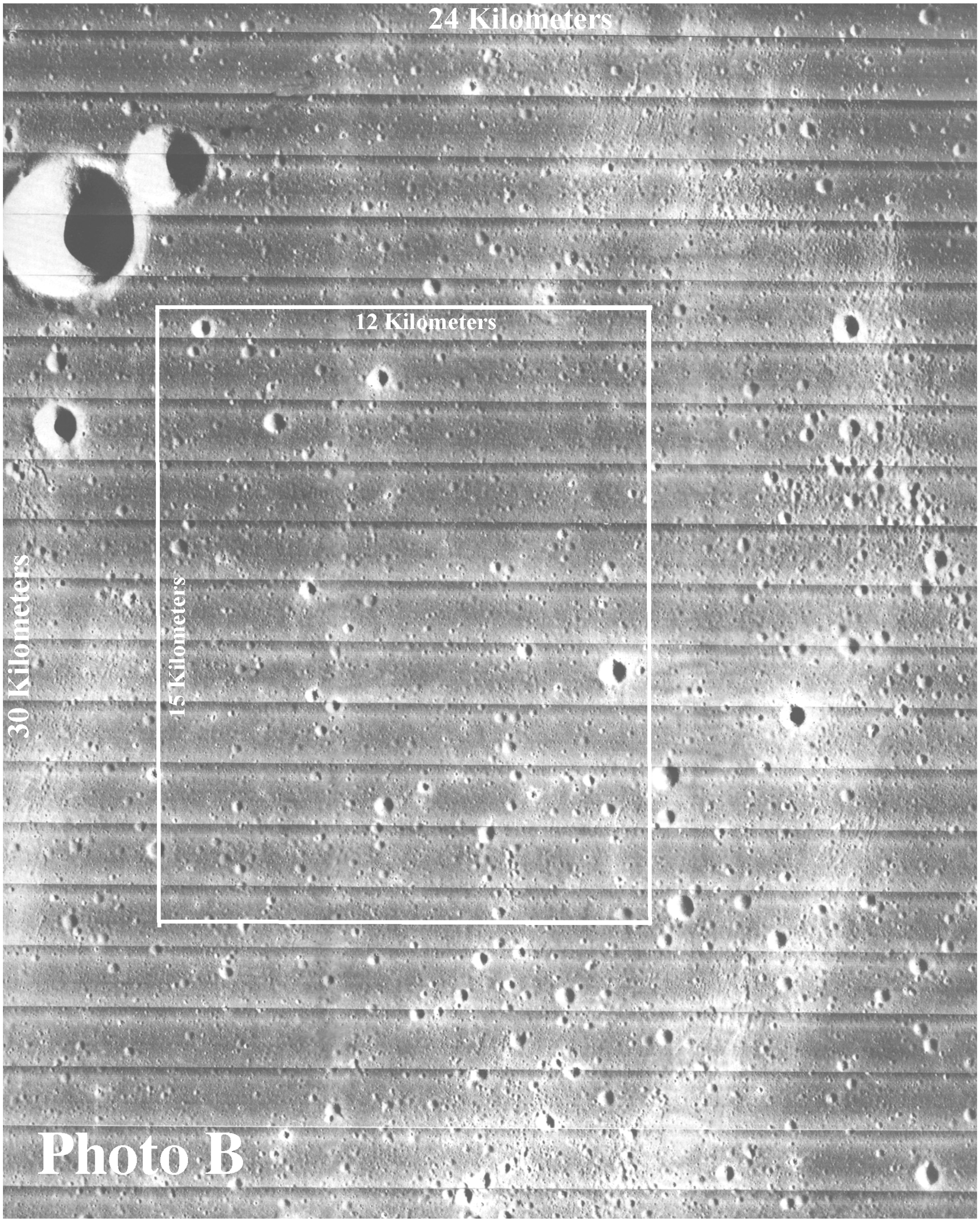

24 Kilometers
12 Kilometers
30 Kilometers
15 Kilometers
Photo B

Figure 6.7

Lab 7

Telescope Optics

Purpose: 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.

Pre-lab Questions

1 In your own words, explain what it 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?

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.

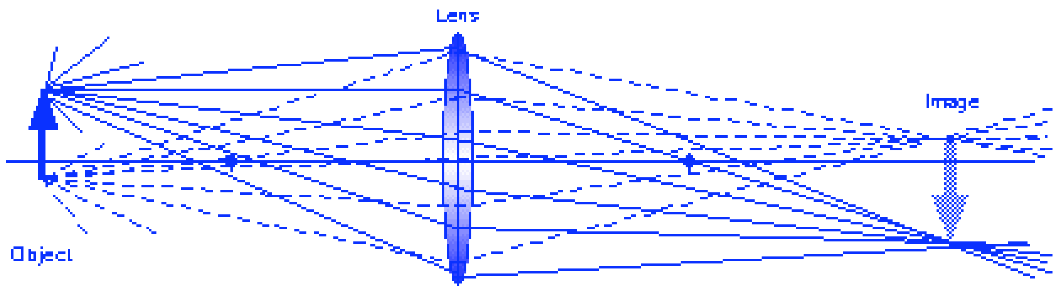


Figure 7.1: Optical ray path.

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

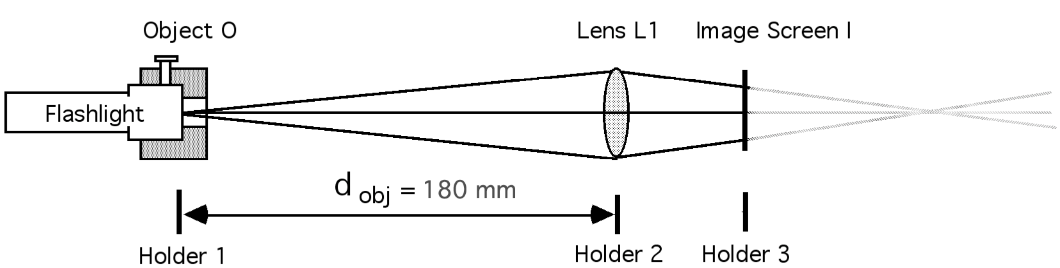


Figure 7.2

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 arrangment, 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:

$$\text{Magnification} = \frac{\text{Image Size}}{\text{Object Size}} \tag{7.1}$$

I.3 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, dimage. 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:

$$\text{Magnification} = \frac{d_{\text{image}}}{d_{\text{object}}} \tag{7.2}$$

I.4 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: dimage = ____________

I.5 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.6 (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.7 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.8 Refocus the image. What is the new image distance with this lens? dimage = ____________ 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.9 Using your experience above: 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.10 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.11 Which of the two lenses produced a larger image under the same conditions? ____________ Which would more likely be considered to be a "telephoto" lens? ____________

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:

$$\frac{1}{f} = \frac{1}{d_{\text{object}}} + \frac{1}{d_{image}} \tag{7.3}$$

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, dobject, and dimage, instead of the actual values themselves.

II.1 Calculate the focal length f of lens L1, using your measured image distance dimage and object distance dobject. 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.7)? 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.

III Lens Diameter and Focal Ratio

Another important property of a lens is the size of its aperture, or diameter D.

III.1 Place the iris aperture A in holder #1. Slide the aperture holder until it is just in front of the lens. Your arrangement should look like the diagram in Figure 7.3.

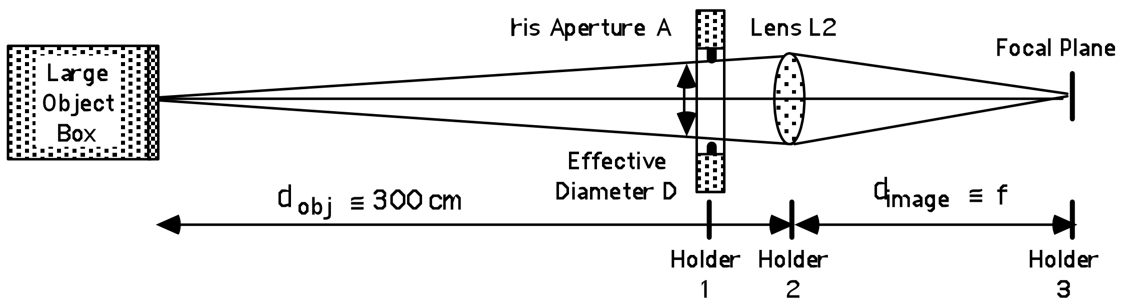


Figure 7.3

If you close, or stop down the iris, you effectively reduce the diameter of the lens (that is, you reduce the portion of the lens that actually "sees" the light).

III.2 Analyze the effect of reducing the aperture: As you slowly stop down the lens, what happens to the brightness of the image?

III.3 Does the image distance change? That is, does the focal plane (where the in-focus image is formed) shift when the lens diameter is decreased?

III.4 Does the image size shrink with smaller aperture? Does a portion of the image get "chopped off" because of the smaller lens opening?

Although you may be surprised at these findings, they merely point out the fact that each tiny portion of a lens forms a complete image. The final observed image is simply the sum of all of the independent contributions.

$$\text{f-ratio} = \frac{f}{D} \tag{7.4}$$

The brightness of an image formed by a lens (amount of light per unit area) is actually determined by the ratio (called the f-ratio) of the len's focal length to its effective diameter. This ratio is of great importance to astronomers and photographers, since it determines how faint we can observe:

III.5 As you stop down the aperture, are you increasing or decreasing the f-ratio of the lens? Do larger f-ratios produce brighter or darker images?

IV 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/dobject 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:

$$\frac{1}{f} = 0 + \frac{1}{d_{\text{image}}} \qquad \text{or} \qquad d_{\text{image}} = f \tag{7.5}$$

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:

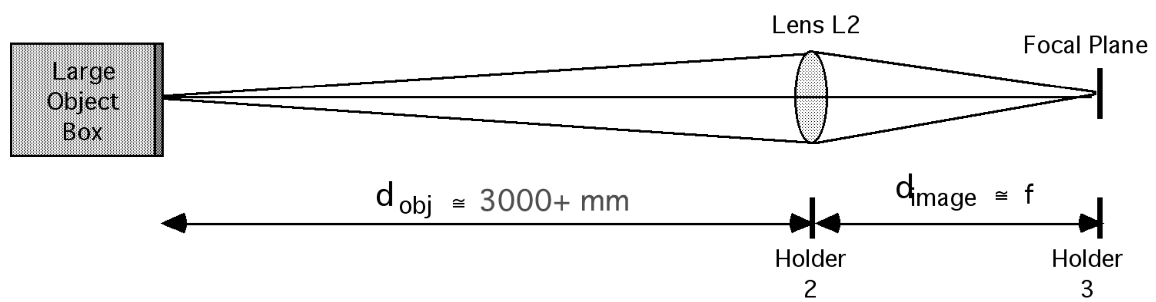


Figure 7.4

IV.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 above. 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 above 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.

IV.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.

IV.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:

IV.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

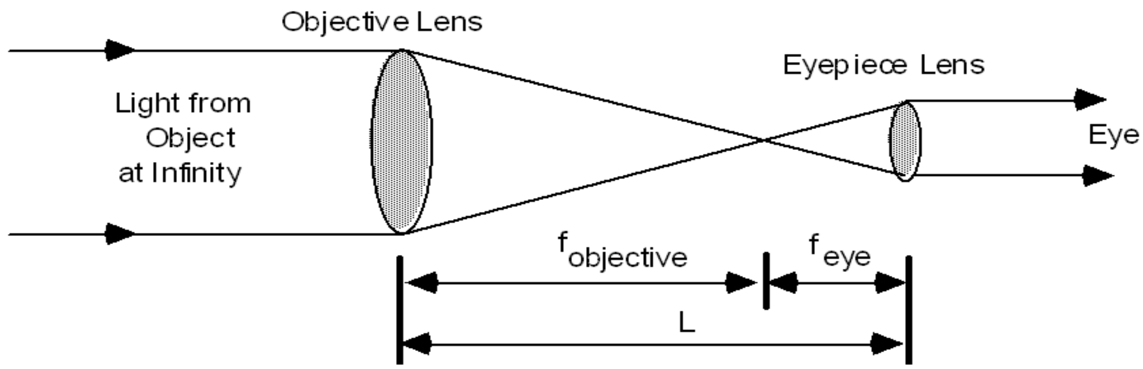


Figure 7.5: Refracting Telescope.

main telescope lens, called the objective lens, takes light from the object at infinity and produces an image exactly at its focal length fobjective 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, feye. Therefore, the total separation L between the two lenses must equal the sum of their focal lengths:

$$L = f_{\text{objective}} + f_{\text{eye}} \tag{7.6}$$

IV.5 Measure the separation between the two lenses (L), and use your value for the objective lens focal length (fobjective, measured in step III.1) and equation (4) to calculate the focal length of eyepiece E_1 (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:

$$M = \frac{f_{\text{objective}}}{f_{\text{eye}}} \tag{7.7}$$

IV.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 $f_{\text{objective}}$ 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).

IV.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: ____________

IV.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!

V 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.

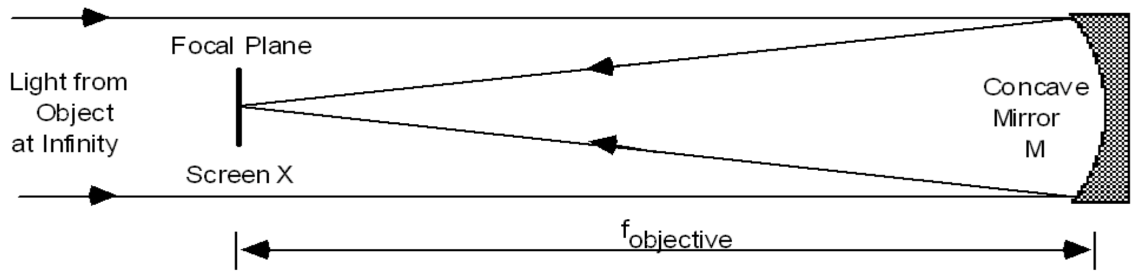


Figure 7.6: Reflecting Telescope.

V.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 at the far right end of the rail, 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).

V.2 Is the image right-side-up, or inverted? ____________

V.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.

V.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:

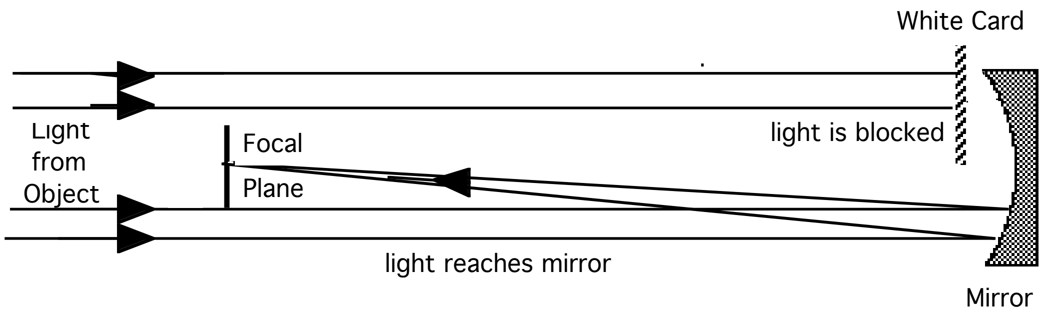


Figure 7.7

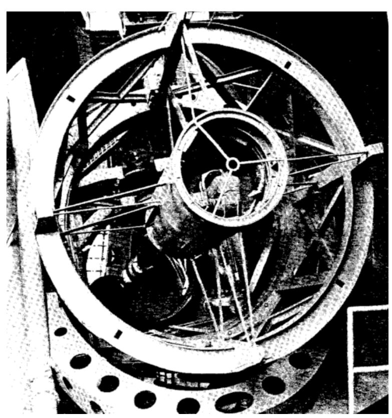


Figure 7.8: The prime focus arrangement cannot be used for eyepiece viewing, because the image falls inside the telescope tube. If you tried to see the image using an eyepiece, your head would also block all of the incoming light. (This, however, is not the case for an extremely large mirror: for example, 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!)s

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.

V.5 Convert your telescope to a Newtonian arrangement:

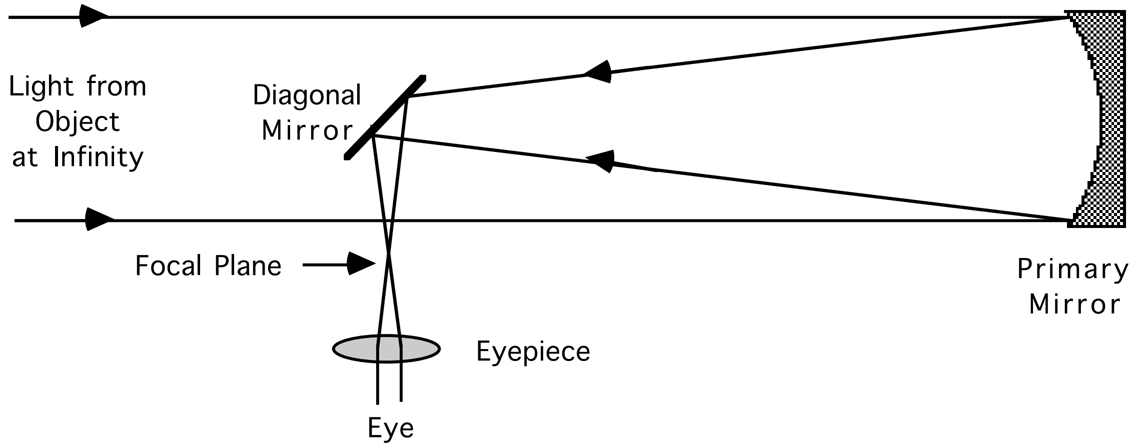


Figure 7.9: Newtonian Telescope.

- 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!

V.6 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.

V.7 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:

V.8 Why does the hole in the primary mirror not cause any additional loss in the light-collecting ability of the telescope?

V.9 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"!

VI Post-lab Questions

VI.1 You now know the importance of focal length when choosing a telescope. The other factor to consider is the telescope's light-gathering power (LGP) which is proportional to the square of the diameter of the lens or mirror. What is the LGP of the SBO 16-inch telescope compared to that of the human eye (which has a diameter of about 5 mm)? What about the 24-inch compared to the 18-inch?

VI.2 The 18-inch telescope at SBO can be used in either f/8 or f/15 mode (this means you can have an f-ratio of 8 or 15). It also has a choice of eyepieces with focal lengths ranging from 6 mm to 70 mm. You are planning on looking at some features on the surface of the Moon. First you need to orient yourself by identifying the maria (large dark regions). Which mode of the telescope do you use, and which eyepiece? Explain.

Now that you have oriented yourself, you want to find a rille (a trench on the lunar surface). Which mode and which eyepiece do you choose now? Explain.

VI.3 Most Cassegrain telescopes use curved mirrors for both the primary and secondary as shown in the diagram below. The arrows indicate the path of light through the telescope. The dashed line shows where the image from the primary mirror would be if there were no secondary mirror. How far is the final image from the secondary mirror in this telescope? Assume you have an f/8 primary mirror (i.e. the f-ratio is 8) with a diameter of 1 meter, an f/6 secondary mirror that is 1/3 the size of the primary, and the mirrors are separated by 2 meters (Note: the diagram is not drawn to scale).

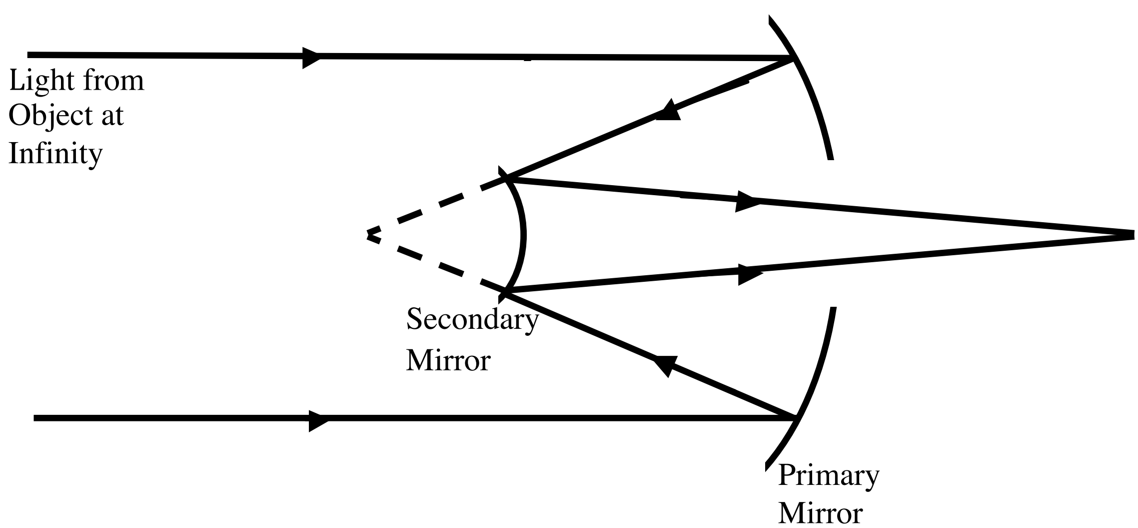


Figure 7.10: Cassegrain's secondary mirror.

Lab 8

Light & Color

Purpose: 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 planets color tell us?

Equipment: Light bulb, set of red, green, and blue filters, and grating or spectroscope.

Pre-lab Questions

1 In general terms, explain how the spectroscope works. (You do not need to explain how the diffraction grating works, just what it does.)

2 Explain why the spectrum of white light looks the way it does.

3 Explain why a blue shirt looks blue when viewed in white light. What happens to all the other colors in the light?

Introduction A spectrum is the intensity of light at different wavelengths. Spectra of planets have a typical "double hump" as shown in Figure 8.1– 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.

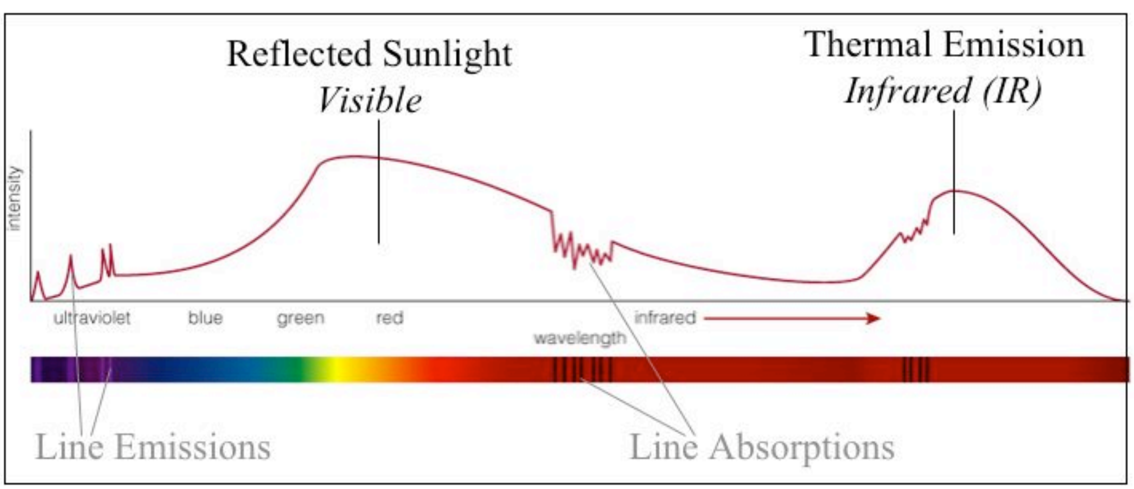


Figure 8.1: The typical "double hump" of a planetary spectrum.

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, and absorb.

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) as shown in Figure 8.2.

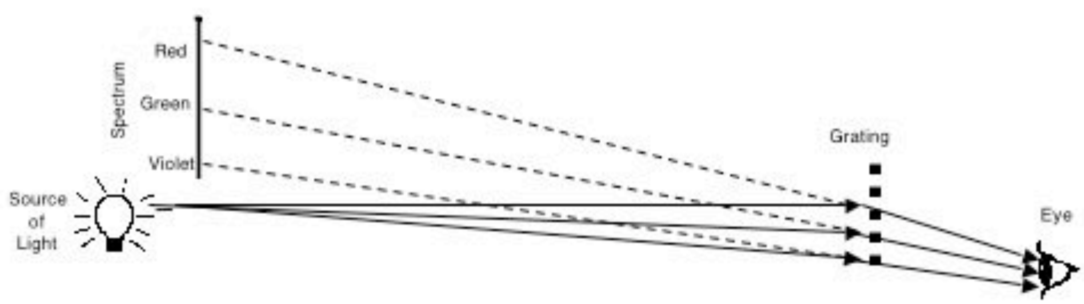


Figure 8.2: A schematic of a grating.

A spectroscope is another device for viewing a spectrum and it is shown in Figure 8.3. 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.

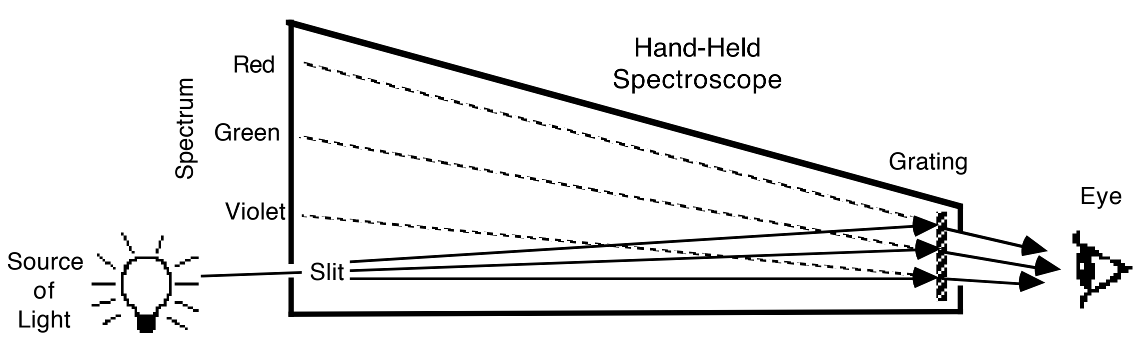


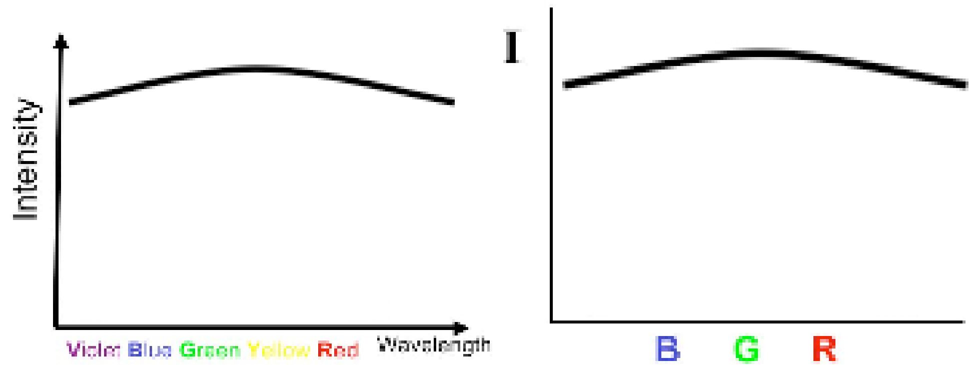
Figure 8.3: A schematic of a spectroscope.

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

(b) Does this make sense? Explain your reasoning.

We can sketch a spectrum of white light like in Figure 8.4a or, to simplify, like in Figure 8.4b.

I.4 Look at the light through the various filters. Draw the spectra of the light being transmitted – "let through" – by the different filters. Use the first three axes in Figure 8.5.



(a) Fully labeled axes. (b) Simpler axes.

Figure 8.4: Spectrum of white light.

I.5 Try different combinations of filters and draw them in the remaining boxes of Figure 8.5. What happens when you add filters together?

I.6 Explain what is happening in your drawings using the concepts of transmission, absorption and reflection.

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

Think about the white light hitting your shirt/sweater.

I.8 (a) What color(s) is it?

(b) What colors are reflected by your shirt/sweater?

(c) What colors are absorbed?

I.9 (a) Without using a grating or a spectroscope, draw in the top two axes of Figure 8.6 the spectrum of light reflected by your shirt/sweater. Then do your partner's shirt/sweater color (find someone else if they are wearing the same color shirt).

(b) Without using a grating or a spectroscope, draw in the bottom two axes of Figure 8.6 the spectrum of light absorbed by your shirt/sweater. Then do your partner's shirt/sweater color (find someone else if they are wearing the same color shirt).

II Red, Green and Blue Spotlights

Go to the station with the red, green and blue spotlights. You will examine how objects exposed to different colored lights appear.

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

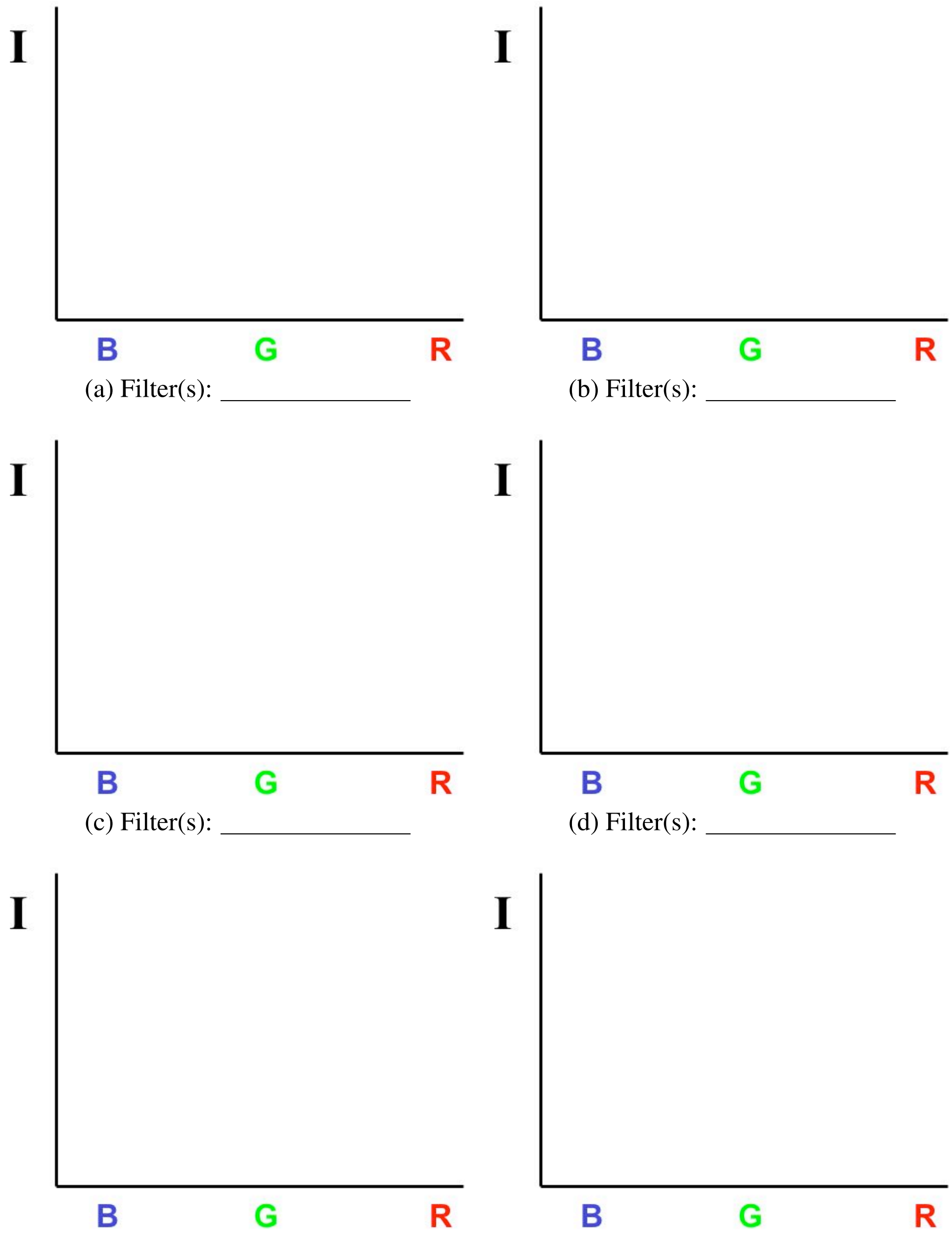
II.2 Try it. What effects do you see? Explain what is causing this effect (Hint: What color is the paper the letters are written on?)

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

II.4 Hold up an 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 Earlier in the lab, you saw one result when you used multiple filters, this time you saw a



(a) Filter(s): _______________ (b) Filter(s): _______________

(c) Filter(s): _______________ (d) Filter(s): _______________

(e) Filter(s): _______________ (f) Filter(s): _______________

Figure 8.5

different result. Explain why the two experiments produced different results.

III Yellow Lights

You will examine how different lights can all appear a similar yellow but have very different spectra.

III.1 (a) Before you enter the room make a prediction: what will your shirt/sweater look like in the yellow room?

(a) Your shirt color: ______________ (b) Partner's shirt color: ______________

(c) Your shirt color: ______________ (d) Partner's shirt color: ______________

Figure 8.6

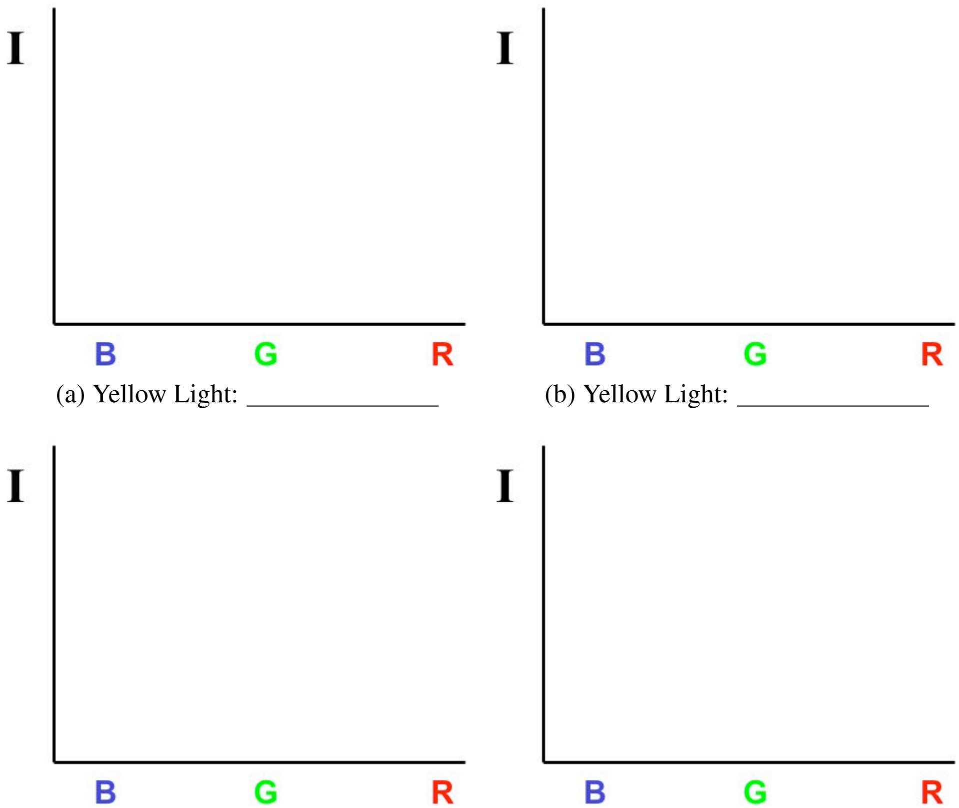
(b) Go inside the station. What was your shirt/sweater like in the yellow room? How did the color of your shirt change?

Yellow Light	Green	Red	Blue
Incandescent Light			
Fluorescent Light			
Sodium Light			
LED Light			

Table 8.1

III.2 You have before you three sheets of paper (green, red, and blue). Fill in Table 8.1 with what color each sheet looks like under each of the different yellow lamps.

III.3 What does this information tell you about the differences between the different yellow lights? Explain what you think is going on.



(a) Yellow Light: _______________ (b) Yellow Light: _______________

(c) Yellow Light: _______________ (d) Yellow Light: _______________

Figure 8.7

III.4 Examine each of the different yellow lights with your spectroscope, and draw them in Figure 8.7.

III.5 Do your spectra agree with what you thought was happening in III.3? Explain what makes each of the yellow lamps different using what you know from III.2 and III.4.

IV Red, White, and Blue Planets:

You have now gotten some practice examining light and color in the world around us, let's examine light and color in other worlds.

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)

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

Figure 8.9 is a spectrum of white light and white light that has passed through methane gas (CH_4).

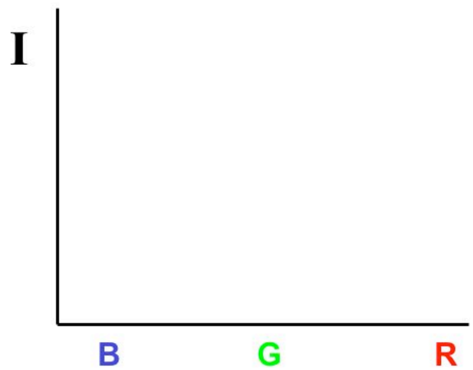
IV.3 (a) What colors of the spectrum are absorbed by methane?

(b) What colors of light are transmitted by methane? (Simplify, think about the BGR scale

(a) Io

(b) Mercury

(c) Mars



(d) Neptune

Figure 8.8

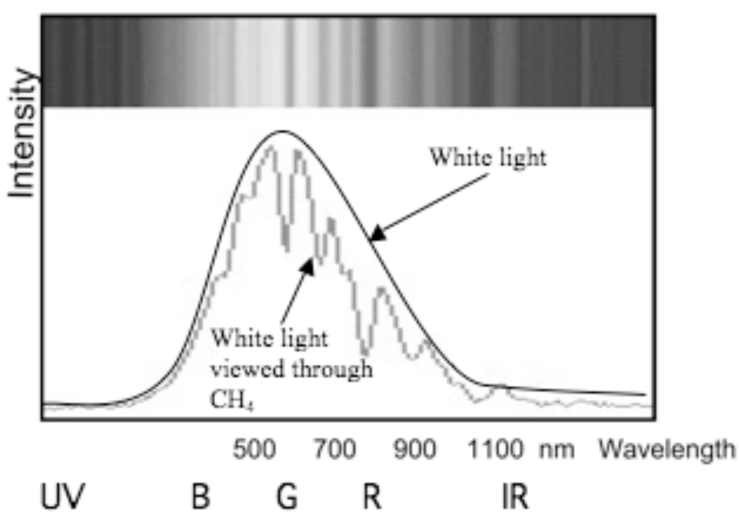


Figure 8.9

we used above).

IV.4 The 3 plots in Figure 8.10 are spectra of reflected light from Saturn, Uranus, and Neptune. Which planet seems to have the most methane in its atmosphere?

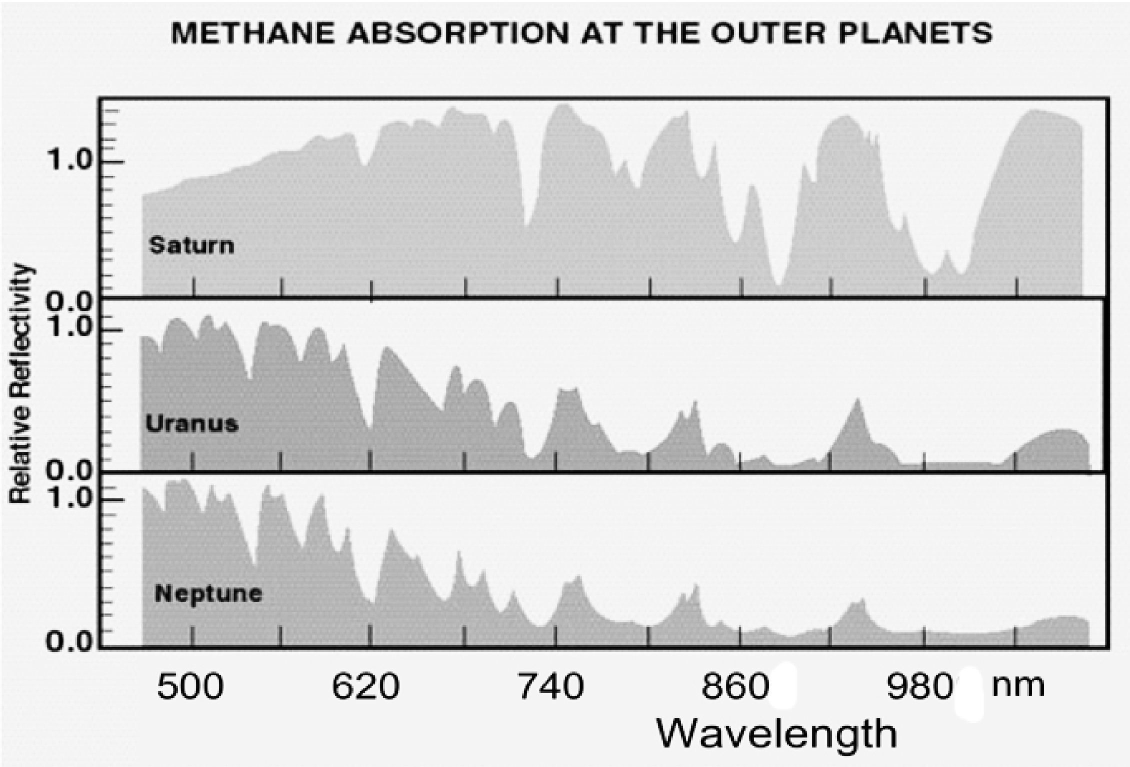


Figure 8.10: Methane in the outer planets.

Methane makes up a big part of the atmospheres of the gas giants, especially Neptune and Uranus.

IV.5 Using Figure 8.9 and your answers to the previous questions, predict why both planets appear blue.

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.

IV.6 (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.)

V Planets and People at Infrared Wavelengths

Remember, that planets also emit in the infrared spectrum, so it is important to understand how infrared light works. Infrared light is proportional to heat. The hotter an object is the more infrared light it will emit.

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 youll learn about when discussing planetary atmospheres.)

VI Post-lab Questions

VI.1 (a) What color would Neptune be if it were orbiting a dim red dwarf star? Explain your reasoning.

(b) What color would Mars be if it were orbiting a bright blue giant star? Explain your reasoning.

VI.2 In an alien world with a methane atmosphere and a yellow sun, what color would you expect the plants to be? Explain your reasoning.

Lab 9

Spectroscopy

Purpose: 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.

Pre-lab Questions

1. When electrons move down energy levels, are the gaining or losing g energy? If gaining, where did this energy come from? If losing, where did this energy go?
2. How does and 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?

Introduction: 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.

I Electron Energy Transitions:

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. Figure 9.1 shows electrons making energy transitions and the resultant emitted photons.

The light produced when electrons jump from a high-energy orbit to a smaller low-energy orbit

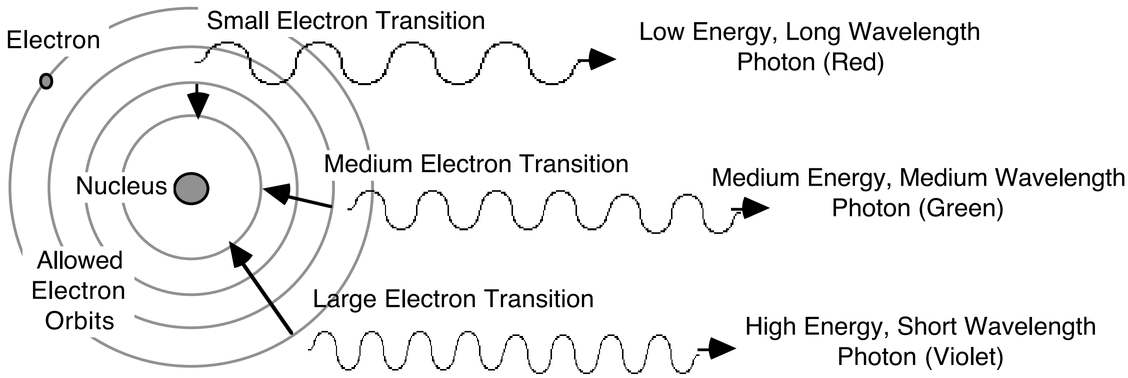


Figure 9.1: A schematic of electrons making transitions.

is known as an emission line. An absorption is produced by the opposite phenomenon: a passing photon of light is absorbed by an atom and provides the energy for an electron to jump from a low-energy orbit to a high-energy orbit. The energy of the photon must be exactly equal to the difference in the energies of the two levels; if the energy is too much (wavelength too short) or too little (wavelength too long), the atom can't absorb it and the photon will pass by the atom unaffected. Thus, the atom can selectively absorb light from a continuum source, but only at the very same wavelengths (energies) as it is capable of emitting light. An absorption spectrum appears as dark lines superimposed against a bright continuum of light, indicating that at certain wavelengths the photons are being absorbed by overlying atoms and do not survive passage through the rarefied gas.

The human eye perceives different energies (wavelengths) of visible light as different colors. The highest energy (shortest wavelength) photon detectable by the human eye has a wavelength of about 4000 Angstroms (one Angstrom equals 10-10 meters) and is perceived as "violet." The lowest energy (longest wavelength) photon the eye can detect has a wavelength of about 7000 Angstroms, and appears as "red."

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

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

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

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

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

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 dont see this.

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

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

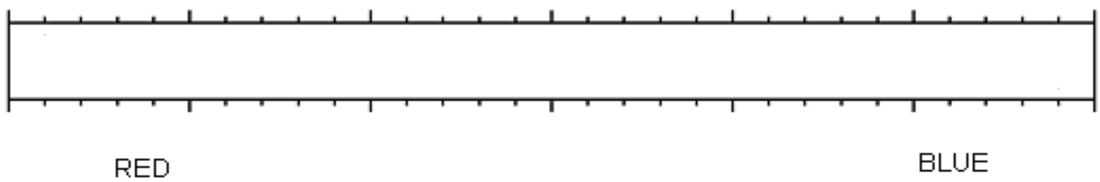


Figure 9.2: Incandescent Lamp

(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.

Now, let's use the gas tubes at each of your stations. 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 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.
- Record the spectrum in the supplied frames in Figure 9.4, include units.
- Turn off the power supply before changing tubes.

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

(a) Helium?

(b) Neon?

(c) Nitrogen?

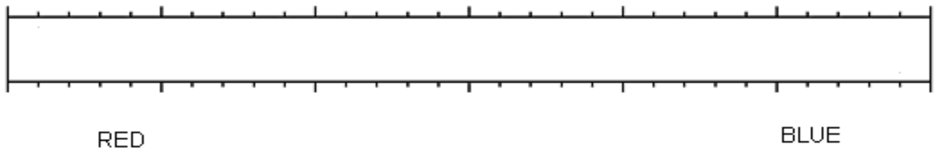
II.4 Judging from the number of visible energy-level transitions (lines) in the neon gas, which element would you conclude has the more complex atomic structure: helium or neon? Explain.

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.

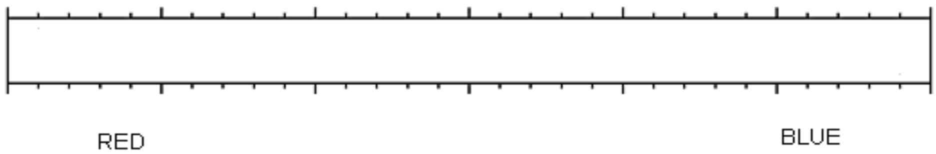
II.5 Point your spectroscope at the ceiling fluorescent lights, and sketch the fluorescent lamp spectrum in the frame.

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

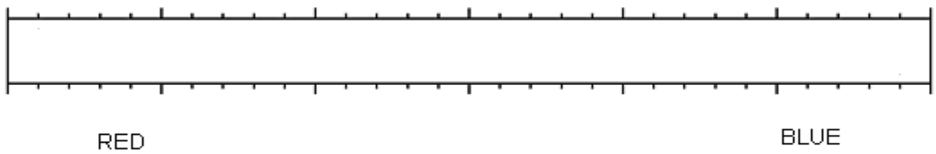
II.7 Which components of the spectrum originate from the solid?



(a) Helium



(b) Neon



(c) Nitrogen

Figure 9.3

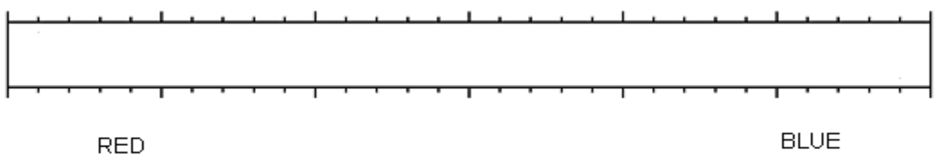


Figure 9.4: Fluorescent Lamp.

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.

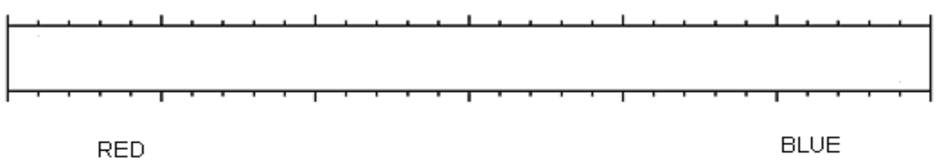


Figure 9.5

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

IV Solar Spectrum

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.

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)

Figure 9.6: 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, nanometers thats 10^{-9} meters.

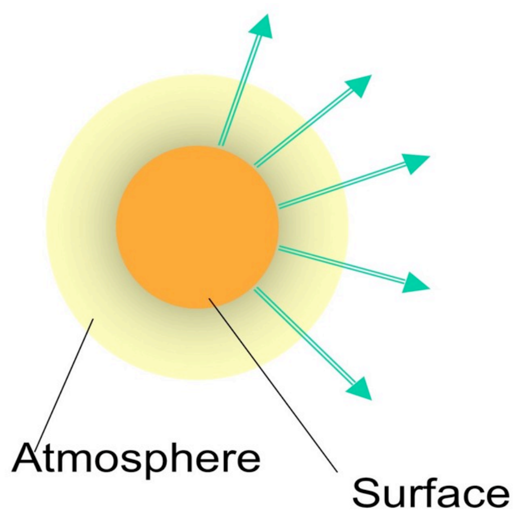


Figure 9.7

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 in Figure 9.7, which component of the spectrum comes from the Suns surface? Which is due to its atmosphere?

Now you'll apply what you learned about gases in the laboratory to gases in the Sun. First, let's study the Sun's continuum spectrum. The gas in the interior of the Sun is so dense that the atoms cannot act independently of each other and therefore they radiate a continuum spectrum just like a solid. The solar continuum is a blackbody spectrum. Like all blackbody spectra, the shape of the solar continuum depends only on its temperature.

The graphs below show the blackbody spectra seen for any object (not just stars!) with different temperatures. The temperatures for the graph on the left are chosen to show the large variation in radiated energy for minor variations in temperature. The graph on the right uses a logarithmic scale to encompass a larger range, and shows the temperatures for O stars (50,000 K - the hottest known stars), the Sun (5783 K), and a person (310 K).

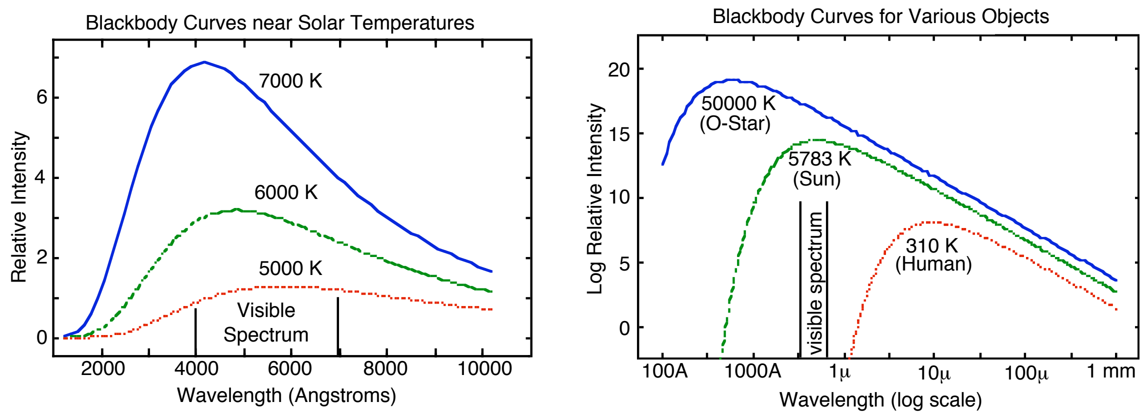


Figure 9.8

IV.3 (a) Why do you suppose we humans have evolved to see light in the wavelength range that we do (4000 to 7000 Angstroms)?

(b) If the Sun were hotter, would it be useful for us to see at longer or shorter wavelengths?

(c) Why cant we see each other "glowing in the dark?" How would our eyes need to change in order for us to do this?

An objects temperature can be determined from the wavelength at which the peak energy occurs using Wien's Law:

$$\text{Temperature} = \frac{2.90 \times 10^7 \text{ K Å}}{\text{Peak Wavelength in Angstroms}}$$

By measuring the peak energy of the solar continuum, we can determine the temperature of the surface of the Sun.

IV.4 (a) Where in the solar spectrum does the continuum emission appear (with your eye) the brightest? Estimate the wavelength using the Fraunhofer Solar Spectrum Chart below the spectrograph screen.

(b) Using a photometer (lightmeter) provided by your instructor, measure where the continuum is the brightest. Estimate the wavelength. How does this compare to your estimation with your eye?

(c) Using Wien's law, calculate the temperature of the Sun using your measured estimate for the peak wavelength. How does this compare to the accepted value of 5783 K?

V Solar Absorption Lines

In the Sun we see both a continuum spectrum and absorption lines from gases in the tenuous solar atmosphere, which selectively absorb certain photons of light where the energy is "just right" to excite an atoms electron to a higher energy state.

Of course, an atom cant absorb light if the atom isnt there. Thus, we can identify the elements that make up the Sun simply by comparing the absorption lines in the solar spectrum with emission lines from gases here on Earth. Your lab instructor will dim the solar spectrum by narrowing the entrance slit, and switch on comparison lamps containing hydrogen and neon; their emission

Line name and element	Abundance per million	Wavelength (Å)	Color	Descriptive appearance	Reason
Oxygen (O_2)	none				
Hydrogen ($H\alpha$)	900,000				
Sodium (Na)	2				
Iron (Fe)	40				
Hydrogen ($H\beta$)	900,000				
Calcium (Ca II)	2				
Calcium (Ca II)	2				

Table 9.1

spectra appear above and below the solar spectrum. If an element is present in the Sun (and if the temperature of the gas is "just right"), its absorption line will appear at the same wavelength as the corresponding emission from the comparison source.

V.1 (a) Which comparison spectrum (top or bottom) is due to hydrogen, and which is neon? What is your evidence?

(b) Do you see evidence that hydrogen gas is present in the Sun? What about neon? Explain your reasoning.

Even though your eye can't see it, the solar spectrum extends beyond the visible red portion of the spectrum to include infrared light, and beyond the violet to include ultraviolet light. The spectrum of ultraviolet light can be made visible by fluorescence (remember the solid material in the overhead tube lights?).

V.2 Hold a piece of bleached white paper up to the viewing screen where ultraviolet light should be present in the spectrum. Note that there are many additional absorption lines in the solar spectrum at wavelengths that are not normally visible to us! Use the Solar Spectrum Chart to identify the element responsible for the two extremely broad, dark lines in the ultraviolet.

V.3 Using the Fraunhofer chart, identify each of the following lines in the solar spectrum - for each, give its wavelength, color, and include a brief descriptive phrase (dark, broad, narrow, fuzzy, etc.). Record these in Table 9.1.

It seems reasonable to assume that stronger (darker, wider) absorption lines would indicate that there are more atoms of that element present in the Sun - but as shown in the "abundance" column of the table, we would be misleading ourselves. Although an atom must be present in order to show its "signature," that doesnt necessarily mean that the element is abundant – otherwise, we would probably assume (incorrectly) that the Sun is mostly made out of calcium.

The analysis of spectral features is an extremely complex task, and there are several important factors to consider. First of all, even if many atoms of an element are present, the temperature may be too cool to excite them, so that they wont emit or absorb (remember, the gas in the discharge tubes was completely invisible until you turned on the power). Or, if the temperature is too hot, the atoms will be ionized (electrons stripped away) so that the electrons responsible for the absorption wont be part of the atom anymore. Or, it could be that a spectral feature that we see didnt really come from the Sun at all, but from the gasses in our own Earths atmosphere.

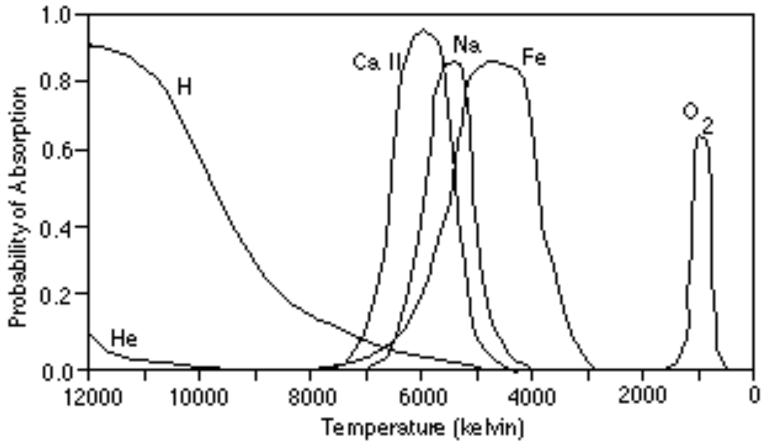


Figure 9.9

Through careful analysis, physicists have figured out the temperature ranges necessary for certain elemental species to "show themselves" through absorption, as indicated in Figure 9.9.

V.4 For each spectral line in the table on the previous page give a reason (A, B, C, or D below) why you think it appears in the solar spectrum.

A. Although only a very small fraction of the atoms absorb light at any one time, this atom is very abundant and therefore shows its signature.

B. This spectral line is actually several lines that are closely spaced together. The sum of the lines makes it appear to be stronger than it really is. Its not really abundant in the Sun.

C. This spectral line is strong because the Sun's temperature is just right for this element to absorb light at this wavelength, even though there arent that may atoms there.

D. The spectral line is actually an absorption band from molecules in Earth's atmosphere rather than in the solar atmosphere. The Sun is too hot for molecules to exist.

V.5 Although 10% (100,000 atoms out of a million) of the Sun is composed of helium (He), we dont see any helium lines in the visible solar spectrum. Inspect the graph of absorption probabilities, and explain why not.

V.6 However, during total solar eclipses astronomers do see helium in the solar corona, the extremely tenuous outermost region of the Suns atmosphere (in fact, the element was named for the Greek word helios, meaning "the Sun." What does this imply about the temperature of the gas in the corona?

VI The Aurora, 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.

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

The Physics of Auroral Light Formation

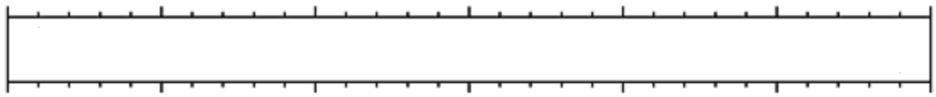


Figure 9.10: Aurora

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.

VI.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

VII Post-lab Questions

VII.1 In Boulder at the NIST laboratories, scientists make detailed observations of all known gases, in order to help astronomers and other scientists identify unknown gases in the field. Once astronomers have correctly identified the spectral lines of an unknown gas, why can they be confident that it isn't another gas with the same spectra? Explain your reasoning.

VII.2 If the sun were hotter, would the absorption lines move to higher wavelengths? Explain your reasoning.

VII.3 Would aurora appear in different colors on other planets? Explain your reasoning.

Lab 10

Planetary Colors and Albedos

Purpose: To understand the importance planetary color and albedo plays in determining the temperature of an object,

Equipment: Soil samples, photometer, IR surface thermometer, and a bright lamp or the Sun.

Pre-lab Questions

1. Explain how the concepts of color and albedo are related using your own words.
2. Estimate the albedo of a pure white object, a pure black object, a grey object, and a dark red object.
3. Write down the Stefan-Boltzman equation and explain its parts.

Introduction: We explored in previous labs what gives a material its color. Light can either be transmitted, reflected or absorbed. The majority of planetary surfaces are opaque, and so light is either reflected or absorbed. If light is reflected that light will travel back into space, and we may see it in our photographs of that planetary surface. That reflected light determines both the color of the planetary surface and how bright that surface appears. The light that is not reflected is absorbed as energy, turned into heat, and eventually is re-emitted by the surface as infrared radiation.

I Effect of Color on Temperature:

When light strikes the surface of a planet and is converted into energy, it is enough energy to substantially change the temperature of the surface. How much the temperature changes depends on the albedo and color of the material.

The same material painted different colors (with oil paints) will have different albedos and reflect different parts of the visible spectrum, but will emit the same infrared light when heated. You will measure the emitted infrared light from five samples using the IR surface thermometer. The IR surface thermometer detects infrared light emitted from a surface, and then uses Stefan-Boltzmann's Law (Equation 10.1) to relate the infrared flux, F, to the temperature, T. We will not be using the full form of this equation, however you do need to know that:

$$Flux \propto Temperature^4 \tag{10.1}$$

As you can see from the equation above, a small change in temperature causes a large change in flux, or IR light, that the thermometer can detect.

You have four samples (white, black, gray, and red painted squares) in front of you. Each color has a different albedo.

I.1 (a) Predict the order of the five samples from greatest to least increase in temperature after being left out under the Sun. Explain your reasoning using the concepts of albedo and color.

I.2 Measure the temperatures of the samples using the IR surface thermometer. Record them in the first column of Table 10.1.

Surface Samples	Initial Temperature	Initial Power	Final Temperature	Final Power	Absorbed Solar Power
White					
Black					
Gray					
Red					
Plain					

Table 10.1

I.3 Take your samples outside and place them directly in the Sun. While your sample is exposed, finish the other sections of this lab, .

I.4 Measure the temperatures of the samples using the IR surface thermometer. Record them in the third column of Table 10.1.

I.5 Were your predictions correct? If not, explain why not.

To determine the absolute power being emitted in the infrared for each of the temperature measurements, a term needs to be inserted into the Stefan-Boltzmann equation to make the units work. With this term the equation reads:

$$P = 5.33 \times 10^{-10} \text{ Watts / Kelvin}^4\, T^4 \tag{10.2}$$

The temperature, T, must be measured in Kelvin, and then the power, P, will be in Watts.

I.6 (a) Calculate the power emitted for each surface, before and after solar exposure. Show an example of your work below.

(b) Is there a difference in the power emitted before and after? Explain why this makes sense.

I.7 Which color absorbed the most power? Which absorbed the least? Describe at least one example from everyday life where you see the same phenomenon.

I.8 Calculate the absorbed solar power by subtracting the final power from the initial power and record this value in column 5.

I.9 An incandescent lightbulb emits 60 Watts of power. How do your samples compare to an incandescent lightbulb? Explain why this makes sense.

I.10 The solar constant is the amount of power the Sun delivers to the Earth over a specified area. For your 10 cm^2 area, the solar constant is 14 W. Does this makes sense with your absorbed solar power? What might explain the difference?

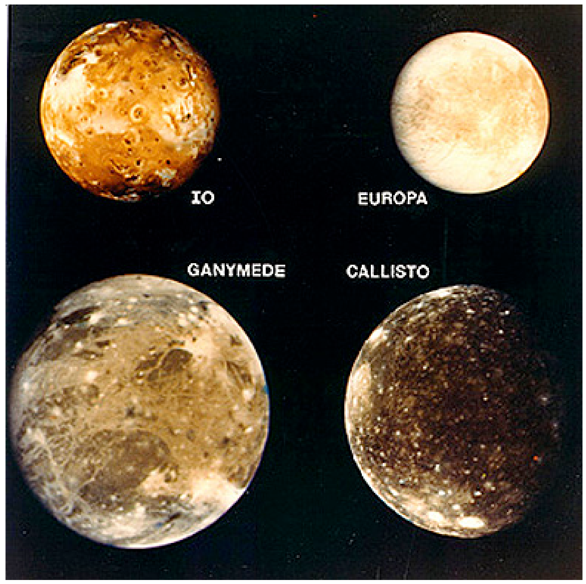


Figure 10.1: Moons of Jupiter.

Examining the moons of Jupiter shows that there is a red moon (Io), a white moon (Europa), a gray moon (Ganymede), and a black moon (Callisto) as shown in Figure 10.1. The moons are all approximately the same distance from the Sun (at the orbit of Jupiter), so their albedo and color plays a large role in determining their temperature.

I.11 From their colors only, predict their order from hottest to coldest. Explain your predicted order.

When the mean surface temperature is measured by spacecraft, the hottest planet is Callisto at 134 K, then Ganymede tied with Io at 110 K, and Europa at 102 K.

I.12 Is there a difference between the spacecraft data and your predictions? If so, what have you learned about the moons of Jupiter that might explain the difference between the spacecraft observations and your measurements.

II Measuring Colors and Albedos

The albedo and colors of a planet or moon provide valuable information about its composition as well as temperature. To get a feel for the process, you will measure and analyze the colors and albedos of various soil and rock specimens.

A photometer (light meter) with a sunshade can be used to measure the reflectivity of different materials, as shown below. The measurements are made as follows:

$$Reflectivity = Sample/White$$

- Measure the brightness of white paper illuminated by sunlight. We consider an albedo of 1 to represent the color white and an albedo of 0 to represent the color black. Therefore we will measure reflectivity of the white paper and use those values to normalize subsequent

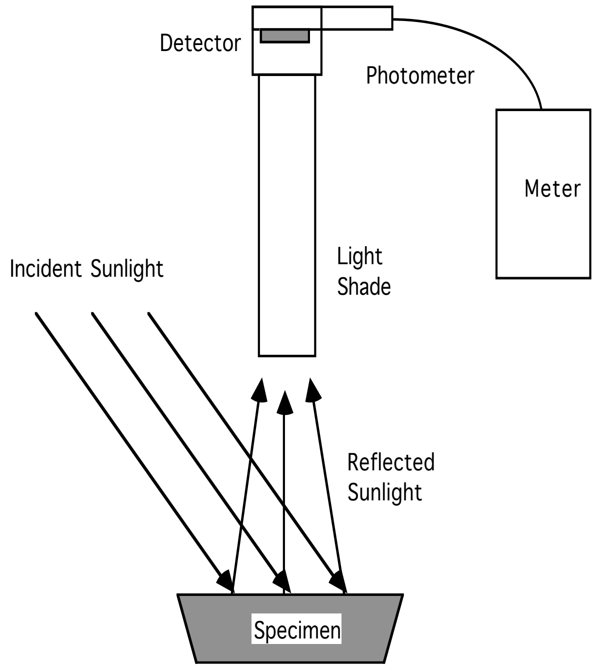


Figure 10.2

measurements thus giving a convenient standard against which to compare the reflectivity of other surfaces. Be sure that nothing (including you or the photometer) is casting shadows onto the area under observation!

- Measure the brightness of the sample. Be sure to hold the photometer close enough to the sample so that its detector only "sees" the sample, not the surrounding area. It is important to hold the photometer the same distance away every time.
- Divide your sample reading by the value you obtained for the white paper. The resulting fraction is the reflectivity of the material.

If we use an unfiltered lightmeter, the process measures the average reflectivity of the sample over the entire visible spectrum. However, if we make separate measurements through red (R), green (G), and blue (B) filters, we will have determined the red, green, and blue reflectivities of the sample instead - a quantitative way to measure its color!

II.1 (a) Measure the RGB reflectivities of the various specimens provided by your lab instructor.

(b) In Table 10.2, for each filter record the brightness of the paper in the first column and the brightness of the sample in the second column.

(c) Calculate the reflectivity and record your answer in the third (shaded) column. Also note the visual color of each specimen. For the remaining spaces of the table, choose other surfaces (e.g. table, carpet, sidewalk, grass, etc.).

II.2 (a) What pattern of RGB values combine to produce a strong visual impression of "red"? Which produces "some shade of gray"?

(b) How do the RGB values relate to the visual color description?

II.3 (a) Now average your measured RGB reflectivities of each sample (penultimate column) to come up with an average measurement of the sample's reflectivity, or visual albedo, over the entire visible spectrum. Add these figures to the table.

Geological Specimens	Color Reflectivity									Visual Color Description	Visual Albedo	Color Index
	Red			Green			Blue					
	W	R	R_R	W	G	R_G	W	B	R_B			
Sand												
Loam												
Basalt												
Charcoal												
Sandstone												
Limestone												

Table 10.2

Geological Specimens	Color Reflectivity									Visual Color Description	Visual Albedo	Color Index
	Red			Green			Blue					
	W	R	R_R	W	G	R_G	W	B	R_B			
Simulated Moon Soil												
Simulated Mars Soil												

Table 10.3

(b) Which sample has the highest overall albedo? Which has the lowest?

(c) Does this match your visual impression? Do any surprise you?

II.4 (a) For each sample divide the value of the red reflectivity (R_R) by the value of the blue reflectivity (R_B), and enter the resultant color index in the final column of the table.

(b) Explain how this color index numerically describes the sample's hue (color balance) independent of its overall brightness or albedo.

(c) What visual color might correspond to a color index of 2.00? A color index of 1.00? An index of 0.50?

(d) Does your data show a relationship between the color index and the visual albedo? Should there be one? Explain your reasoning.

III Martian and Lunar Analysis:

Ideally, we would like to be able to provide you with real-life soil specimens from Mars and the Moon, and have you compare those with the earthly samples you've just analyzed. Unfortunately, fresh rock samples from Mars have yet to be retrieved, and those from the Moon are far more precious than gold. As a result, we have to resort to the next-best thing: using simulated samples, developed here on Earth to be as identical as possible to the "real thing." These samples were developed after extensive color imaging and spectrographic analysis of the actual lunar and martian soils.

III.1 Using the same procedure that you used in Section II, measure the red, green, and blue reflectivities of the simulated soils, visually describe its color, calculate its albedo and a color index. Record your work in Table 10.3.

Assume that the lunar and martian soils are composed of one or more of the materials you analyzed in Section II.

III.2 (a) Based only on the your data, which specimen is most similar to simultated Mars soil? Explain your reasoning.

(b) Which specimen's albedo is most like that of the simulated lunar soil? Explain your reasoning.

III.3 (a) Now, using just the color index, which specimens hue most resembles martian soil? Explain your reasoning.

(b) Which most resembles the lunar material? Explain your reasoning.

Attempt to make a reasonable conjecture about the composition of the soils of the two celestial objects. If you had to choose among one (or more) of our (very limited) selection of measured materials, suggest what you feel would be the most probable composition of the martian and lunar soils. Think about both the visual albedo, color index, and the individual RGB reflectivities.

III.4 (a) Which, if any, materials might be likely candidates for explaining the colors we see in the Martian landscape? Explain your reasoning.

(b) How about for the Moon? Explain your reasoning.

IV Post-lab Questions:

IV.1 In the lab (and in class) you used an albedo of 1 for the color white. Based on your measurements of the reflectivity of the white paper, did it really have an albedo of 1? Explain your answer and use it to justify our normalization of all the subsequent measurements.

IV.2 Most people are surprised to find that the Moon has such a low albedo. Why, then do you suppose the Moon appears to be so bright in the nighttime sky?

On Earth we see basalt in several forms. When it is first created (i.e. when it comes out of the Earth in the form of lava) it is very dark; however, over time it gets "weathered" - exposure to oxygen reacts with the iron in the basalt and turns it reddish.

IV.3 What planet do you think might have oxidized basalt based upon its color?

What would this suggest about that planets atmosphere?

Would you expect to find basalt on this planet, i.e. is there evidence that volcanism has occurred/is occurring?

IV.4 Returned lunar samples from the Apollo missions shows that the Moon contains very old basalt in its maria regions. Why hasn't it turned red?

Lab 11

Planetary Temperatures and Greenhouse Effect

Purpose: The purpose of this lab is to understand the role albedo, distance from the sun, and greenhouse gases play in determining the surface temperature and habitability of the planet.

Equipment: Computer with internet connection to the Solar System Collaboratory.

Pre-lab Questions

1 Define albedo, using the concepts of reflection and absorption.

2 Define a greenhouse gas. Discuss absorption and transmission of visible, infrared, and ultraviolet light in your definition.

3 What are the primary greenhouse gases in the Earth's atmosphere?

4 Rank how important you think each factor is in determining planetary temperature: distance from the Sun, albedo, and greenhouse gases. Explain your reasoning. (It's ok if you're wrong, but you need to justify your rankings.)

Introduction Understanding why Earth can support abundant life but Venus and Mars cannot is fundamental in the field of astrobiology. You will be able to answer this question at the end of this lab, and that answer is the beginning of the answer to the much larger question of what determines the habitable region around a star.

This lab focuses on the importance of planetary temperature in determining habitability. Why temperature? Of all the factors that affect the presence of abundant life on a planet (chemistry, radiation, biology, etc.) the presence of liquid water is of paramount importance, and liquid water can only exist in a narrow temperature range. You will study the effects of distance from the sun, planetary albedo, and greenhouse gases on planetary temperature.

In the Computer Lab, launch an internet browser, turn-off pop-up blockers, and go to the website http://solarsystem.colorado.edu/cu-astr/. Click on either the "Low Resolution" or "High Resolution" link, depending upon which is appropriate for your monitor. Then click on the "Modules" link, and finally, select the "The Greenhouse Effect: EARTH/VENUS/MARS" module.

Useful information is linked to in the sidebar. The "Give me a HINT" link provides a basic understanding of the applet. "Show me the MATH" provides the mathematical formulation that is programmed into the computer. The "PHYSICS PAGE" link provides background information on the physical processes that go into the models. The "FACT SHEET" shows important information about the inner planets.

I Distance from the Sun

The Sun heats the planets through radiation; since radiation falls off with distance, planetary temperatures depend on distance from the Sun.

Notice in the bottom of the apple that the "Model" used to calculate the temperature of a planet is displayed. It should be set on "Fast-rotating, dark planet." The planet must be "fast-rotating" to ensure that the temperature at night is similar to the temperature during the day. The planet is "dark", so that all the sunlight is absorbed rather than reflected.

I.1 Move Planet X to the orbit of the Earth (1 AU).

(a) What is the temperature of Planet X?

(b) Is this the temperature of the Earth? If not, why not?

We all know that if we move the planet to a larger orbit so that it's further from the Sun, its temperature will go down. But by how much? Make a prediction: what do you think will happen if you double the size of the Earths orbit? Here are some possibilities:

A If the temperature follows an inverse law, doubling the distance should cause the temperature to drop by a factor of 2.

B If the temperature follows an inverse square law, doubling the distance should cause the temperature to go down by a factor of 4.

C If the temperature follows an inverse square-root law, doubling the distance should cause the temperature to drop by a factor of square root of 2 which is about 1.414.

I.2 (a) What is your prediction if we double the size of the Earth's orbit? Explain your reasoning.

(b) Now go ahead and move Planet X to 2 AU (twice Earths orbital distance), what is the temperature?

(c) Which of the above laws does temperature follow? Does this agree with your prediction?

(d) Click on the "Show me the MATH" link, read how the model works, and explain in your own words why the temperature is related to the distance according to the correct law above.

Continue to study the material through the "Show me the MATH" link.

I.3 (a) Does the temperature of a planet depends on the size of the planet in this model? Explain why (or why not).

(b) This formula applies only to a fast rotating dark planet. Why?

(c) Assume that you have a slow rotating dark planet. How does this change the temperature relation? Explain your reasoning.

The "FACT SHEET" from the quick navigation frame (the gray frame on the left) gives temperature data for some of the bodies in the inner solar system. Use this information to evaluate the accuracy of the model.

I.4 How good is this model? Does it calculate the average temperature of a dark body correctly? State your conclusion and show all the steps you took to reach it.

II Adding Albedo to the Model

Albedo (represented by the symbol A) is the fraction of sunlight falling on a surface that is reflected back into space. (The word albedo comes from the Latin word for ”white” - albus.) The albedo represents the average reflectivity over the entire visible surface; hence it differs slightly from the reflectivity of different portions of it. For example, the surface of the Moon has an albedo of 0.07 (on average, 7% of the incident sunlight is reflected, 93% is absorbed), even though there are bright and dark regions that have reflectivities different from the average.

We can measure the albedo of a planet or moon by comparing its brightness to how much sunlight it receives. We know how much sunlight it receives because we know its distance from the Sun (remember the $1/R^2$ rule!), and we can measure how much light is coming from the object with a photometer on a telescope. If the object has an albedo of 100% it will reflect all the sunlight incident upon it. Note: We are assuming that the object is not producing its own light. Planetary scientists are also interested in knowing the albedo of a planet or moon because it provides information on the composition of the object. By comparing the albedo of a planet or moon to the albedos of substances found here on Earth we can learn what substances may or may not be on that object.

But first let's consider how the planet's albedo affects its temperature. Click on the “PHYSICS PAGE” link in the quick navigation frame (the gray strip on the left) and look up albedo to get more background information on the physics behind this applet.

Select the ”Fast rotating, dark planet with adjustable albedo” model from the menu at the bottom of the applet.

II.1 (a) What happens to the temperature of Mars if you increase its present day albedo by 0.05? The temperature goes from ____________ to ____________.

(b) What happens to the temperature of Mars if you increase its albedo from 0.999 to 0.9999?The temperature goes from ____________ to ____________.

In general, if you increase the albedo, you ____________ the temperature. Explain why this is the case.

II.2 How good is this model? Does it calculate the average temperature of the planets correctly? How could you improve the albedo model? State your conclusion and show all the steps you took to reach it.

III Greenhouse Gases

The atmosphere allows most of the sun's radiative power (which is at visible wavelengths) through to the surface, but absorbs the radiation from the planet (which is at infrared wavelengths) and prevents the planets heat from being radiated back into space. This is the principle of the greenhouse effect. We will use two new applets, the “Greenhouse Effect” applet, and the “Radiative Transfer” applet to explore the way the greenhouse effect affects the temperature of a planet. The main greenhouse gasses for the planets are water vapor (H_2O), carbon dioxide (CO_2) and methane (CH_4). Look at the “FACT SHEET” for more details.

III.1 (a) What is the main greenhouse gas for Earth's atmosphere?

(b) What is the main greenhouse gas for Venus' atmosphere?

Use the “Greenhouse Effect” applet to compare the terrestrial, Venusian and Martian atmospheres:

III.2 (a) Which planet has the most total amount of atmosphere?

(b) Which atmosphere has the largest percentage of greenhouse gasses?

(c) Which atmosphere has the highest greenhouse effectiveness?

(d) What is the major difference between the atmospheres of Mars and Venus?

Understand how the net greenhouse strength depends on these three factors by reading the information through the "Show me the MATH" link.

III.3 What factor is the most important? Which the least? Explain why this makes sense.

III.4 Write down the net greenhouse strength for the three planets:

Earth: ____________ Venus: ____________ Mars: ____________

We can now go back to the "Planet Temperature" applet and use the "Fast rotating planet with adjustable albedo and greenhouse strength" model.

III.5 What is the effect of adding greenhouse strength to the model of the planet temperature? (Fill in the blanks in Table 11.1.)

	Average Temperature (look in the FACT SHEET)	Model Temperature with Albedo Only	Model Temperature with Albedo and Greenhouse Strength
Earth			
Venus			
Mars			

Table 11.1: Effect of Greenhouse Strength.

Let's try and make Mars habitable by adjusting its greenhouse strength. You will need to use both applets.

III.6 (a) First, what is your criteria for habitability? Think about what sustains life on Earth but is not present on Venus or Mars.

(b) Come up with some scenarios that will help you meet this criteria. Be sure to list all of the steps you took and all of your data. (Hint: You are not adding any new components to Mars atmosphere, just changing the amounts of what is there.)

III.7 Now do the same with Venus. Remember to record what you did and why you did it.

III.8 We have kept albedo the same while changing the atmosphere. Is this likely to be realistic? Why or why not?

Go back to the Planet Temperature applet.

III.9 (a) Using the albedo and greenhouse strength of Earth, determine and record the range of orbital radii that allow for liquid water on the planets surface. Does this surprise you?

(b) Discuss the importance of an atmosphere in the habitability of a planet.

IV One-Layer Atmospheric Models

You will now use the "Convective Equilibrium Radiative Transfer" applet to study in a little more detail the models that lie behind the "Greenhouse Effect" applet that you have just been using. You are now getting into some pretty sophisticated physics. The applet will take care of the math for you, but you should read the physics page (use the "PHYSICS PAGE" button on the left) to get an idea of the principles involved. The main point that you should get out of this applet is that we can model a physical system (in this case Earth's atmosphere) in several different ways. Each model has its advantages and its limitations, and you have to be aware of both before you try using a particular model to answer a question.

Note that the calculations behind the "Radiative Transfer" applet apply only to the Earth. The physical principles still apply to all of the planets, but the detailed formulations inside the applet would need to be changed.

The simplest of all atmospheric models is the one-layer semigray model. It assumes that the atmosphere is thin enough that a typical photon emitted by the ground will be absorbed only once (hence single-layer). The model also assumes that the visible wavelengths radiated by the Sun are not absorbed by the atmosphere, but the infrared wavelengths radiated by the ground are absorbed with a uniform absorption coefficient. Hence the term semi-gray: "semi" because the atmosphere does not absorb visible radiation, and "gray" because the IR radiation is absorbed uniformly across the IR wavelength range.

Choose the semigray model, and set the absorption coefficient to 0.0%.

IV.1 (a) What temperature does the model give for the Earth?

(b) Refer back to the "Planet Temperature" applet (you may want to use the "EXTRA WINDOW" button on the left, so that you can have both applets running at the same time) and choose the third model from the menu, "Fast rotating planet with adjustable albedo and greenhouse strength." Put in the appropriate albedo for the Earth (check the "FACT SHEET"). To what value of greenhouse strength do you think an absorption coefficient of 0.0% corresponds?

(c) Set the absorption coefficient to 1.0 (100%). What temperature does the model give for the Earth?

(d) Now look up the measured average temperature for Earth (check the "FACT SHEET"). Approximately what value of the absorption coefficient gives the measured temperature for the Earth?

Now let's look at the semi-gray model with one spectral window. This model is a simple improvement on the previous one. It attempts to address the fact that the Earth's atmosphere does not really have a uniform absorption coefficient over the entire infrared region of the spectrum, by allowing for a radiative window. Think of the absorption spectrum of the atmosphere as a blanket that covers the entire infrared spectrum. A radiative window is a hole in that blanket that allows part of the Earth's IR radiation to escape directly to space without being absorbed by the atmosphere. The absorption curve for this model resembles the absorption curve of the semigray model except for the hole.

IV.2 Keeping the absorption coefficient at 100%, find the two approximate locations in the IR spectrum of the radiative window (in micrometers, 1 um = 1 millionth of a meter) that will give you the measured temperature of the Earth.

Finally, in the three gas model, approximate absorption curves of three greenhouse gasses (water vapor, carbon dioxide, and methane) have been incorporated into the applet. By moving the sliders, you can change the relative concentration of these gasses in the Earth's atmosphere, and see what effect that has on the atmosphere's absorption curve (at the middle) and on the Earth's temperature. (Remember the limitations of the model - it is still a single-layer model). The sliders have been scaled to the present-day average concentrations of these gasses, so that a value of 2.0 for the carbon dioxide slider for example corresponds to doubling the amount of carbon dioxide in the atmosphere over current levels.

IV.3 (a) Set all three concentration values to 1.0 (present-day values). Does the applet give the measured temperature for the Earth? If not, how many degrees off is the model?

(b) With all three concentration values set to one, look at the absorption curve. Where is the position of the biggest dip in the absorption curve? Does the position of that dip correspond to the position of the radiative window that you found with the semigray with one spectral window model?

IV.4 Which of these three gases is the most effective greenhouse gas? (Hint: try increasing/decreasing the concentration of each gas relative to present values and see which gas changes the temperature the most). Be sure to give evidence to support your choice.

IV.5 (a) Now double the amount of CO2 in the atmosphere. What does the model give for the temperature of the Earth?

(b) How many degrees warmer is this than the current measured average temperature?

(c) Do you think this is a good prediction? That is, if the amount of CO2 in the atmosphere were to actually double over the next few years, would you expect the actual temperature of the Earth to be higher, lower, or the same as that predicted by this model? Can you explain why the actual temperature might differ from your prediction using this model?

V Post-lab Questions

V.1 Since 1995 scientists have been discovering planets orbiting other Sun-type stars. So far, two planets have been found orbiting the star called HD37124. The inner planet has an orbital radius of 0.54 AU. Use the Planet Temperature applet to determine whether or not you can make this planet habitable by adjusting the atmosphere. Try different scenarios (e.g. do you need an abundance of greenhouse gases or can you do it with none at all?) NOTE: Remember, the applet assumes that the central star is our Sun. HD37124 is slightly smaller (R = 6.44 x 105 km) and a little cooler (T = 5658 K) than our Sun so you will need to scale the planet temperature value that the applet gives you.

V.2 (a) Aldebaran (the eye of Taurus the bull) has a surface temperature of 4000K and a radius of 2.76 x 107 km. Assume that there is a planet orbiting Aldebaran at 1 AU with the same albedo as Earth (A = 0.3). What is the planets surface temperature?

Now assume the planet has the same average surface temperature as Earth without any greenhouse effect (T = 255 K). What would the planets albedo be?

If we wanted to find an Earth-like planet around Aldebaran (i.e. A = 0.3 and T = 255 K), how far from the star must the planet orbit? Express your answer in AU. Which planet in our solar system orbits about this distance from our Sun?

V.3 Now, consider the questions posed to you at the beginning of the lab. Why can Earth support abundant life but Venus and Mars cannot? and What determines the habitable region around a star? Use what you have learned in this lab to answer these two fundamental questions about our place in the solar system.

Lab 12

Seasons

Purpose: This exercise involves making measurements of the Sun every week throughout the semester, and then analyzing your results at the semesters 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.

Pre-lab Questions

1 How is local apparent solar time different than the time shown on your watch?

2 In measuring the apparent solar diameter on the Sun, does the magnification power of the heliostat affect the results you will get for the relative size of the Sun throughout the year? Why or why not?

3 Can the Sun ever be measured at 90 altitude from here in Boulder? If so, on what date? If not, why not?

Introduction: 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 semesters end, you will return to this exercise and analyze your findings to determine just what factors are responsible for the Earths heating and cooling.

I Making Solar Measurements:

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?

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 Suns 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:

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

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 = ____________

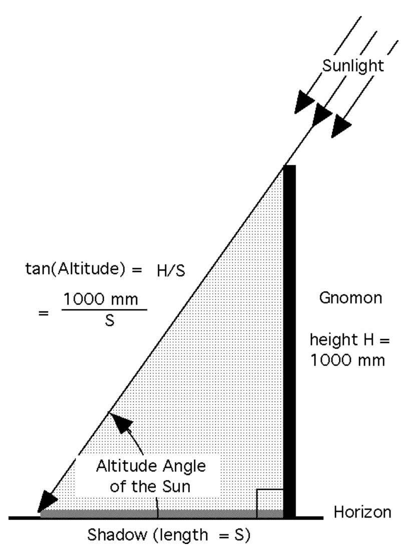


Figure 12.1

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 Earths surface where the Sun is, at this moment, directly overhead at the zenith.

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-centimeters worth of sunlight.

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

I.6 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.7 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: Relative Solar Intensity = $\frac{100cm^2}{Area}$ =

In the lab room, your instructor will have an image of the Sun projected onto the wall using the Observatorys 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.8 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 = ____________

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 everyones 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 its important for you to understand the procedure.

I.9 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.10 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.11 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.12 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.

Week	(a) Date	(b) Maximum Solar Altitude (deg)	(c) Number of Daylight Hours	(d) Maximum Solar Intensity	(e) Solar Diameter (mm)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					

Table 12.1

You will not be marked down for incorrect predictions.)

II 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 everyones measurements will be available for analysis the following week and throughout the remainder of the semester.

II.1 Every week take a few moments to analyze the previous weeks graphs, and record in Table 12.1:

(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.

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: Maximum Solar Altitude (Figure 12.2), Hours of Daylight (Figure 12.3), Maximum Solar Intensity (Figure 12.4), and Solar Diameter (Figure 12.5). Be sure to include the appropriate date at the bottom of each chart.

III Analyzing 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.

III.2 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.3 (a) Measured at noon, did the Suns altitude become higher or lower in the sky during the course of the semester?

(b) On average, how many degrees per week did the Sun's altitude change?

(c) Explain why this happened, using the motions of the Earth. Draw diagrams.

(d) How would this be different if you were in Bhutan? Explain your reasoning.

(e) How would it be different if you were on the equator? Explain your reasoning.

III.4 (a) Did the number of daylight hours become greater or fewer?

(b) On average, by how many minutes did daylight increase or decrease each week?

(c) Explain why this happened, using the motions of the Earth. Draw diagrams.

(d) How would this be different if you were in Australia? Explain your reasoning.

(e) How would it be different if you were on the equator? Explain your reasoning.

III.5 (a) 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.)

(b) On that date, how many hours of daylight did we have?

(c) 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. Based on this reasoning and your measurement, what is the latitude of Boulder?

III.6 How would you determine, and prove, on which day of the year the Summer Solstice occurs (if you have no written calendar)?

III.7 Did the sunlight meter indicate that we, in Boulder, received more or less solar intensity at noon as the semester progressed?

III.8 (a) Did the Suns apparent size grow bigger or smaller?

(b) Does this mean that we are now closer to, or farther from, the Sun as compared to the beginning of the semester? Explain your reasoning.

(c) Did the Earth go through periapse or apoapse during the semester? Explain your reasoning.

III.9 (a) Has the weather, in general, become warmer or colder as the semester progressed?

(b) 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?

(c) Which factor or factors seems to be contrary (or anti-correlated) to an explanation of the seasonal change in temperature?

IV Solar Energy

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 100% efficient 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.

IV.1 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: ____________

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.

IV.2 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.

From 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) in Table 12.2.

IV.3 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.)

$$\frac{\text{Final Week's KWH}}{\text{First Week's KWH}} = \frac{\rule{3cm}{0.4pt}}{\rule{3cm}{0.4pt}} \times 100\% = \text{Percent Change in Solar Energy}$$

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.

IV.4 What is the ratio of the apparent diameter of the Sun between the end and the start of the semester?

$$\text{Diameter ratio} = \frac{\text{Final Week's Diameter}}{\text{First Week's Diameter}} = \frac{\rule{3cm}{0.4pt}}{\rule{3cm}{0.4pt}}$$

The energy delivered to the Earth by the Sun varies inversely as the square of its distance from

Week	(f) "Weight" of Sunlight (grams)	(g) Solar-Const. Hours	(h) KWH/Meters^2 per Day
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			

Table 12.2

us. The diameter ratio calculated above is already an inverse relationship (that is, if the diameter appears bigger, the Suns 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 (1.102 = 1.21). If the ratio is 0.90 (Sun 10% further away), it will deliver 0.902 = 0.81 = 81% as much energy (equivalent to 19% less energy).

IV.5 (a) 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?

(b) 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.

IV.6 Compare the relative importance of the sunlight intensity-duration effect with the solar-distance effect. Which of the two factors is clearly the most important in causing seasonal changes? Explain clearly how you arrived at your conclusion.

IV.7 (a) 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?

(b) If we were at a lower (more southerly) latitude in the northern hemisphere?

(c) If we were at the same latitude as Boulder, but in the southern hemisphere?

V Post-lab Questions

V.1 Earth has an eccentricity of 0.016, but Mars has an eccentricity of 0.093. Earth has an axial tilt of 23.5° and Mars has an axial tilt of 25.19°. How do you think seasons are different on Mars? Would seasons for one hemisphere be different than the other? Explain your reasoning.

V.2 Venus has an eccentricity of 0.006 and an axial tilt of 2.7°. How do you think seasons are different on Venus? What other factors might have a greater effect on the Venusian climate than seasonal effects? Explain your reasoning.

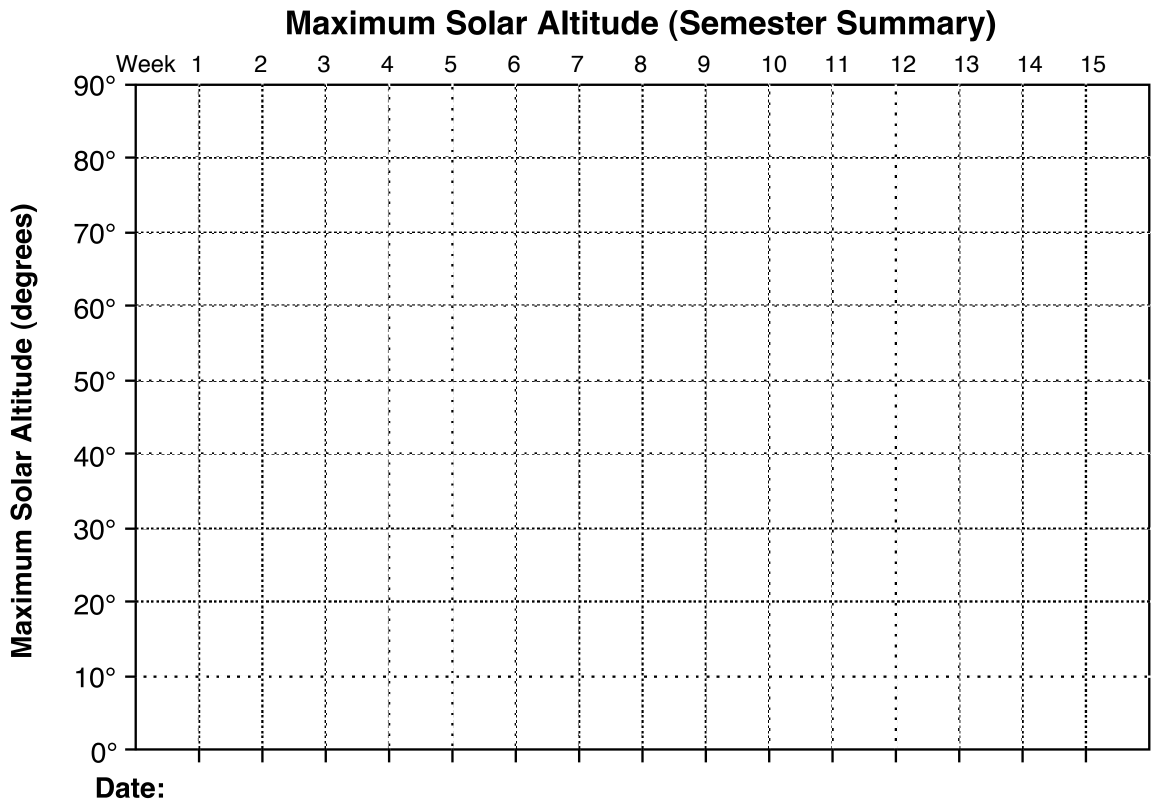

Maximum Solar Altitude (Semester Summary)
Week 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
90°
80°
70°
60°
50°
40°
30°
20°
10°
0°
Maximum Solar Altitude (degrees)
Date:

Figure 12.2

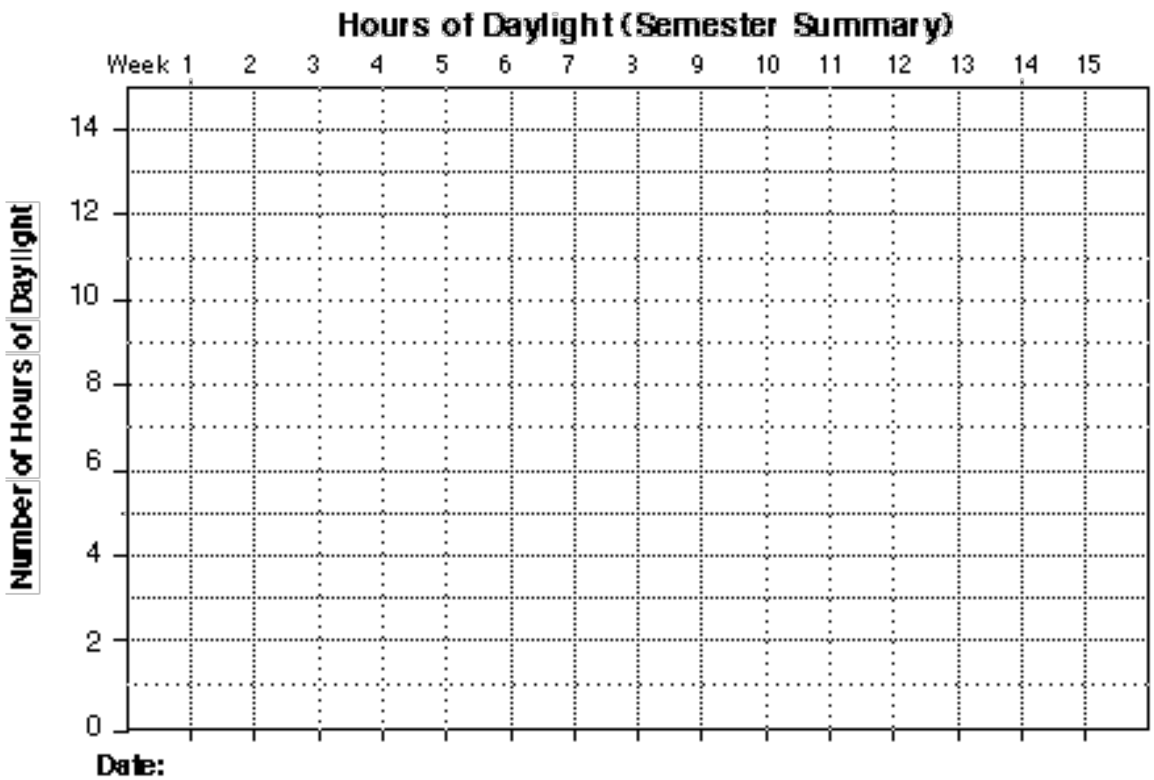

Hours of Daylight (Semester Summary)
Week 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Number of Hours of Daylight
0 2 4 6 8 10 12 14
Date:

Figure 12.3

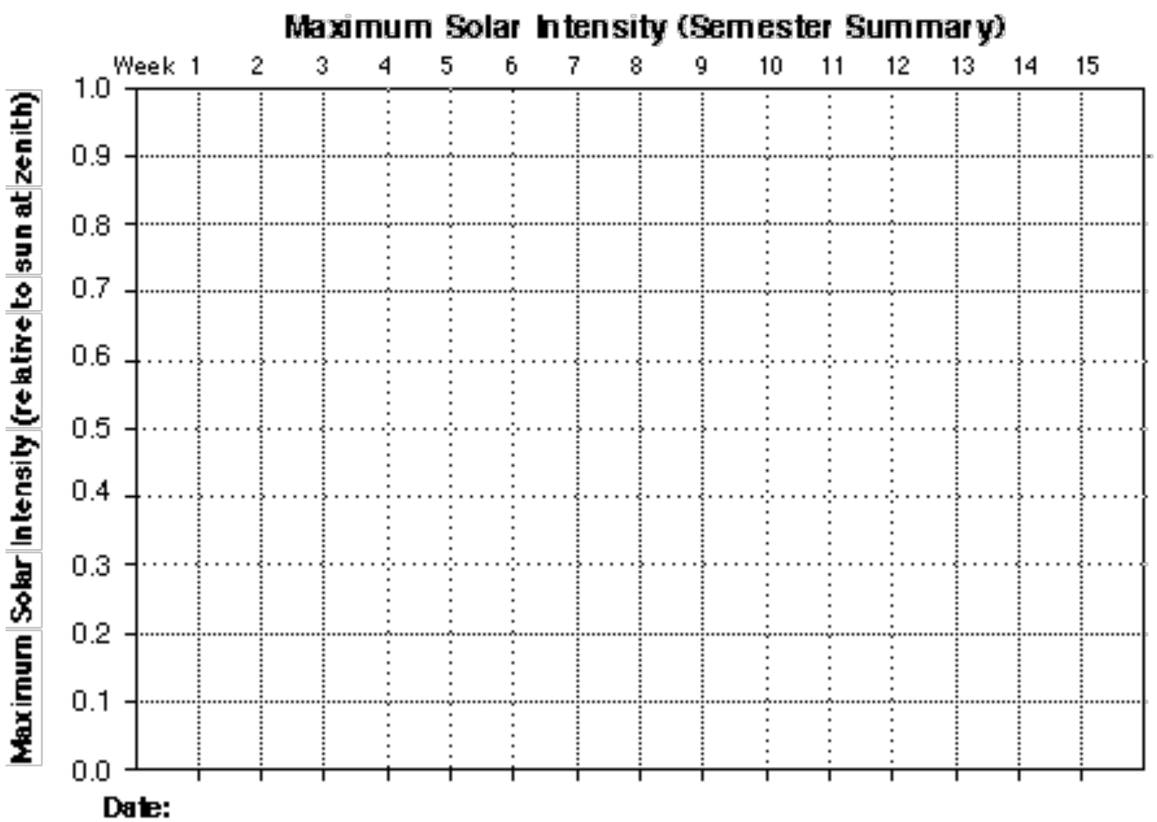

Maximum Solar Intensity (Semester Summary)
Week 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Maximum Solar Intensity (relative to sun at zenith)
Date:

Figure 12.4

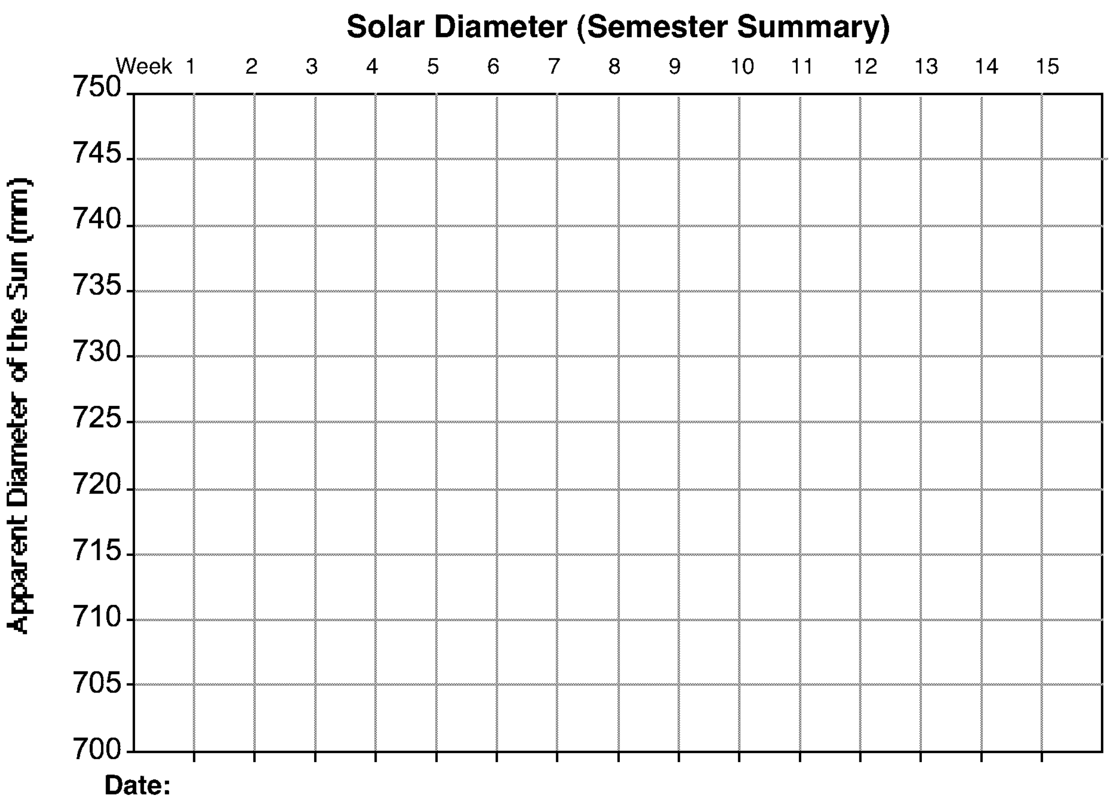

Solar Diameter (Semester Summary)
Week 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Apparent Diameter of the Sun (mm)
750
745
740
735
730
725
720
715
710
705
700
Date:

Figure 12.5

Lab 13

Detecting Extrasolar Planets

Purpose: 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^{TM} orrery (with a variety of detachable planets), light sensor, laptop (or other) computer with LoggerLite^{TM} software, modeling clay (available from your lab instructor for the optional section at the end), and calipers.

Pre-lab Questions

1 Summarize Keplers 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? The area of a square?

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.

Introduction: 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 Keplers 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 Keplers 3rd Law (P^2=a^3). Keep this in mind.

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 planets interactions with its central star. By detecting a repeating dimming of the stars brightness, scientists can infer that a planet is orbiting around the star and occasionally blocking some of the stars light from the telescope.

In this lab, the light sensor will simulate both Keplers 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 youll 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 youll 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: ____________

Next youll 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.

I.2 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 its not periodic, this will not effect your measurements. Most real stars actually show some variability.)

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 1/2 the diameter of your star. What percent of the stars 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 1/2 the diameter of the star (use circles, dont do a 3-dimensional drawing). To help make the point even clearer, temporarily pretend the star and planet are squares, with the smaller one 1/2 the width of the larger (start the square planet in the corner of the square star).

Star & Planet Star & Planet (drawn as 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 stars 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.

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?

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 dont 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	
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 Keplers 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 youve detected? Be as specific as possible (i.e. can you guess exact sizes?) Explain your reasoning.

IV.5 Once youve 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.

V Detecting Earth-size Planets

V.1 Earths radius is 6000 km and the Suns radius is 700,000 km. Using the reasoning you came up with in II.5, calculate the percentage of the Suns light that Earth would block during a transit.

V.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.

VI Post-lab Questions

VI.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.

VI.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.

VI.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?