Hands-On Astronomy

Laboratory Manual

Department of Astronomy
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with assistance from
Dr. Francisco Reyes

TENTH EDITION

Revised and edited by Alex M. Garcia

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Night Labs on Tuesdays at the Campus Teaching Observatory (CTO):

Lab 12: Observe The Moon

Lab 13: Observe The Planets

Lab 14: Observe The Deep Sky

Your instructor will provide advance notice and additional information regarding these night labs.

Forward

This manual resulted from a complete two-year revision of the undergraduate astronomy laboratory course, AST 1022. The revision represents an effort to replace the former, rather passive exercise, with real, hands-on laboratory experiments. The original experiments presented here were conceived, tested, and written up by Professor Alex G. Smith. The final design and fabrication of the many pieces of apparatus testify to the skill and dedication of our Observatory Engineer, Mr. John Baker. Dr. Francisco Reyes, who was in charge of the day-to-day operation of AST 1022, contributed ideas through many conferences. None of this would have been possible without the enthusiastic support and encouragement of Professor Stanley Dermott, former Chairman of the Department of Astronomy.

Essential financial support for acquisition of the necessary computers and other equipment was provided by the Department of Astronomy, the office of the Vice Provost of the University, Dr. Gene Hemp, and the office of the Dean of the College of Liberal Arts and Sciences, Dr. Willard Harrison. Our most sincere appreciation is expressed to all who contributed to equipping of what we believe is one of the finest laboratories of its kind.

In the design of experiments, recognition was given to the fact that some AST 1022 students have not had a course in astronomy, much less a course in physics. An underlying goal of the experiments is to teach a little astronomy and a little physics, but most importantly to impart a feeling for the methodology of science. Regardless of their inclinations and future careers, the lives of all students will be impacted *in a major way* by science. Hopefully we can help them to see that science is *not* a mass of "laws" engraved in stone and carried down a mountain by an old man with a white beard. Hopefully they may come to appreciate science as a very human endeavor, an ongoing process, carried on by people like themselves, and subject to the limitations and errors of all human endeavors. Three of the exercises are computerized, rather realistic simulations of observations made at a major astronomical observatory. Not only do these exercises impart some feeling for such observations, but they give the student practice in running scientific applications on a computer. The simulations were developed under Federal sponsorship at Gettysburg College.

A very key role in the laboratory is played by our carefully selected graduate teaching assistants. These teachers will provide necessary background information for each experiment. They will provide one-on-one assistance to students who need help in operating unfamiliar apparatus, and they will assist students in interpreting and evaluating their results. Students are urged to take full advantage of this available individual tutoring in a small-class environment.

AGS 08/19/97

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We wish to thank Professors Steve Eikenberry, Veronica Donoso, Paul Sell, and Triana Almeyda for their corrections, suggestions and comments regarding the text of the lab manuals and their critical comments regarding the subjects and material of the experiments.

Lab 0: Math And Science Basics

"I Hate Science"

Teachers often hear these words uttered from the mouths of their students. It seems incomprehensible that anyone could say such a thing! Curiosity lies at the heart of science, and curiosity is a basic human trait. Science is, to put it simply, curiosity with guidelines.

The reason so many students might dislike science is that it is presented to them in many classes as a *product*. The teacher tediously rattles off scientific fact after fact, often without mentioning anything about how these principles came about. The student is expected to simply regurgitate this information, some of which might seem inconceivable, back to the teacher. Because of this, many students hate science and think of it only as an erudite body of knowledge. The late astronomer Carl Sagan wrote:

"It is enormously easier to present... the wisdom distilled from the centuries of patient and collective interrogation of Nature than to detail the messy distillation apparatus. The method of science, as stodgy and grumpy as it may seem, is far more important than the findings of science"

For practicing scientists, science is almost wholly a *process*. Through this lab book and class, it is hoped that the student may gain significant insight as to the process of science and how, through detailed observation and independent experimentation, scientists come to agree on what are considered scientific facts.

The basic idea of science is not that hard to understand. Many of us, regardless of whether or not we think we like science, invoke the scientific method every day. Say you are riding your bicycle and you suddenly get a flat tire. You realize right away that the air escaped from the tire too fast for it to be a leak in the valve. You get off your bicycle and look at the tire. After a little searching you find a tack through the rubber tread. You conclude that you got the flat because the tire was punctured by a tack.

You just performed science! A phenomenon occurred that seized your curiosity, you observed it carefully, and based upon the data collected from these observations you came up with an explanation or hypothesis that best explains the occurrence. This is the **method of science** in its most fundamental form: observe, collect data, draw a hypothesis. In science, a hypothesis is tested through repeated experimentation and is either confirmed, changed or dismissed.

It should be stressed that in this class, just as in scientific practice, there is no "right answer". Many times when performing experiments we don't know what the results are going to be. Careful data collection is the key to the success of an experiment. When performing good science, we do not dismiss "bad" data points, or massage the data so that it will conform to the results expected. If an experiment is performed properly and carefully, we must trust our data, regardless of whether we think it will yield the desired results. We must also assign errors to the data we collect. Errors give us an idea of how careful our observations were, and to what degree we can trust our data. The conclusion of the experiment is the answer or explanation that best describes *all* of the data, in light of the errors.

Science is by no means perfect, but it is the best tool we have for acquiring truth from Nature, and it does not merit hatred. It is the goal of this book, and the hands-on teaching in this course, that students will acquire a new appreciation for science and its methods.

James DeBuizer
December 1997

Scientific Notation

In astronomy, we often have to deal with HUGE numbers. For instance, the age of the Universe, the distance to a galaxy, or the mass of a star. These measurements are well beyond our everyday experience and understanding. Astronomers have two ways to cope with this inconvenience. The first is to use an intelligent way to represent numbers called "Scientific Notation". The second is to use different units that are more appropriate for the scale (see Units section).

The scientific notation is a way to express very large (and very small) numbers as powers of 10

$$\begin{array}{lllllll}
10^0 & = & 1 & & & & \\
10^1 & = & 10 & & 10^{-1} & = & 0.1 \\
10^2 & = & 100 & & 10^{-2} & = & 0.01 \\
10^3 & = & 1000 & & 10^{-3} & = & 0.001 \\
10^4 & = & 10000 & & 10^{-4} & = & 0.0001 \\
10^5 & = & 100000 & & 10^{-5} & = & 0.00001 \\
10^6 & = & 1000000 & & 10^{-6} & = & 0.000001 \\
\text{etc...} & & & & \text{etc...} & &
\end{array}$$

A quick way of changing a number from a decimal representation to a scientific notation representation is simply to count the number of positions to the left or right of the decimal point. The number of positions corresponds to the power of ten. In most cases, scientific notation expresses numbers as the product of a number and a power of ten. For example, the mean distance from the Earth too the Sun is approximately $149,600,000.0$ km. In scientific notation, we would express this as 1.496×10^8 km. The decimal point was moved 8 positions to the left.

Measuring Angles

Modern science has adopted the ancient Babylonian system for angular measures, where a circle is divided into 360 degrees. Then, related to timekeeping

$$1 \text{ degree} = 60 \text{ arcminutes } (1^\circ = 60') \qquad \text{and} \qquad 1 \text{ arcminute} = 60 \text{ arcseconds } (1' = 60'')$$

Astronomers measure apparent/projected distances in the sky with these angular units.

With knowledge of the distance, d, we can then use trigonometry as in Figure 0.1, to calculate a perpendicular length / physical size, s, using an angular size, θ.

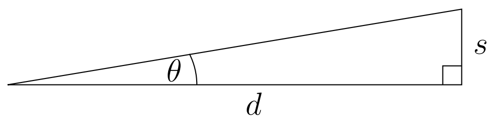


Figure 0.1: Triangle used when determining the physical size of an object

Using our trigonometric functions (SOH: <u>S</u>ine is <u>O</u>pposite over <u>H</u>ypotenuse, CAH: <u>C</u>osine is <u>A</u>djacent over <u>H</u>ypotenuse, TOA: <u>T</u>angent is <u>O</u>pposite over <u>A</u>djacent),

$$\tan\theta = \frac{s}{d}$$

When the angles are very small ($\theta \lesssim 1°$), which is very common in astronomy, we commonly use the "small-angle approximation", $\tan\theta \approx \theta$, to more simply write

$$\theta \approx \frac{s}{d}$$

Importantly note that θ in this equation must be in <u>radians</u>, not degrees, a very common mistake. When you are using a scientific calculator, be careful which angular unit is being assumed. As can be seen by the small angle approximation above, θ is just a ratio of lengths, so it is a dimensionless number. Since there are 2π radians around a circle, we have the conversion factor: $360° = 2\pi$ radians.

Units

In the section about scientific notation, we saw how to write numbers in scientific notation in order to conveniently express very big or very small numbers. Our second solution to these large numbers was to use appropriate units, so that we do not have to deal with cumbersome numbers at all. For example, using miles to measure the distance to the Sun is much like using inches to measure the distance from New York to Los Angeles.

So, when we deal with distance of objects within our solar system, we use a "yardstick" called the **Astronomical Unit (AU)**. One astronomical unit is equal to the average distance of the Sun and the Earth

$$1 \text{ AU} = 1.496 \times 10^8 \text{ km} = 9.3 \times 10^7 \text{ miles}$$

However, the distances between the stars of our galaxy are huge compared to the distance of the Earth from the Sun, so the astronomical unit is not a convenient unit any more. Therefore, we have to further stretch out our “yardstick” and use a unit defined by the distance a light beam travels through free space in a year. We call this unit **lightyears (ly)**. Although “years” is traditionally a unit of time, “lightyear” represents a unit of *length*

$$1 \text{ ly} = 6.324 \times 10^4 \text{ AU} = 9.46 \times 10^{12} \text{ km}$$

There is yet another unit to measure interstellar distance within galaxies. It is called a **parsec (pc)**, notable of *Star Wars* fame (though they incorrectly referred to parsecs as a unit of time, while it is a measure of distance)

$$1 \text{ pc} = 3.26 \text{ ly}$$

You should also be aware of commonly used prefixes. For example, one **kiloparsec (kpc)** is equal to one thousand parsecs:

$$1 \text{ kpc} = 10^3 \text{ pc}$$

and one **megaparsec (Mpc)** is equal to one million parsecs:

$$1 \text{ Mpc} = 10^3 \text{ kpc} = 10^6 \text{ pc}$$

Although the awe-inspiring size of the Universe makes necessary use of such long “yardsticks”, the measurement of distances is not the only case where we have to introduce new units. For instance, masses of stars and galaxies are so huge that instead of using kilograms (kg), we use our Sun’s mass itself as a unit of mass. It is called a **Solar Mass** (oftentimes shown as $M_\odot$)

$$1 \ M_\odot = 1.992 \times 10^{30} \text{ kg}$$

The pantheon of units goes on and on. Some of the more useful units for this course with which you should be familiar (other needed conversions can be found using reliable internet searches or by asking your instructor):

1 kilogram (kg)	=	1000 grams (g)	
1 meter (m)	=	100 centimeters (cm)	= 1000 millimeters (mm)
1 nanometer (nm)	=	10^{-9} m	= 10 Ångstroms (Å)
1 inch (in)	=	2.54 centimeters (cm)	
1 foot (ft)	=	0.305 m	
1 mile (mi)	=	1.609 kilometers (km)	

Significant Figures (SigFigs)

The idea behind significant figures is to indicate useful and trustworthy digits in a number. Suppose you measure a child’s height to the nearest centimeter as 63 cm. This means that you are sure of the 6 and have determined that the 3 is better than a 2 or 4; therefore, both the 6 and 3 are significant figures. A significant figure represents a number whose value is supported by a reliable measurement.

Exact Numbers may be defined or counted and known to be exactly correct. For example, you can count the number of pages in this lab. If there are 10 pages, there is no doubt that this is *exact* and not 9.6 or 10.2 pages. Defined numbers are exact as well. A kilometer is defined to be *exactly* 1000 meters. Exact numbers have an infinite number of significant figures. Though many constants or conversions have an uncertainty, we will generally not be concerned with this detail in this course.

Inexact Numbers are what is yielded by most measurements, whose accuracy is limited by the measuring device used. For example, the smallest unit on most metric rulers is millimeters. The first estimated digit in length obtained from such a ruler would be 0.1 millimeters. One can still measure the diameter of a penny to be 18.9 millimeters using this ruler. When measuring the penny you see that its size lies somewhere between 18 and 19 millimeters and is most likely 18.9 millimeters. The last digit is considered significant because it is the best estimate of the person who measured the penny.

If only the results of a measurement are reported, the following conventions are used to tell which digit is significant:

1. All non-zero numbers are significant
2. Zeros used only to position the decimal point are not significant. Three statements cover all cases involving zeros:

Case 1) **Leading Zeroes** - these are to the left of the first nonzero digit and are never significant

Case 2) **Imbedded Zeroes** - these are between nonzero digits and are significant

Case 3) **Trailing Zeroes** - these are to the right of nonzero digits and are significant only if the decimal point is shown

For example...

(a) 0.00334	Three Sig Figs
(b) 1.0058	Five Sig Figs
(c) 34.00	Four Sig Figs
(d) 0.678	Three Sig Figs
(e) 0.00004	One Sig Fig
(f) 1.38×10^5	Three Sig Figs
(g) 1.3800×10^5	Five Sig Figs

The rules used in this lab for determining the number of significant digits in a calculated final answer are given below:

Rule 1) When adding or subtracting numbers, the result should not be carried beyond the first column having a doubtful figure. For example...

$$8.16 + 74 = 82, \quad \text{not } 82.16$$

Rule 2) When multiplying or dividing, the result should have the same number of digits as the least significant number used in the calculation. For Example...

$$8.3 \times 1045 = 8700, \quad \text{not } 8673.5$$

Rule 3) To show the results of calculations to the proper number of significant figures, rounding must be used (see previous two examples)

In all labs, be sure that all the measured and calculated numbers that you record have the intended number of significant figures.

This may seem pedantic, but where this really comes into play is with large or small calculations. For example, if we wanted to calculate the circumference of the orbit of the Earth, we would use the radius of the orbit of the Earth in the equation of the circumference of a circle:

$$C_{\text{orbit}} = 2\pi(1.496 \times 10^{11}\ \text{m})^2$$

Plugging this straight into our calculators gives us an answer of something like 140,618,692,484,328, 294,087,424.2... m^2. This level of precision is FAR too high for what we know and writing this number not using scientific notation is absurd. Based on our radius (1.496×10^{11} m), we are only really certain of our answer up to 4 decimal places. Therefore, we shouldn't make any statements of certainty past those four decimal places. Thus, our answer is $1.406 \times 10^{23}\ \text{m}^2$.

Note: The number 2 may seen to only have one significant figure in the above example, but actually we know this formula to be exactly true. Thus, 2 in this case is an exact number. Also, the irrational number π with an infinite number of digits does not limit or affect the number of digits in the answer.

Unit Transformations

With so many units around, it is not surprising that we often have to make unit transformations. For instance, we may want to express a result in certain units, but we are given data in different units. We will have to use unit transformations many times during this course, so it is imperative that you feel comfortable with them.

There is a very simple and general way to perform unit transformations, which will be illustrated with the following two examples. This method is sometimes called the Factor-Label Method or the Unit Factor Method.

Example 1: You measured the length of your desk to be 48.0 inches long. What is the length of the desk in centimeters?

We should realize that we need the conversion factor from inches to centimeters:

$$1 \text{ in} = 2.54 \text{ cm}$$

By definition, we can also write

$$\frac{2.54 \text{ cm}}{1 \text{ in}} = 1$$

Since we can multiply anything by 1 without changing the number, we can carry out this operation to convert the units (making sure you always use a conversion no less precise than needed):

$$48.0 \cancel{\text{in}} \times \left(\frac{2.54 \text{ cm}}{1 \cancel{\text{in}}}\right) = 122 \text{ cm}$$

Now notice that by doing this, the unit of inches has been canceled, leaving just centimeters as the unit. When multiplying an equation by another equation that is equal to one the whole point is to put in the denominator the unit that we want to get rid of, so that it eventually cancels. If we knew that the length of the desk is 122 cm and wanted to find it in inches, we simply invert the conversion factor:

$$122 \cancel{\text{cm}} \times \left(\frac{1 \text{ in}}{2.54 \cancel{\text{cm}}}\right) = 48.0 \text{ in}$$

Example 2: A car is traveling at a speed of 60.0 miles per hour. How many meters per second is this?

$$1 \text{ mi} = 1.609 \text{ km} \qquad 1 \text{ km} = 10^3 \text{ m} \qquad 1 \text{ hr} = 3600 \text{ s}$$

We now have to perform transformations several times, which is straight-forward and easy to follow with this method:

$$\frac{60.0 \cancel{\text{mi}}}{1 \cancel{\text{hr}}} \times \left(\frac{1.609 \cancel{\text{km}}}{1 \cancel{\text{mi}}}\right) \times \left(\frac{10^3 \text{ m}}{1 \cancel{\text{km}}}\right) \times \left(\frac{1 \cancel{\text{hr}}}{3600 \text{ s}}\right) = 26.8 \text{ m/s}$$

Errors

When we perform an experiment, we usually want to make measurements of physical quantities, such as lengths, times, weights, etc. We may then substitute these numbers into formulae and seek relations among them. In this process, there are two sources of error involved:

Human Errors

- *Reading Errors*: e.g. misreading a ruler when measuring
- *Calculation Errors*: e.g. punching the wrong number into a calculator
- *Bias*: e.g. errors induced into data collection by the experimenter when they know the outcome of the experiment

These errors can be avoided by being more careful, repeating the experiment, asking a friend to verify our numerical results, and so on.

Errors Due To Limitations Imposed By Nature

- *Measuring Errors*: e.g. when we measure the length of a line with a ruler, our reading cannot be any better than the ruler's smallest subdivision

We can, of course, use a better ruler or a different measurement tool, but this will only decrease the error; it will not eliminate it altogether. Unlike human errors, these errors (a.k.a. uncertainties) are unavoidable.

In the course of this lab, you will have to take many measurements. In most labs you will only be asked to explain what are some possible sources of error in your results. It should be understood that you are asked to mention errors that occur due to the second reason, i.e. due to limitations imposed by the laws of nature, and *not* due to human error.

Occasionally, you will be asked to find a numerical answer to describe the errors of the experiment. The easiest way to do this is mathematically compare your observed result with the known result value in the following way, known as **percentage error**:

$$\%\text{ error} = \left| \frac{\text{Result}_{\text{true}} - \text{Result}_{\text{observed}}}{\text{Result}_{\text{true}}} \right| \times 100.0$$

Scale Factors

We will need to use scale factors when examining photographs and pictures. These pictures are representative of real life in every way except one: scale. The distances between objects in the pictures are obviously not the real distance between actual objects. They are scaled so as to fit on your photograph. The best way to explain the concept is with an example.

Suppose you have an aerial photograph of the University of Florida and you want to determine the size of campus. On closer inspection of the photograph, you find that The Swamp is clearly visible. You know that the length of a regulation football field is 120 yards (100 yards + two 10 yard endzones). Knowing this, you can develop a scale for the photograph. Suppose you measure the length of the field in the photograph to be 5 centimeters. Then we say that:

$$\text{scale} = \frac{120 \text{ yards}}{5 \text{ cm}} = 24 \text{ yards/cm}$$

Now you can determine the true length of campus along University Avenue. Suppose you measure the length of University Avenue on the photograph, and you find it to be 40 centimeters. Now multiply by the previously determined scale:

$$\text{real length} = \text{ scale} \times \text{ ruler measurement} = \frac{24 \text{ yards}}{1 \text{ cm}} \times 40 \text{ cm} = 960 \text{ yards}$$

In other words, to find the scale of a picture, we find a feature whose length we somehow know. Then we measure its length on the picture with a ruler. The ratio of these two lengths is the scale, and we can use it to determine the sizes of other features on the picture.

Common Math Functions on Calculators

This section is designed to refresh your memory on basic math functions you will see in this course, as well as to acquaint you with how to use the special functions keys of your calculator.

Logarithms

To perform logarithms with your calculator, locate the key marked `LOG` or `log`. If you want to calculate log(5) and your calculator is a graphing calculator, you will most likely have to press `LOG` then 5. Sometimes you have to press = to get the answer. Otherwise you first press 5 and then `LOG`. Try it! $\log 5 = 0.698970004$

If you have the equation $x = \log y$ and you have to solve for y, you must put both sides in the exponent of 10 (in this course, all logarithms are base 10, unless otherwise noted). It will look like this:

$$10^x = 10^{\log y}$$

A basic identity of logarithms is $10^{\log y} = y$ so we get:

$$10^x = y$$

Exponents

To perform $10^{7.9}$ on your calculator, first locate the button labeled 10^x or 10^y. On calculators like TI-84's you will press the 10^x (or 10^y) button first and then input 7.9, but on other calculators type 7.9 first and then press the 10^x (or 10^y) button. For some calculators you must press = to get the answer. Try it! $10^{7.9} = 79432823.47$

There is yet another important exponent key that you should know about. What if the base of the exponent isn't 10? Occasionally, you must perform calculations like 5^3 or $3.2^{7.89}$

To perform a calculation such as 5.6^9, first find the button marked x^y or y^x. Most of the time you get the result by typing 5.6 then pressing x^y (or y^x) then 9 and finally pressing =. Try it! $5.6^9 = 5416169.448$

Inverses

Often we have an answer already displayed on our calculator for which we would like to take the inverse. Rather than writing the number down or storing it, clearing the calculator and doing the operation, many calculators are equipped with a special button just for this task.

To perform an operation like $\frac{1}{2.867}$, first locate the button labeled $1/x$. Type in the number, 2.867, then press the $1/x$ button. Try it! $\frac{1}{2.867} = 0.348796651$

Math And Science Basics Worksheet

Name: ______________________ **Date:** ______________ **Section #:** ________

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

1. Whether it be a friend, a family member, etc., there will be someone you encounter with the attitude of "I Hate Science..." or something similar. Reflect upon what you have learned in this first section of this lab by writing a few sentences / short paragraph for how you could respond to such a statement. Such a response may better educate the person regarding how science works and improve their appreciation of the natural and logical process of science.

2. Express the following numbers in scientific notation:

   i) 394,000,000

   ii) 0.00077985

   iii) 52

   iv) 0.65

3. If the Andromeda galaxy (M31) is approximately 750,000 pc away from us and it is approximately 65,000 pc in diameter, what is it's angular size in degrees? What about in arcseconds?

4. These questions are designed to give you a feeling for metric and astronomical units as compared to imperial units. Express:

    i) 1 centimeter in inches

    ii) 1 kilometer in miles

    iii) 8.9×10^9 kilometers in AU

5. Find the answers to the following with the correct number of sig figs

    i) 4.256 + 0.008

    ii) 50 / 5.876

    iii) (4.6789×10^{24}) - (9.267×10^{23})

6. The purpose of this question is to see if you can keep track of units an compute answers to a simple formula. Calculate the mass of the Earth by using:

$$M = \frac{4}{3}\pi\rho r^3$$

Where M is the mass of the Earth, $\rho = 5.5$ g/cm^3 is the average density of the Earth, and $r = 6.4 \times 10^8$ cm is the radius of the Earth. Express your results in scientific notation **(i)** in grams and **(ii)** in kilograms

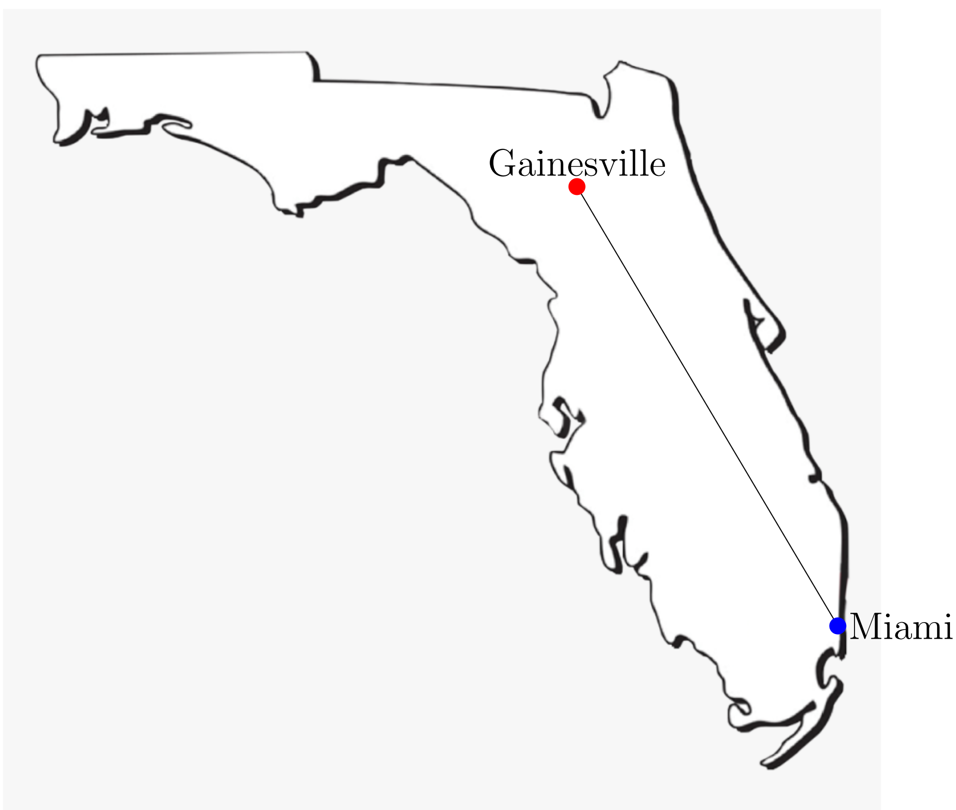
7. Suppose your car was modified so you can travel through space. At a velocity of 65 mi/hr, and driving non-stop, how long would it take for you to get to:

   i) Pluto – at a distance of 5.85×10^9 km

   ii) Proxima Centauri (the nearest star to the Sun) – at a distance of 1.33 pc

8. Through an experiment you conducted you found that the Moon's diameter is 3.550×10^3 km. The accepted value for the Moon's diameter is 3.476×10^3 km. What is the percentage error of your result?

9. Measure the distance from Gainesville to Miami on the map below. The actual distance between the two cities is approximately 300 miles. What is the scale of this picture?



10. When solving these problems, use the calculator techniques described in the earlier sections:

   i) $\dfrac{6.67 \times 10^{13}}{5^{3.9}}$

   ii) You have the following equation, let $s = 32.4$:

$$s = \log_{10} t$$

   Solve each of the following problems both symbolically and numerically:

   a. Find t

   b. Find $1/t$

   c. Now find 5.4^s

Lab 1: How Big is the Sun?

Purpose

This experiment will show you how the size of an object as huge and as distant as the Sun can be measured with simple home-made equipment. It will also acquaint you with the formation of images by lenses, and with the structure of a rudimentary astronomical telescope.

Warning! Need we tell you that the light of the Sun is very intense? At no time here or elsewhere should you attempt to look directly at the Sun through a lens or any other instrument (unless it is a special solar telescope). Never stare at the Sun with the naked eye. Failure to observe such precautions can result in the creation of a permanent blind spot on the retina of your eye!

Observation of the image of the Sun on a screen, as we do in this experiment, is perfectly safe.

Introduction

If one knows how far away an object is, one can estimate its true size by noticing how large it appears to be. (Astronomers denote this apparent size by measuring the angle subtended by the object). As long ago as the "classical" period of ancient Greece, thinkers attempted to guess the size of the Sun by using this kind of reasoning. The crucial importance of the Sun as the prime source of light and heat was evident to the Greeks, as it was to all cultures, many of whom understandably elevated the Sun to the status of a deity.

When Anaxagoras suggested in 434 BC that the Sun was a ball of molten rock as large as the Greek peninsula, his reward was to be banished from Athens. In the 3rd century BC, Aristarchus concluded that the Sun was at least as big as the entire Earth, and a century later Hipparchus raised its size to seven times the diameter of the Earth. While the reasoning of these worthies was sound, large errors in their methods of estimating the distance of the Sun led to vast underestimates of the solar diameter. It was not until 1672, over 1800 years later, that the Italian astronomer G. D. Cassini, who now had the use of telescopes, arrived at what we would regard as a "reasonable" value for the distance of the Sun.

In our experiment, we will assume that we know the distance of the Sun and use some simple geometry to calculate its diameter. Our results will be much better than those of the famous Greeks, and should even improve on Cassini's, whose error was about 10%. We will use a rudimentary solar telescope rather like the ancient device illustrated in Figure 1.1 (dress is optional in our lab). The principle of the experiment is shown in Figure 1.2. A simple lens forms an image of the Sun on a screen at a distance from the lens f, which is called the focal length. We carefully measure the diameter i of the image. Notice that the triangles on either side of the lens are similar triangles, so we can write

$$\frac{i}{f} = \frac{s}{d}$$

where s is the diameter of the Sun and d is its distance. Since we can measure i and f in the laboratory, and since d is now well-known ($\sim$1 AU), we can readily solve for s.

Figure 1.1: Astronomers observing a solar eclipse. The image of the sun is projected upon a screen and the limit of the obscured portion carefully recorded. From Heveluis's *Machina Coelestis*

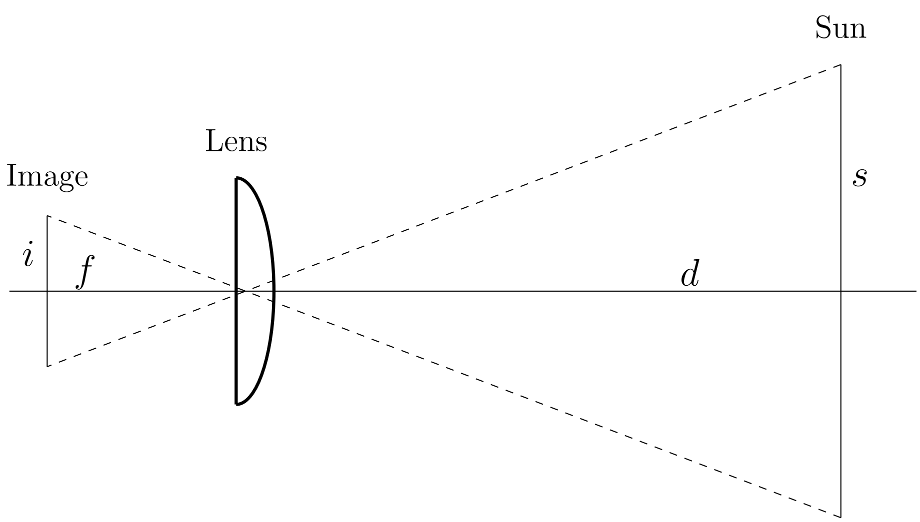


Figure 1.2: Similar triangles set-up to calculate the diameter of the Sun

Laboratory Procedure

You are entering the world of observational astronomy, not unlike the one shown in Figure 1.1. One of the persistent problems of this world is that you cannot observe an object unless it is visible. If there are intermittent clouds, you will likely be able to make your observations, which should take only 10 or 15 minutes, but if the cloud cover is continuous you will be unable to work.

You are provided with a rudimentary solar telescope. Position the instrument as directed by the instructor and point the lens toward the Sun. Again: Do not attempt to look through the lens! Maneuver the telescope until the image of the Sun falls on the white screen near the lower end of the instrument. Slide the screen back and forth until the image is at its smallest and sharpest; here you are "focusing" the telescope. Now use the provided millimeter scale to measure carefully the diameter i of the image. This is the most critical part of the experiment! Each person should make several measurements and average them to yield the best result. Next, use a meter-stick to measure the distance f from the lens to the screen. Record all of your data.

You have been provided with a second lens for the telescope, which will yield a different image size. Repeat the experiment with this second lens in place, again recording all data.

You are also provided with a pinhole that can be substituted for the lenses. Put it in place on the telescope and note that it yields a faint but reasonably sharp image of the Sun. The camera obscura, in which images were formed by pinholes, was known to the Arabs as early as 1000 A. D., long before the invention of telescopes with lenses. Does your pinhole have a focal length? Measure the diameter of the image for at least three different distances between the pinhole and the screen. How does the size of the image relate to the distance between the pinhole and the screen?

If you are fortunate enough to be observing when the Sun is active, you may be able to see sunspots in your images. Galileo first observed sunspots in 1611, and you'll learn more about them in Lab 2: Space Weather. The solar disk shows "limb darkening", meaning that the edge of the disk is not as bright as the center, because at the edge or limb you are seeing a higher, cooler layer of the Sun's atmosphere. Can you see this effect in your images?

How Big is the Sun? Worksheet

Name: ______________________ **Date:** ______________ **Section #:** ________

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

For this experiment, you will be using two lenses (A and B) of different focal lengths as well as a pinhole. Focus the image of the Sun and measure the distance f between the lens and the image (focal length of the lens). Measure the diameter i of the image. Repeat this step three times and repeat with the second lens.

Lens A

Measurement No.	f (cm)	i (cm)
	$f_{\text{avg}} =$	$i_{\text{avg}} =$

Data Table 1.1

Calculate the value of the diameter of the Sun, s, using the calculated averages of the focal length, f, and the image size, i. For the mean distance to the Sun, use the value $d = 1.496 \times 10^8$ km

$$s_A = d\left(\frac{i_A}{f_A}\right)$$

Calculate the percent error for your calculated value of s with the accepted value of 1.392×10^6 km

$$\%_{\text{error}} = \frac{s_A - s_{\text{accepted}}}{s_{\text{accepted}}} \times 100$$

Lens B

Measurement No.	f (cm)	i (cm)
	$f_{\text{avg}} =$	$i_{\text{avg}} =$

Data Table 1.2

Again, calculate the value of the diameter of the Sun, s, using the calculated averages of the focal length, f, and the image size, i. For the mean distance to the Sun, use the value $d = 1.496 \times 10^8$ km

$$s_B = d\left(\frac{i_B}{f_B}\right)$$

Calculate the percent error for your calculated value of s with the accepted value of 1.392×10^6 km

$$\%_{\text{error}} = \frac{s_B - s_{\text{accepted}}}{s_{\text{accepted}}} \times 100$$

Using the calculated <u>mean</u> values of the focal length for **each** lens, calculate the power of the lenses in diopters. (Don't forget to convert the focal length to meters!)

$$\text{Power [diopters]} = \frac{1}{f \text{ [meters]}}$$

Pinholes

Measurement No.	Distance (cm)	Diameter (cm)

Data Table 1.3

Questions

Answer the following questions, be sure to clearly explain you answers

1. Which of the two values of i have the largest relative experimental error and why? (Hint: think about the tools we used to measure them)

2. How does the percentage error of your experimental values of s compare to the Cassini experimental error of 10%

3. How do you interpret the sign (positive/negative) of the percentage error of the value of the diameter of the sun?

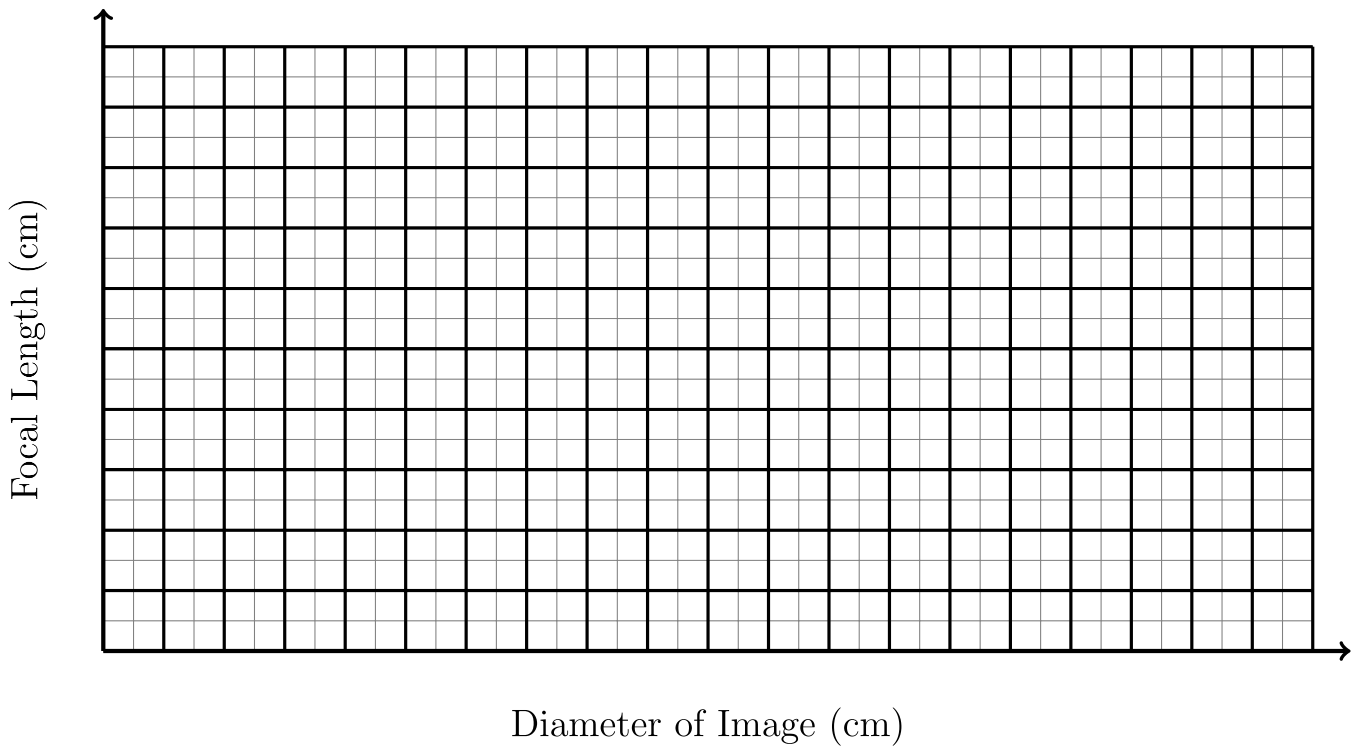
4. Which of your two experimental values for the diameter of the sun depart more from the accepted value? Is this consistent with what you found in question 1?

5. Plot all of your data points for Lens A and B on the first plot. How does the size of the image change when we change the focal length?

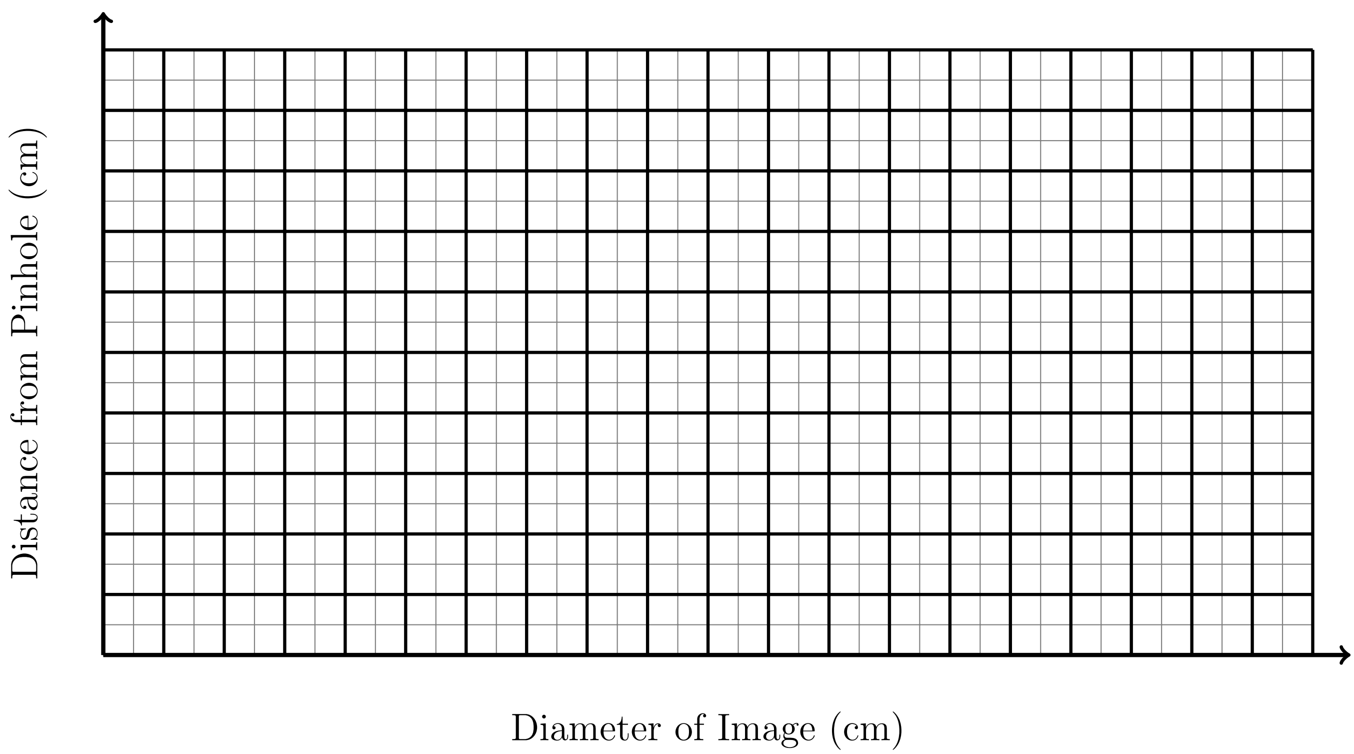
6. Use the plot of size of the image versus focal length of the lens. If you are asked to design a telescope that can produce an image of the sun of 1.4 cm in diameter, what would be the focal length of the lens that you will choose?

7. Plot your data for the pinhole on the second plot. How did the sizes of the images obtained with the pinhole relate to the distance from the pinhole?

Plots



Graph 1.1



Graph 1.2

Lab 2: Space Weather

Purpose

After years of calm, the Sun is becoming more active, and is predicted to reach its maximum around 2025. As the Sun becomes more active, it produces more high energy particles, which create space weather. Solar activity can affect our communications, trigger displays of aurorae, cause gyrations of compasses, damage power lines, and possibly even affect our weather. In this lab, you will have the opportunity to observe sunspots safely, which are the most visible evidence of solar activity. We will view the Sun at various wavelengths of light to view its activity in multiple ways.

Introduction

On the 2$^{\text{nd}}$ of September in 1859, the most intense geomagnetic storm in history hit the Earth, known as the Carrington Event. A geomagnetic storm is a disruption of the Earth's magnetosphere, the area around the Earth affected by charged particles interacting with its magnetic field, caused by a solar wind shock or a cloud of particles created by a Coronal Mass Ejection (CME). The Earth's magnetic field keeps us safe from high energy particles which would otherwise tear at the atmosphere and expose the planet to harmful radiation.

On September 1$^{\text{st}}$, 1859, Richard Carrington and Richard Hodgson were observing the Sun when they witnessed an extraordinarily bright burst of light from the Sun. This was the first ever directly observed solar flare. The flare released a CME which reached the Earth in only 17.6 hours. When the CME hit, it's interaction with the Earth's magnetic field produced brilliant aurorae. These aurorae, usually only visible from the frigid North or South polar regions, became visible far closer to the equator, as far as Colombia. The aurorae were so bright that they lit up the night sky like early morning, waking gold miners for an early breakfast and letting night owls read the newspaper by aurora light.

Across the world, telegraph operators noticed strange electrical effects due to the passing storm. The telegraph systems failed, some operators received small shocks while trying to use their devices. There was even a case where a telegraph operator disconnected their device from electricity, yet was still able to send and receive messages. When a magnetic field changes, it induces an electric field, creating a current. Telegraph pylons sparked, causing minor fires as the Earth's magnetic field was warped by the CME.

The Carrington Event (illustrated in Figure 2.1) is still the most intense geomagnetic storm to strike the Earth within recorded history, but there is evidence that something like it may happen again. In 1859, the most advanced communication technology used was telegraphs. Another CME of such magnitude hitting the Earth today could cause failures in the electronics in satellites within the magnetophere. Over the years, less extreme events have caused disruptions in radio communications and problems in electronics. In March 1989, a solar storm caused an electric grid in Quebec to shut down for nine hours, causing concerns for electric grids to be shielded against currents induced by geomagnetic storms. As recent as July 2012, a solar storm on the level of the Carrington Event just barely missed the Earth by days. In early 2022, a relatively mild CME caused the Earth's atmosphere to puff up like a balloon, causing 40 recently launched Starlink satellites to burn up in low Earth orbit.

Along with geomagnetic storms, which are caused by solar flares and high speed winds from coronal holes, other space weather effects are solar radiation storms and radio blackouts. Solar radiation storms are caused by major eruption events on the Sun, which launch protons at high velocities up to 10,000 km s^{-1} and can last for days at a time. Such radiation storms can cause health concerns in astronauts and people flying at high altitudes. Radio blackouts are caused by solar flares which expose the sunlit side of the Earth to high energy photons, which ionize part of the Earth's atmosphere and disrupts radio communications as the radio light is absorbed instead of refracted by the atmosphere.

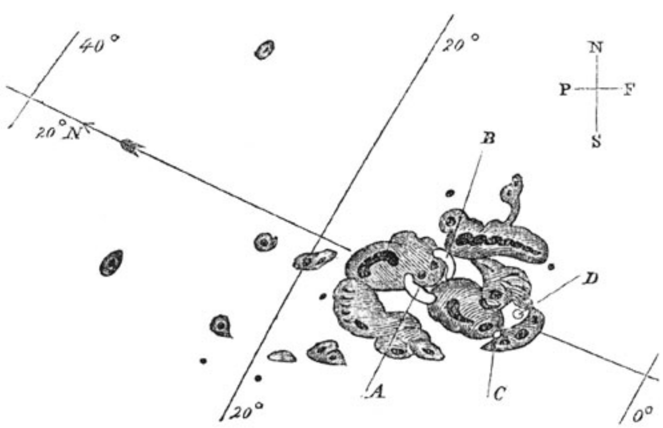


Figure 2.1: Carrington Event Sunspots

Space weather such as geomagnetic storms are different from weather on Earth. Rather than the water cycle and atmospheric pressure gradients, space weather is caused by solar activity and background radiation. The Sun goes through cycles of magnetic activity every 11 years where it's magnetic field flips, at a time when the total number of sunspots peaks. During this time, solar flares, coronal loops, the size and number of sunspots, and the amount of material and radiation that the Sun produces increases.

Solar activity can be measured in terms of the average sunspot number, which fluctuates over time, but tends to follow the solar cycle. The sunspot number is not the number of spots on the solar disc. It is a number devised in 1848 by Rudolph Wolf, who felt that the number of groups of sunspots were a better measure of solar activity than raw number. The *Wolf* or *Zurich* sunspot number, R, is defined as:

$$R = k(10g + f)$$

Where k is a fudge factor (approximately 1) related to the size of the telescope, g is the number of sunspot groups, and f is the total number of sunspots both in groups and as individuals. More modern measures of the Sun's activity exist, such as radio emissions, but R is most widely used due to the advantages of simplicity, ease of observation, and a long historical record.

In 1863 Richard Carrington, yes the same who the Carrington Event was named after, discovered that early in a solar cycle, spots tended to appear further away from the Sun's equator, at north and south latitudes near 35°. As the cycle went on, the majority of the spots appeared closer and closer to the Sun's equator, until they reached latitudes of 5 to 10 degrees by the end of the cycle. According to this measure, one can figure out in what stage of the sunspot cycle an image what taken.

Figure 2.2 shows a region of sunspots. Notice that each sunspot has a very dark center, known as the *umbra*, surrounded by a much lighter, fibrous fringe termed the *penumbra*. Spots appear dark for a simple reason: they are cooler than the rest of the solar surface. The general surface of the Sun has a temperature of 5778 K, while sunspots are 2000 degrees cooler. Since the Stefan-Boltzmann law of thermodynamics tells us that radiation from a hot body varies with the fourth power of the Kelvin temperature, the spots emit far less light than the surrounding photosphere.

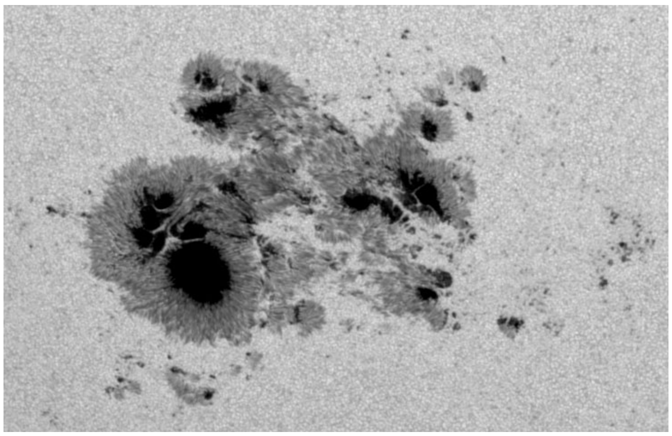


Figure 2.2: Sunspot region AR2192. Captured by NASA's Solar Dynamic Observatory on Oct. 23, 2014. Image credit: NASA/SDO

The mottled "rice grain" structure of the photosphere outside of the spots is due to small bubbles or cells of hot gas rising to the surface, somewhat like the surface of a pan of furiously bubbling water, named granules. In 1908, George Hale made the discovery that sunspots are accompanied by strong magnetic fields. Moreover, large spots occur in pairs. Almost invariably, one spot of the pair is a north magnetic pole, while the other is a south pole, much like the poles of a horseshoe magnet. It seems that the spots are cooler than the rest of the photosphere due to the magnetic fields inhibiting the flow of hot gases to the surface of the region.

Sunspots are the surface manifestation of much deeper-lying solar activity. Near a sunspot maximum, the Sun emits copious quantities of ultraviolet radiation, X-rays, radio waves, and streams of charged particles. It is the interactions of these charged particles with the Earth's magnetic field which generate magnetic storms that can burn out transmission lines, cause compasses to gyrate, and evoke magnificent displays of aurorae. The most violent events are associated with solar flares, great explosions near the Sun's surface. The Earth's magnetic field and atmosphere shield us from the most dangerous solar radiation, but astronauts and passengers in high flying aircraft are at risk. Long distance radio communications are affected by changes in the ionosphere, a high-altitude layer of the atmosphere that is crucial in such communications.

Because of the Sun's influence, there are numerous solar observatories scattered over the Earth. Up to date images of the Sun, together with data on sunspots and other phenomena, can be retrieved daily from the internet. Useful tools for recent updates on space weather are spaceweatherlive.com and spaceweather.com.

Laboratory Procedures

Part I - Atmosphere

You will be using the Coronado Personal Solar Telescope (PST) for observing the Sun. Each telescope is equipped with a special solar filter which is placed over the front of the instrument to reduce the entering light to a safe level. The PST is fit with a special Hα filter for solar observing. This Hα filter has a very narrow bandwidth of 1 Angstrom (Å). *Never attempt to look at the Sun with any instrument that is not equipped with an equivalent filter.* In particular, filters inserted at the eyepiece end of a telescope are dangerous because they may suddenly shatter with the heat. Also, do NOT use the small finder telescope that is mounted on the telescope; it is not safeguarded with a filter! Finally, do NOT look at the Sun with the naked eye or using any optical instruments such as binocular or lenses without a proper solar filter. Repeated experience has shown that failure to observe the foregoing precautions can cause permanent eye damage, do not be like Galileo. Your properly equipped telescope will allow you to view the Sun in comfort and safety through the telescope.

Equipped with a very low-power eyepiece, your telescope will take in the entire disk of the Sun, which is about half a degree in apparent diameter. Your view should be similar to the image in Figure 2.3, taken on February 2$^{\text{nd}}$, 2022. However, the Hydrogen alpha filter on the PST will allow you to have a far more interesting look at the Sun's chromosphere, which would look different from the intensity observations in Figure 2.3.

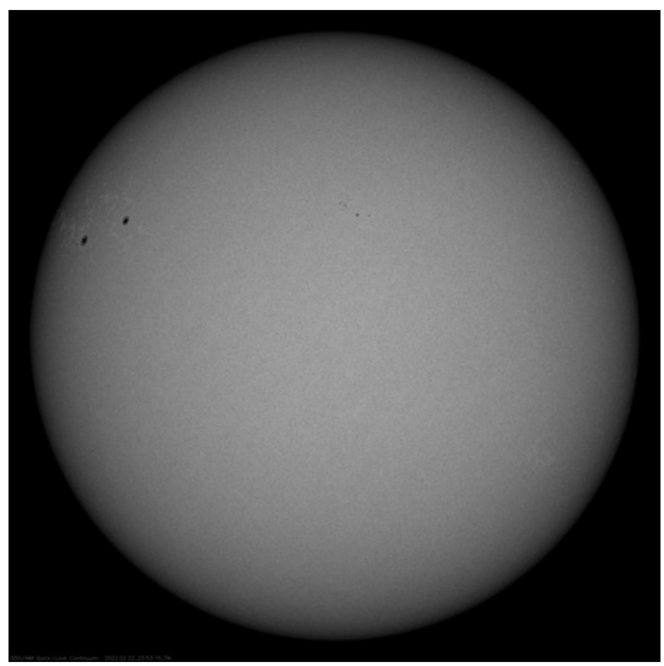


Figure 2.3: A visible light image of the Sun. Image credit: NASA/SDO and the AIA, EVE, and HMI science teams.

Focus the telescope sharply for your eye, preferably using one of the sunspots as a target. Now, using the circle provided on the data sheet, make a careful sketch of everything you can see on the Sun's disk IN PENCIL. Can you see the limb darkening that is conspicuous in the photo? If so, try to indicate it on your sketch. Do you see anything poking out from the Sun's surface, such as a solar prominence taking the shape of arcing loops or streaks of plasma above the Sun's surface? Make sure to include these in your sketch! Note what you are using to observe the Sun on the line provided under the circle, and write your observations on the lines provided.

You will notice increased trembling and blurring of the image, caused by daytime thermal currents in Earth's atmosphere. This highly variable phenomenon is what astronomers refer to as "seeing" and it is normally much worse during the day than it is at night. It is a fundamental limitation on the amount of detail you can see, and on the magnification that can be usefully employed.

In Case of Bad Weather

If the weather is too poor to observe the Sun, go to gong.nso.edu and then click **H-alpha**. Click on the clearest image of the Sun, or one of the images with a green check mark below. Avoid images that look blurry. Using one of the circles provided, use a pencil to sketch the Sun. Write your observations using the lines provided. Be sure to draw anything you might see protruding from the Sun's surface. Note what you are using to observe the Sun on the line provided under the circle.

Part II - Intensity

Once you have finished your sketch of the Sun through the PST, it is time to sketch the Sun again. If available, use the solar telescope fitted with a solar filter to observe the Sun. Follow the same steps as before to focus on the Sun, and make a sketch. Note any observations you have, including differences in texture, color, and prominent features. The Sun should look a bit different when you compare your observations in Hα and with the solar filter. The Hα filter in the PST only allows light from the Hα emission line to pass through, which lets you observe where hydrogen is excited in the Sun's atmosphere, higher than the photosphere.

In Case of Bad Weather

If the weather is too poor to observe the Sun, go to spaceweatherlive.com, click the drop-down menu that says **Solar activity**, choose SDO for the Solar Dynamics Observatory, and make a sketch of the image under **HMI Intensitygram**. Using one of the circles provided, use a pencil to sketch the Sun. Write your observations using the lines provided. Note what you are using to observe the Sun on the line provided under the circle.

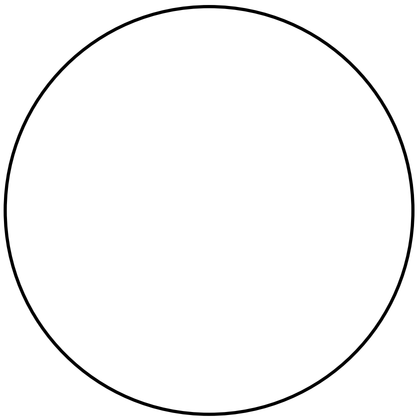
Part III - Corona

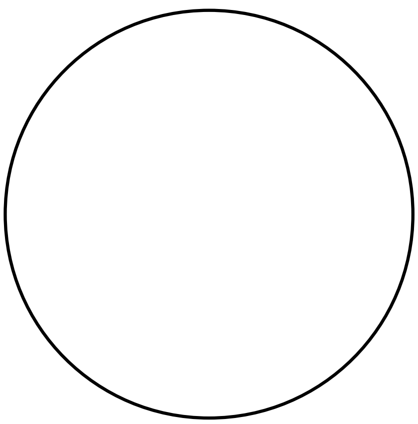
Once you have finished your sketch of the Sun through the telescope, head inside and use one of the computers to access spaceweatherlive.com. Go to the website, click the drop-down menu that says **Solar activity**, and choose SOHO for the Solar and Heliospheric Observatory. You will be greeted with two images of the Sun, but these are different from the images seen before. In order to see the much fainter atmosphere or *corona* of the Sun, we must immensely reduce the glare from its surface by using what we call a *coronagraph*, a mask conservatively larger than the Sun's surface in the middle of the telescope's field. This mask is labelled B on your data sheet. The little white circle in the center of where the Sun is blotted out represents the disk of the Sun on the sky. On your datasheet, this circle is labeled A. Measure its diameter gently with a ruler on the screen. Choose one of the two images, make a note of which on the line under the box provided. You may see several radial lines protruding from the Sun, or even the curved, lightbulb shape of a Coronal Mass Ejection. Make sketches of these features in the box. Measure how far the protrusions extend from the surface of the Sun radially. If the protrusions extend past the limit of the FOV, measure to the edge of what you can see and make a note on your observations. Write down your measurements and observations.

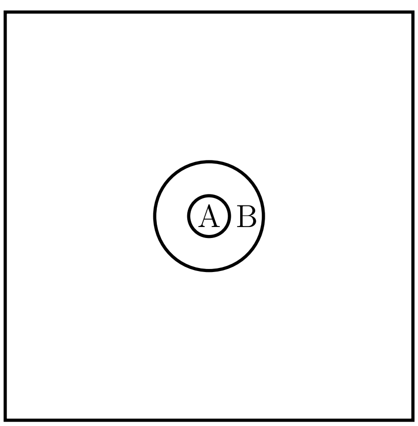
Space Weather Worksheet

Name: ______________________________ **Date:** ________________ **Section #:** ________

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.







Questions

1. What are today's weather conditions? (Sunny, partly cloudy, overcast, etc.)

2. Did you use the Personal Solar Telescope with the Hα filter, or did you view the Sun using the GONG Hα data?

3. Did you use the telescope fitted with a solar filter, or did you view the Sun using the SDO HMI Intensitygram?

4. What are the similarities and differences between the two of your sketches of the Sun (in the first two circles)?

5. What is the formula for the sunspot number, R?

6. Define each variable in the formula for the sunspot number. (R, k, g, f)

7. Rearrange the formula for the sunspot number to solve for the number of individual spots.

8. Go to spaceweather.com and find today's sunspot number on the left column. Write it down here.

9. Using either your observations of the Sun or the image of the Sun given on spaceweather.com, write down how many groups of sunspots there are. The website assigns a number to each sunspot region.

10. Taking the fudge factor to be approximately 1, solve for the total number of individual spots on the Sun today using the formula above.

11. Rewrite the measurements you took in Part III (third sketch) here. How large was the Sun (the white circle) on your screen? Where there any radial features, how long were they? Were there any coronal mass ejections? How far did they extend from the surface of the Sun?

12. If you observed a coronal mass ejection, find the ratio of its size compared to the diameter of the Sun (divide the size of the coronal mass ejection by the diameter of the Sun you measured).

13. The diameter of the Sun is 695,700 km. Using the ratio you calculated, what is the size of the coronal mass ejection?

14. The website spaceweather.com lists the current speed of the solar wind on the left column. Write the current solar wind speed here.

15. The Sun is around 1.496×10^{11} meters away from the Earth (1 AU). If a proton was ejected from the surface of the Sun at the current solar wind speed, how long would it have to travel radially out from the Sun to reach Earth's orbit? (Convert to days).

16. If a proton is directly facing the Earth at the moment it is released from the surface of the Sun, would it hit the Earth as the proton travels radially outwards? Why or why not?

17. Why does SOHO need to block out the Sun's light to learn more about the Sun?

18. Why is it important for us to monitor the Sun's activity?

Lab 3: Impact Craters

Purpose

This exercise is designed to familiarize you with a process whereby the surfaces of nearly every solid planet and satellite in the Solar System became pock-marked with myriad craters. The process even has implications for the demise of the dinosaurs! We also hope to give you a little more experience with the techniques of performing a science experiment and writing a report for the experiment. Please follow guidelines provided by your instructor to write the report.

Introduction

One of the most prominent features on the Moon are craters – cavities formed due to the impact of infalling debris from space. Some of these craters on the lunar surface are even visible with binoculars.

We believe most of the cratering occurred during an “era of heavy bombardment” about four billion years ago, when the Solar System was filled with fragments of material that had failed to condense into planets or satellites. Whizzing about in space, these fragments bombarded and marked the surfaces of the planets and their satellites including the Earth. One of those impacts on Earth about 66 million years ago was the likely cause of the sudden disappearance of the dinosaurs. Material flung aloft spread over the Earth and darkened the skies for years, creating a global cooling that made the dinosaurs’ habitat unlivable. This impact left behind an enormous crater called the Chicxulub crater in the Gulf of Mexico. This crater is measured to be 180 km in diameter while the Chicxulub impactor is estimated to be about 10 km in diameter.

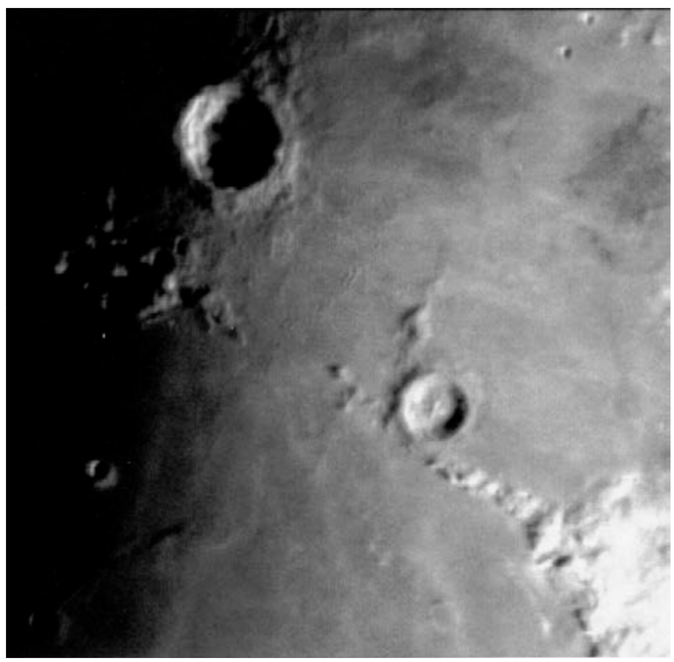


Figure 3.1: Lunar craters Copernicus (upper left) and Eratosthenes (lower right of center) imaged with the 12.5-inch reflector at the UF Campus Teaching Observatory. Image credit: F. Reyes.

There are only about 200 craters identified on Earth, while there are thousands of craters visible on the Moon (see Figure 3.1). However, if the Earth is bigger and more massive than the Moon, why do we not see as many craters on Earth as we see on the Moon? In fact, the Earth did have more impacts than the Moon, but why don’t we see those craters anymore?

Could an asteroid impact occur now and threaten our own environment? The answer, unfortunately, is yes. Hundreds of asteroids are in orbits that cross the orbit of the Earth. Another collision is probably inevitable, though the largest and most threatening are rare. Still, serious government-funded programs are detecting and tracking these "Earth-crossing asteroids." What to do if one is found to be on a collision course is unclear!

In this lab we will perform experiments to learn more about the process of crater formation! Experiments are an integral part of the scientific process since they enable us to test various theories of how an event occurred and consequently enable predicting the implications of that event if it occurs in the future.

We will ask the following questions: (1) Can we deduce the size of the impacting object if we know the size of the crater? (2) Can we deduce the velocity of the impacting object by studying the size of the crater? and (3) How accurate are our measurements? Finally, an interesting question, can we use the results of this experiment and compare with a real asteroid impact?

Laboratory Procedure

Equipment

For the first lab, we will provide you with a list of all the equipment being used in the lab. This would be something very good to note for a methods section of a report (hint, hint). In future labs, you will need to generate this list yourself.

- Tray of loose, dry sand: Your "target"
- Cardboard: Use it to carefully smooth the sand in the tray before each trial.
- A set of 8 metal-spheres: The "impactors" of different sizes (see Table 3.1).
- A meter stick with meter scale: You will use this to measure the height (in meters) from which the impactor is dropped on the sand.
- Ruler with centimeter-scale: Used to measure the size of the craters.

Sphere	**Diameter (mm)**
1	20.66
2	19.05
3	17.46
4	15.1
5	12.7
6	9.53
7	6.35
8	4.75

Table 3.1: Diameter of the metal spheres used in this lab

Effect Of Impactor Size

In this section we will devise an experiment to help us understand and quantify whether there is a relationship between the impactor size and the crater size.

- Use the cardboard to even the surface of the sand.
- In this first experiment, you will drop each of the spheres from a height of 1 meter. To obtain neat, symmetrical craters, try to drop the spheres so that they strike near the center of the tray; also try to drop without imparting spin or horizontal motion.
- Use a centimeter scale to measure the crater diameter to the nearest mm from the peak of one wall to the peak of the opposite wall. You will find it easier to determine the locations of the peaks if the tray is illuminated very obliquely by a portable lamp so that the shadows are pronounced.
- Repeat steps 1 to 3 for all the spheres recording the measurements of the crater in Data Table 3.1 with the corresponding sphere diameter.
- Once you've dropped all the spheres, plot your data in Graph 3.1

Effect Of Velocity

In this part of the experiment, we ask: how does the velocity of the impactor affect the size of the crater? We don't have a neat device to measure the velocity of the impactor as it hits the sand. However, assuming all the potential energy is converted to the kinetic energy, the velocity, v, of the impactor can be obtained using the equation below provided we know the height (h) from which the impactor was released and the value of g (i.e., acceleration due to gravity) which is constant at 980 cm s^{-2}. Thus, the easiest way to vary the velocity in a controlled manner is by varying the initial height of the impactor.

$$v = \sqrt{2gh}$$

Where v = velocity of the object, h = height of the drop and g = acceleration due to Earth's gravity equal to 980 cm s^{-2}

- Select one of the medium-sized spheres.
- Start at a height of 1 m and decrease the drop height 10 cm at a time, recording the height and crater size for each trial in Data Table 3.2
- Plot your data in Graph 3.2

Error of Measurement

In this part of the experiment, we are interested in learning more on errors of measurement. We will repeat a single observation N times and record the resulting diameter of the craters. After we've taken all of the measurements, we'll take the average crater size, given by:

$$D_{\text{avg}} = \frac{\sum_i^N D_i}{n} = \frac{D_1 + D_2 + D_3 + ... + D_N}{N}$$

With the average in hand, we can see how far each of our individual measurements deviates from this mean value. This is known, appropriately, as the deviation. We can get the deviation of each measurement and can be calculated in the following way (note which term comes first):

$$\Delta_i = D_i - D_{\text{avg}}$$

The deviation tells us about how far our individual measurements are from the mean, but given a sufficiently long data set, trying to interpret what this means can be quite cumbersome. In order to avoid this, we look at a summary statistic of the whole data set called the **standard deviation**. The standard deviation helps us cleanly represent all of our deviations in one number. The formula for the (sample) standard deviation of a data set is as follows:

$$\sigma = \sqrt{\frac{\sum_i^N \Delta_i^2}{(N-1)}} = \sqrt{\frac{\Delta_1^2 + \Delta_2^2 + ... + \Delta_N^2}{(N-1)}}$$

The standard deviation is a valuable, much-used measure of the scatter or dispersion of observational data. For example, the mean for human IQ's is 100 and the sigma is about 15. (Note: Many inexpensive hand-held calculators automatically compute means and standard deviations since they are so widely used in statistics.)

- Select one of the medium-sized spheres and drop it repeatedly from a height of 1 m, measuring the crater diameter each time. Do this at least 8 times, tabulating the results of each drop in Data Table 3.3, which will be included in your report.

Impact Craters Worksheet

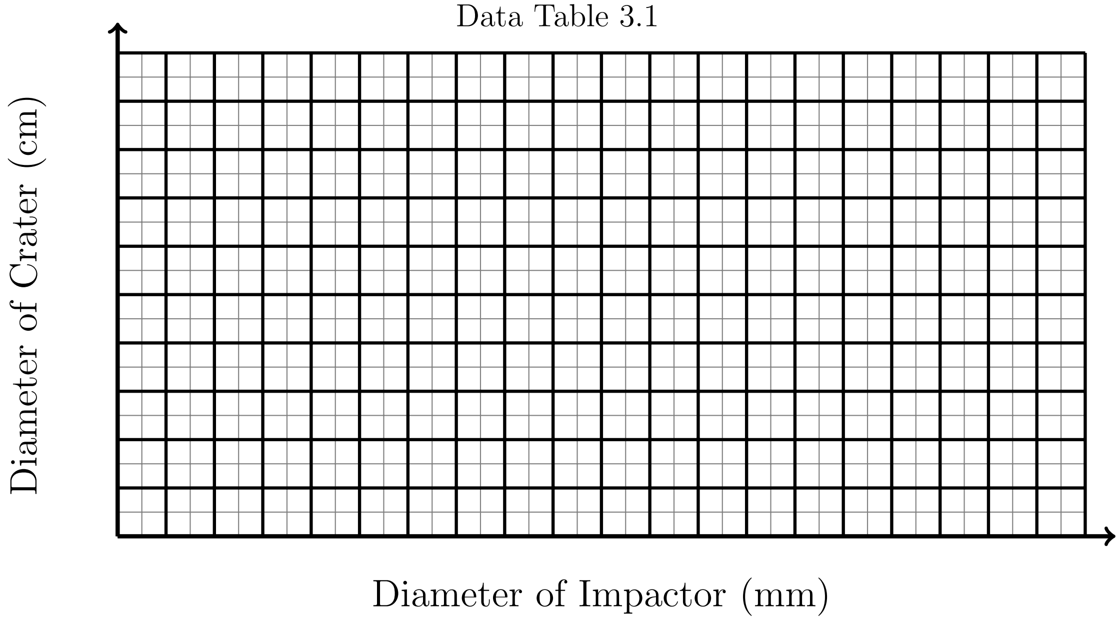
Name: ______________________________ **Date:** ________________ **Section #:** ________

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

Effect of Impactor Size

Diameter of Crater (cm)	**Diameter of Sphere (mm)**	**Ratio of Crater Size to Diameter**
		Average Ratio:

Data Table 3.1



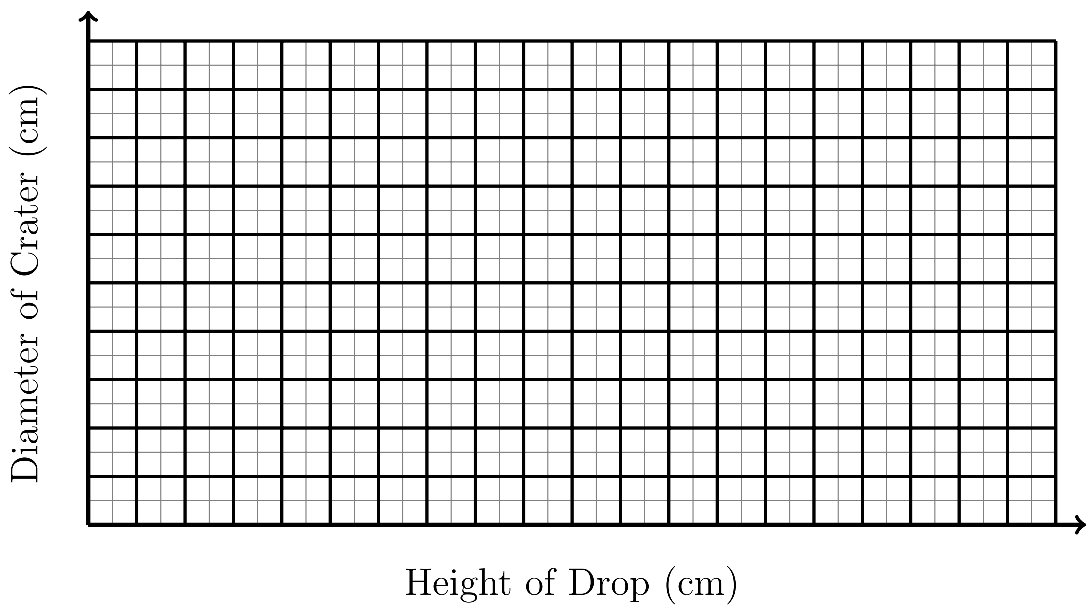
Graph 3.1

Effect Of Velocity

Sphere Diameter: ________ mm

Drop Height (cm)	**Diameter of the Crater (cm)**

Data Table 3.2



Graph 3.2

Error Of Measurement

Sphere Diameter: ________ mm

Measurement Number	**Diameter of Crater (cm)**	Δ	Δ^2
	Average:		**Sum**:

Data Table 3.3

Calculated standard deviation: __________ mm

(No plot associated with Error of Measurement)

A Study of Impact Craters

Guidelines for Writing the Report

In this report you will summarize the results from "Impact Craters," where you learned about and will focus on the following concepts:

- The relationship between crater size and impactor size and the relationship between crater size and drop height
- The meaning of a standard deviation, and how to calculate it
- How to identify sources of valid error in an experiment

You must submit your own work. You can collaborate and exchange ideas with your lab partners, but do NOT copy and paste, your work must be entirely your own. Your submissions will be checked by Turnitin.

Your report should contain all of the following sections, in this order, with **headers**

1.	Abstract	(5 points)
2.	Introduction	(10 points)
3.	Explanations of Physical Principles and Equations	(15 points)
4.	Methods and Purpose	(20 points)
5.	Data	(10 points)
6.	Discussion	(25 points)
7.	Conclusions	(10 points)
8.	Original Data Sheets attached	(5 points)
Total		100 points

Please read through this lab guide carefully. If you're unsure of the requirements of this report, please ask your instructor for clarification as soon as possible.

How to Address Each Section:

Abstract (5 points)

An abstract is just a brief overview/summary of the work. Abstracts are particularly important to scientific writing and thus we'll get some practice writing them in this course. This section should be a very brief overview of the what we're doing and what we achieved. In general, this section should be $\sim$150 words, but I won't hold you to exactly that number. Be succinct and get your point across.

Introduction (10 points)

Briefly tie your experiment and its motivations to the "big picture" of astronomical research. What key concepts can you introduce the reader to for them to understand the work you will present? Is there any history or examples you can point out to get your point across?

Explanations of Physical Principles and Equations (20 points)

Type out the equations, define the variables in the equations, and explain what the equation means in the context of the lab.

- Kinetic Energy
- Impact Velocity
- Standard deviation
- What is a normal distribution? Note: You do not need to write down as an equation, just explain the concept of a normal distribution and how it relates to your experiments.

Methods and Purpose (20 points)

Describe what you and your group did in the experiments in this lab. This should not be a paraphrase of the lab manual procedures, but instead details on how and why you conducted each experiment. What were the experiments teaching you about astrophysics and statistics?

- What supplies/tools did you use for this lab? Describe any characteristics of objects used.
- What activities did you do for each experiment? Include numbers of trials and specifics about the actions you took.

Data (10 points)

Include the data collected during the experiment here. Tables and graphs should be made in a computer program (Microsoft Excel and equivalent). Make sure to include axis labels and that you are using the appropriate plot type (scatter) for the given data. Include:

1. All three tables
2. Plot of crater diameter (y-axis) vs. impactor diameter (x-axis)
3. Plot of crater diameter (y-axis) vs. drop height (x-axis)

Discussion (25 points)

Error Analysis (10 points):

- Discuss the errors of your results from the second experiment in terms of the standard deviation calculated from your data. What determines if your results are relatively precise or not?
- Describe any sources of error in your experiments. The table below gives a detailed look at what sources of error to consider and what sources of error are invalid.

Questions (15 points total):

1. (5 points) Looking at the plot for crater size vs. drop height, what is the relationship between the two parameters - linear or nonlinear? How does the given equation relating impact velocity and drop height explain the trend you see?
2. (5 points) Why should performing more trials in an experiment reduce the standard deviation of those measurements?
3. (5 points) The Earth should have had more impacts than the Moon because it is bigger and more massive. However, we observe far fewer impact craters on the Earth. This implies some processes on Earth must have removed past craters, similar to you smoothing the sand with the cardboard. Identify and explain at least 2 possible real physical processes acting to remove craters from the surface of the Earth.

Do	Do Not
• Think about the tools used in the experiment and any **reading errors** introduced by the accuracy of those tools (limitations on your ability to settle on a specific value when reading your measuring instrument) and how those will influence the final values. • Consider the effects of individual perception and how you used the available tools. • Consider the assumptions made in the experiment (are there measurements made that may not precisely characterize the object involved?)	• Include human error as a source of error. If you can improve upon your results through better use of the tools, etc. that is not a valid error source. • Speculate on possible scenarios or 'what ifs' (i.e. suggesting equipment is faulty) • Consider the uncertainty of the results in the context of real-world circumstances (of course these experiments do not accurately represent real astronomical impacts - we are interested in how your results compare with laboratory expectations)

Conclusions (10 points)

Briefly summarize your results. Also discuss some ways in which your experiment was, and was not, a realistic representation of what happens in nature. (Consider that cosmic projectiles enter Earth's atmosphere going *at least* Mach 33, so they bring *far* more energy into the equation!)

Attach Data Sheets at the End (5 points)

Attach the measurement you made from the lab manual. This can either be in a separate pdf file or at the end of this pdf.

Lab 4: Light Is A Wave

Purpose

If the some of these figures remind you of ripples spreading out from a stone thrown into a pond, the analogy is a good one. The purpose of the experiment is to convince you that light not only behaves like a wave, but that this behavior has a major effect on astronomers, microscopists, photographers, spectroscopists, and others who use light in their work. The phenomena you will see are studied by every student of physics or astronomy, but very few of them have ever actually seen these phenomena with their own eyes.

Introduction

Figures 4.1, 4.3, and 4.5 are diffraction patterns created by a laser beam shining through various filters onto a distant screen. You will study such patterns in this laboratory. We can think of diffraction most simply as the bending of light around an obstacle. Light can do this only because there is a wave side to its nature. Other waves, such as sound and water waves, also show diffraction.

The bending of light, for example into a shadow, was first reported by the Italian scientist Francesco Grimaldi around 1665. Encouraged by such observations, in 1690 Christiaan Huygens published a treatise describing light as a wave in an invisible, universal medium called the ether. However, the great Isaac Newton was unable to conceive of his beloved planets having to plow their way through such a medium. Ergo, no medium, no wave; so in 1704 Newton espoused a competing concept of light as a stream of particles or corpuscles.

The wave vs. corpuscular debate continued for generations. Experiments during the 18^{th} and 19^{th} Centuries, such as the diffraction and interference demonstrations of Young, seemed to lend more and more support to the wave theory. Unfortunately, research near the beginning of the present century pointed in the opposite direction! Planck's radiation theory, the photoelectric effect, the Bohr atom, all suggested Newton's streams of corpuscles, now called quanta or photons. To make a long story short, modern physicists have learned to live with the so-called dual theory of light. In experiments where light behaves like a wave, it is treated as a wave. In other experiments, where it acts like a particle, it is treated as a particle. In the present experiment, we shall be concerned entirely with the wave nature of light.

Laboratory Procedure

WARNING: The laboratory is based on the use of lasers, which are powerful sources of focused beams of monochromatic (single wavelength) light. Although the lasers we use are very low power, only 3 milliwatts, you should nevertheless treat them with respect. Do NOT allow the laser beam to enter your eye, as damage to your retina could occur. Your sight is too valuable to place at risk!

Diffraction by a Circular Aperture

We will begin with the classical case of diffraction by a circular aperture. This is the case that has long concerned astronomers, microscopists, photographers, and others who use light for technical or scientific purposes. The fundamental problem is the effect of such an aperture on the image of a point source, such as a star. While this may seem to be a very limited case, it must be remembered that any image is simply the sum of its myriad points!

The lens of a telescope or microscope is certainly not a pinhole, but such lenses are nevertheless circular apertures, and they produce diffraction just as a pinhole does. It is this diffraction of light, due to the wave nature of light, that limits the ability of telescopes and microscopes to see fine detail. Even photographers must exercise caution; if a camera (or enlarger) lens is "stopped down" to too small an aperture, the image will blur due to diffraction.

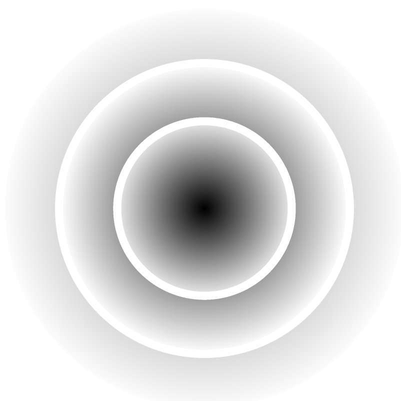


Figure 4.1: Airy Disk pattern (colors are inverted for clarity)

In the laboratory, you should see an image of the diffraction pattern of the pinhole similar to Figure 4.1. Notice that the image consists of a central disk surrounded by a series of circular diffraction fringes. While it is not evident in the figure, the central disk will contain about 85% of the total energy of the image in a good optical system; i.e., it is far brighter than the surrounding fringes, as you will see during the experiment. The central disk is often referred to as the Airy disk in honor of the British Astronomer Royal, Sir George Airy, who called attention to its importance in star images.

Since most of the light is concentrated in the Airy disk, it is the size of this disk that determines the resolving power or ability to see detail in an image; the smaller the Airy disk, the finer the detail that can be seen. Optical theory predicts that the angular diameter θ of the Airy disk (as seen from the lens or the pinhole) will be

$$\theta = \frac{2.44\lambda}{D}$$

where λ is the wavelength of the light and D is the diameter of the lens or pinhole. Notice that the Airy disk shrinks as the lens (or pinhole) becomes larger (for a fixed wavelength). This means that, at the same wavelength, a larger (diameter mirror/lens) telescope produces smaller star images than a smaller telescope (down to an atmospheric limit unless in space)!

For example, the James Webb Space Telescope (6.5 meters) produces about three times crisper images than than the Hubble Space Telescope (2.4 meters) at the same wavelength. However, critically note that, because James Webb is designed to image further into the infrared (longer wavelengths) than Hubble, Hubble produces more detailed images when the difference in wavelength is different by more than about a factor of three. Also, this means that radio observations

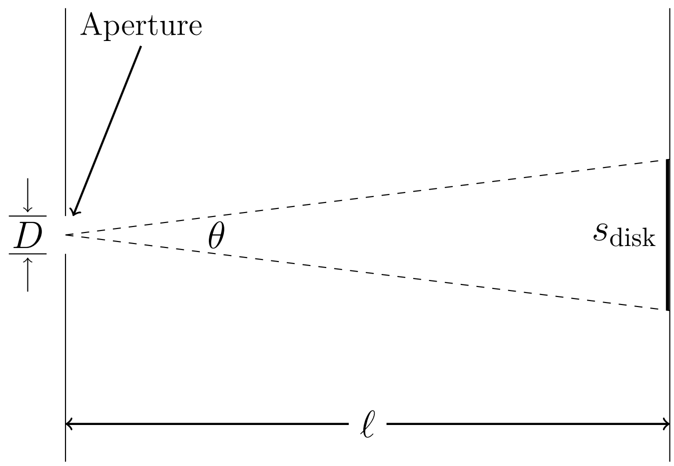


Figure 4.2: Circular aperture: incident light coming through the hole

(very long wavelengths) typically struggle to produce very crisp images unless they use special techniques beyond the scope of this course to describe (e.g., interferometry).

If we want to know the linear size of the Airy disk, we can calculate it with the help of Figure 4.2. Let s_{disk} be the diameter of the disk, defined as the diameter of the first dark circle, while ℓ is the distance from the lens or pinhole to the image. Then, since θ is in radians,

$$\theta = \frac{s_{\text{disk}}}{\ell} \implies s_{\text{disk}} = \frac{2.44\lambda\ell}{D}$$

Let's now undertake a laboratory test of these relations. Set up your laser on a bench exactly 1.5 meters from your screen. Clamp a clean sheet of paper on the screen. You are provided with 3 pinholes in a slide mount that fits in a special stand.

Place the pinholes an inch or two in front of the laser. The largest pinhole is big enough to accommodate the entire laser beam. Line up your apparatus so the laser beam passing through this hole falls near the center of the screen. Note the size of the beam. Now slide the second pinhole into the laser beam. Use the adjusting screws to center the beam on the hole. This adjustment is critical; look at the pinhole obliquely from the front and adjust the beam until the hole is most brightly illuminated (do NOT place your eye directly in front of the hole!). With the lights dimmed, you should see on the screen the Airy disk and 4 or 5 circular fringes. If the disk and the fringes are not circular, the illumination of the pinhole needs to be readjusted. Carefully mark on the screen the diameter of the first dark circle (i. e., the diameter of the Airy disk). Make notes of what you see. (Note: Experienced researchers will tell you that it is virtually impossible to make too many notes! Almost always, when an experiment is over, the researcher wishes that he/she had taken better notes.) With the lights back on, measure your marks with a millimeter scale to record the diameter of the Airy disk. Now repeat the entire procedure for the third and smallest pinhole. For future calculations, record the wavelength of your laser as 675 nm or 6.75 $\times 10^{-5}$ cm.

Diffraction by a Single Slit

Slits are widely used in optics, especially in spectroscopy (you will encounter examples in two other labs in this course). Figure 4.3 shows the diffraction pattern of a rectangular, narrow, vertical slit like the one you will see. Instead of producing repeating, fuzzy fringe images of the circular pinhole, we produce repeating, fuzzy fringe images of the slit. Since we are treating similar phenomena, the equation giving the locations of the fringes is naturally similar to that of the pinhole. Optical theory tells us that the distance from the center to the fringes, s_{slit}, is

$$s_{\text{slit}} = \frac{n\ell\lambda}{2D} \qquad \text{for integers } n > 1$$

where D is the width of the slit. As shown in Figure 4.3, if n is odd ($n = 3, 5, 7...$), then s_{slit} is the distance to the bright fringes ($n = 1$ corresponds to the central fringe). If n is even ($n = 2, 4, 6...$), then s_{slit} represents the distance to the dark fringes.

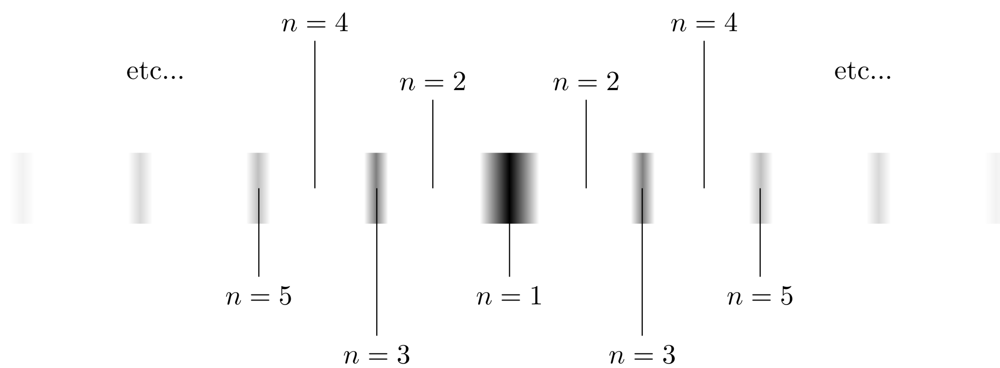


Figure 4.3: Single slit diffraction pattern, odd n refer to bright fringes and even n refer to dark fringes (colors are inverted for clarity)

You are provided with a second slide mount containing three slits. Replace your pinholes with this mount. The widest slit will accommodate the entire laser beam. Line up your apparatus so this beam falls near the center of the screen, and note its appearance. Now slide the second, medium-width slit into the beam and adjust it until the fringe pattern on the screen is brightest. What do you see now? Carefully mark on the screen the middle of the bright central fringe and the centers of several light and dark fringes on either side. With the lights on, use the millimeter scale to tabulate the distances of these fringes from the middle of the central fringe. Now repeat the process for the third and narrowest slit. How does its fringe pattern differ from that of the 2$^{\text{nd}}$ slit?

Diffraction by Two Pinholes

Probably the most convincing proof of the wave nature of light came in 1801 with Thomas Young's demonstration of the interference of two beams of light. If the beams merge "in phase" with the crests of the waves in one beam coinciding with the crests of the other beam, then the beams reinforce each other and a bright fringe results. On the other hand, if the beams merge with the

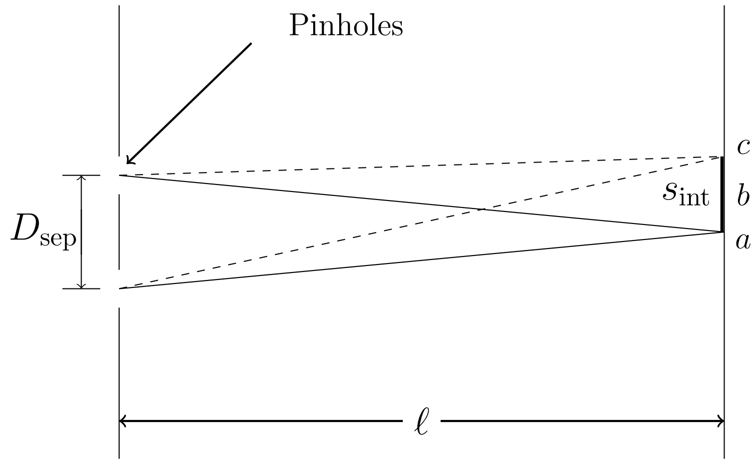


Figure 4.4: Two pinholes: incident light coming through the two pinholes

crests of one falling on the troughs of the other, then the beams cancel each other and a dark fringe is produced. This behavior is naturally explained with the wave and not the corpuscular theory theory of light. While interference plays a role in producing the diffraction patterns of single holes or single slits, the most clear-cut demonstrations involve a pair of holes or slits. We shall perform such an experiment here, using pinholes.

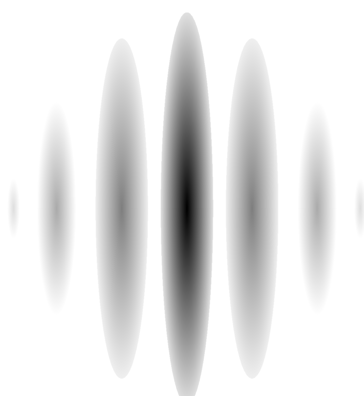


Figure 4.5: Diffraction pattern for two pinholes (colors are inverted for clarity)

Figure 4.4 shows the setup of this experiment. At the left is a pair of pinholes in an opaque surface. D_{sep} is now the spacing between the holes (instead of their widths, as before), which are illuminated from the left. The screen is at a distance, ℓ, to the right.

The solid rays meeting at a at the center of the screen have traveled the same distance, so they merge in phase, crest to crest, and a bright fringe is produced. As we go up the screen, the lower ray has to travel farther, so the rays get out of phase. At some point such as b they meet crest to trough and cancel, leaving a dark fringe. Still further up the screen at c the paths differ by exactly one wavelength, so the rays again merge crest to crest and create a bright fringe. This pattern is repeated as we continue farther up the screen, and it is of course symmetric, so the same alternation of fringes occurs below the center of the screen. Figure 4.5 shows the resulting image of the diffraction pattern produced by the a pair of pinholes.

Optical theory shows that the spacing between two adjacent bright fringes or between two adjacent dark fringes, s_{int}, is given by the relationship

$$s_{\text{int}} = \frac{\ell\lambda}{D_{\text{sep}}}$$

Light Is A Wave Worksheet

Name: ______________________________ **Date:** ________________ **Section #:** ________

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

Important constant: Wavelength of laser (λ) – 675 nm (6.75×10^{-5} cm)

Diffraction By Circular Aperture

For the measurements use only the middle and small openings. The large opening is only for adjusting the image.

1. **Sketch** and describe the diffraction patterns you saw on the screen for the two openings.

Middle Opening Small Opening

2. What is the brightest part of the image?

3. How many circular fringes were you able to see?

4. Record your measurements of s_{disk} and ℓ (with the correct units) for the middle and smaller pinholes.

s_{small}: ____________ s_{middle}: ____________

ℓ_{small}: ____________ ℓ_{middle}: ____________

5. Rearrange the following equation to solve for D symbolically

$$s_{\text{disk}} = 2.44\frac{\lambda\ell}{D}$$

6. Use your results of s_{disk} and ℓ to determine D for the middle and small openings. Show your work (and remember sig figs!)

$D_{\text{small}} =$ $D_{\text{middle}} =$

7. From your results, what did you learn regarding the size of the aperture and the corresponding size of the airy disks? How that will have an effect in the resolution of a telescope?

Diffraction by a Single Slit

Again, for the measurements use only the middle and small slits.

8. **Sketch** and describe the diffraction patterns you saw on the screen. How many fringes were you able to see?

Middle Slit | Small Slit

9. Record your measurements of ℓ and s_{slit} (with the correct units) for the middle and small slits. Also note which value of n you used to count fringes. Remember that odd values of n ($n = 3, 5, 7...$) corresponding to bright fringes and even values n ($n = 2, 4, 6...$) correspond to dark fringes!

s_{small}: ____________ s_{middle}: ____________

ℓ_{small}: ____________ ℓ_{middle}: ____________

n_{small}: ____________ n_{middle}: ____________

10. Rearrange the following equation to solve for D symbolically

$$s_{\text{slit}} = \frac{n\lambda\ell}{2D}$$

11. Use your results of s_{slit} and ℓ to determine D for the middle and small slits. Show your work (and remember sig figs!)

$D_{\text{small}} =$ $D_{\text{middle}} =$

12. Was the overall spread in the diffraction pattern parallel or perpendicular to the slits? What happens when you rotated the slit by 90°?

Diffraction by Two Pinholes

13. **Sketch** and describe the diffraction pattern you saw on the screen.

14. Record your measurements of s_{int} and ℓ (with the correct units) here.

$s_{\text{int}} =$ $\ell =$

15. Rearrange the following equation to solve for D_{sep} symbolically

$$s_{\text{int}} = \frac{\lambda \ell}{D_{\text{sep}}}$$

16. Use your results of s_{int} and ℓ to determine D_{sep} for the double pinhole. Show your work (and remember sig figs!)

17. Was the overall spread in the diffraction pattern parallel or perpendicular to the relative positions of the pinholes? What happens if you rotate the pinholes by 90°?

Diffraction Grating

18. In the spectra you saw on the grating, which color was diffracted through the largest angle (i.e. which was the furthest from the center)?

19. Which color was diffracted the least?

20. Is this in agreement with the following equation? Explain your reasoning. (Hint: is there anything is this equation affected by the change in color?)

$$s_{\text{slit}} = \frac{n\lambda\ell}{2D}$$

General Questions

21. What famous experiment demonstrates the wave nature of light? What famous experiment (or effect) demonstrates the particle nature of light?

22. **Error Analysis:** List at least 3 specific sources of error that affect your results and identify whether they are random or systematic. Mistakes are not considered errors, as they can be corrected.

23. Why are the results of this lab important to the design of telescopes?

Lab 5: The Astronomical Telescope I

Purpose

The purpose of this experiment is to acquaint you with some of the properties of the astronomer's most important tool - the telescope. Probably few of the general public understand why astronomers have, for centuries, fought for ever larger telescopes. We hope that you will derive from this laboratory some understanding of one of the important advantages of a larger instrument.

Introduction

The telescope was invented accidentally by the Dutch spectacle-maker Hans Lippershey in 1608. In less than a year, the great Italian scientist Galileo had heard of the discovery and was making his own telescopes to study the Sun, Moon, planets, and stars. In the nearly 400 years that have ensued, the history of astronomy has been one of developing ever larger and larger telescopes. Galileo's little instruments could scarcely rival a modern pair of binoculars. Today we have glass giants with optical elements 8 meters (26 feet) in diameter! Why have astronomers always yearned for bigger telescopes? This laboratory is designed to shed some light (pun intended) on that question.

The astronomical telescope is a rather simple optical device. As Figure 5.1 shows, it consists of a large lens in the front of the telescope; since this lens is nearest the object being looked at, it is called the objective lens, or simply the objective.

The objective's function is to create a bright, sharp image of the object. Notice that the image is inverted or upside down. A second, much smaller lens, called an eyepiece, is used simply as a magnifier to enlarge the image so you can examine it more closely. If F is the focal length of the objective, or distance from the lens to the image (when the object is at a large distance), while f is the focal length of the eyepiece, or distance of the eyepiece from the image, then the magnification M of the telescope is given by the simple formula $M = F/f$. That is, to have a large magnification, we need an objective of long focal length and an eyepiece of very short focal length. For technical reasons, good eyepieces consist of at least two lenses. The familiar pair of binoculars

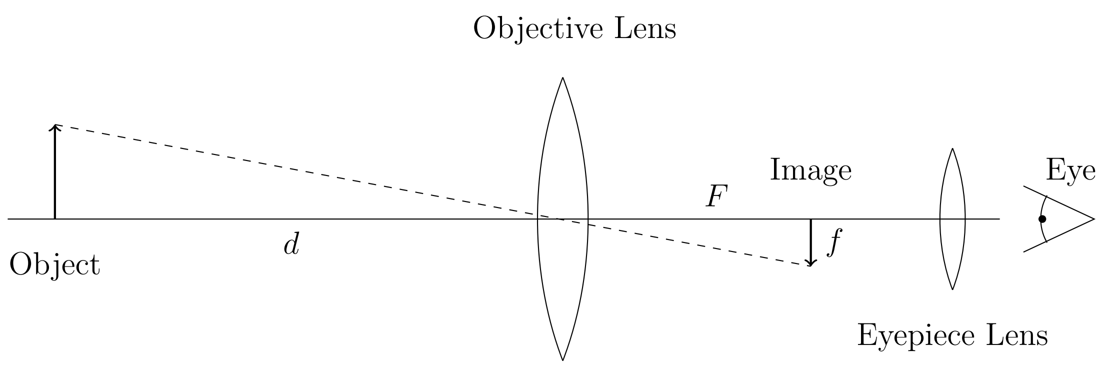


Figure 5.1: An example of what happens as you look through an eyepiece

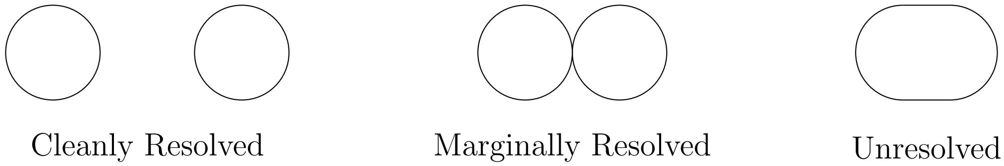


Figure 5.2: The three different types of resolution for two distinct objects

is actually two telescopes placed side by side. Internal prisms are used to fold the optical path and erect the image so that the binoculars are compact and easy to carry and hold. In large, modern astronomical telescopes, the objective lens is often replaced by a concave mirror, which is much lighter and cheaper, but which serves the same purpose of creating an image to be examined by the eyepiece.

An astronomer's telescope serves two functions. One is to gather more light. Even the lens of a large binocular has 50 times the area of the pupil of your eye; thus the binocular collects 50 times as much light as your unaided eye. The second function of the telescope is to show fine detail in an object. Astronomers refer to this as resolving power, which increases with the size of the optics due to the wave nature of light.

All stars (except the Sun!) are so far away that they appear as points of light in the sky. However, because of the wave properties of light, the image of a star in a telescope is not a point, but a disk. Curiously, as the lens of the telescope grows larger in diameter, the disk grows smaller. As shown in Figure 5.2, if we have two stars that are very close together in the sky, a so-called "double star," the disks may overlap in a small telescope and we say that the stars are "not resolved". Using larger telescopes enables us to see these disks as separate images, and we say that the double star is "resolved."

Near the middle of the 19$^{\text{th}}$ Century a keen-eyed British observer, the Reverend W. R. Dawes, proposed a rule of thumb that has been widely used. Known as Dawes' Limit, it states that the resolving power of a telescope is given by

$$\text{Resolving Power} = 4.56 \text{ arcseconds} / \text{aperture in inches}$$

Thus, according to Dawes, a telescope of 4.56 inches diameter should resolve a double star whose components are 1 arcsec apart. The validity of Dawes' Limit has subsequently been confirmed by theoretical calculations based on the wave nature of light.

This is also pertinent for imaging the details of an extended object such as a galaxy or a planet, such as Mars. Near the end of the last century a wealthy Bostonian, Percival Lowell, set up an observatory in Arizona to study the "canals of Mars," a phenomenon discovered by the Italian G. V. Schiaparelli in 1887.

As illustrated in Figure 5.3, reproduced from Lowell's book, *Mars and Its Canals*, Lowell (who was not a great artist) drew networks of canals covering the face of Mars. His hypothesis, detailed in half-a-dozen semi-popular books, was that the canals were constructed by Martians desperate to irrigate the mostly desert surface of the planet for agricultural purposes. According to Lowell,

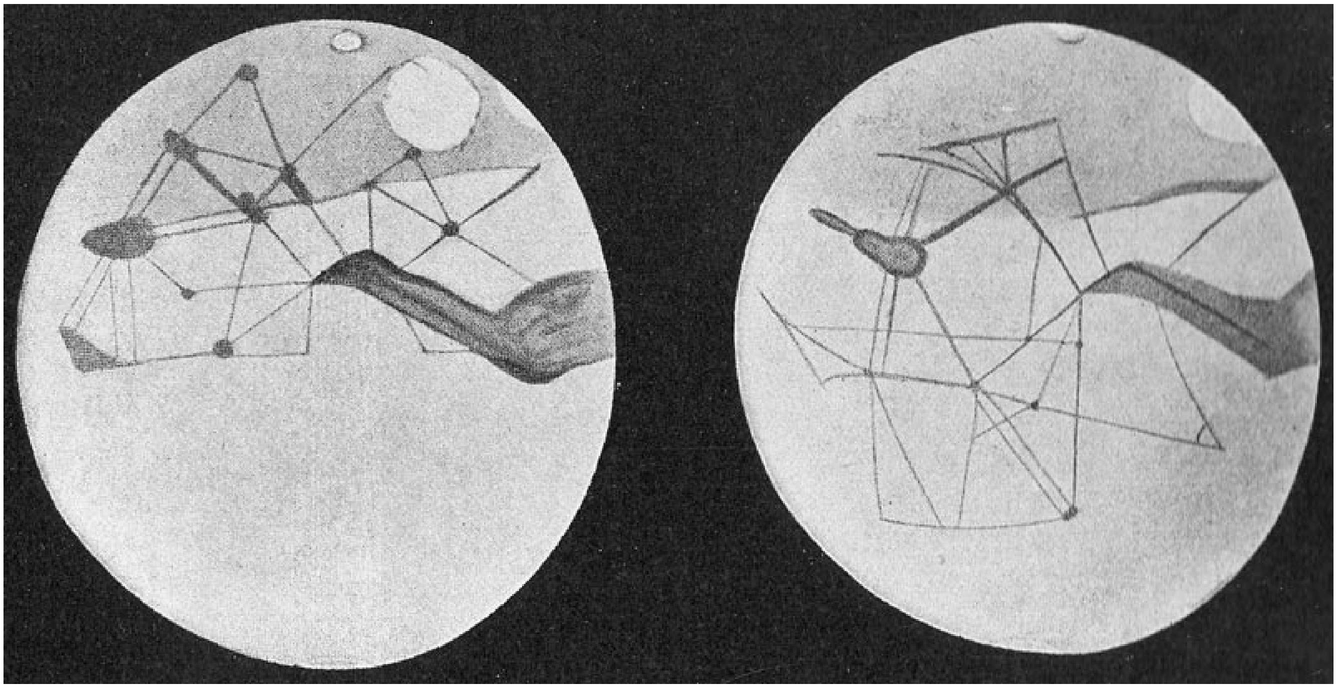


Figure 5.3: Sketch of Martian Canals from *Mars and Its Canals* by Percival Lowell (Macmillan & Co. 1907)

in certain Martian seasons many of the canals “geminate,” by which he meant that a previously single canal became double.

He was so obsessed with the Martian canals idea that, as a popular story goes, he ignored the astute point made by one of his assistants: many of his double canals were so close together that they could not possibly have been resolved by the 25-inch telescope he was using. Since then, copious observations have debunked such claims of canals on Mars.

Laboratory Procedure

You are provided with a small telescope mounted on a stand. The aperture (i.e., the diameter of the objective) can be varied by means of an iris diaphragm like that used in cameras. You also have an illuminated target that presents closely spaced parallel lines (the “canals of Mars”) and a simulated “double star.” Place the target about 3.5 meters from the telescope and measure accurately the distance ℓ from the target to the objective of the telescope.

Now turn the target light on and dim the room lights. Open up the iris diaphragm to its maximum aperture. Look in the telescope and focus it on the target as accurately as you can (good focus is important!). Next, slowly close the iris, concentrating your attention on the “canals.” As the aperture decreases, you will see the lines becoming broader, and at some point the space between them will vanish and the canals will no longer be ”resolved” as separate lines. Note the setting of the iris when this happens. As in many scientific experiments, there will be some subjectivity in deciding exactly when the lines are no longer resolved; this is one reason experimenters often take averages of several trials. Now repeat the experiment, concentrating on the “double star.”

Each laboratory partner should make his/her own measurements. The aperture measured in these experiments is the D you will use in your calculations.

The Experiments

1. A major objective is to compare your results with Dawes' Limit. You will need to calculate the angular separations of the details in the target as seen by your telescope. A simple way to do this is to use the relation

$$\theta = 2.063 \times 10^5 \left(\frac{h}{\ell}\right) \text{ [arcsec]}$$

   where h is the separation of the detail in the target and ℓ is the distance to the target. Note that h and ℓ must be expressed in the same units since they are a ratio.

   Now we must calculate the telescope aperture that would be required by Dawes to resolve these targets. Since the Reverend was very British, he used inches to measure aperture, but we are working in the metric system, so we convert his formula to Resolving Power $= 114/D$, where D is the telescope aperture in mm. We can think of this resolving power as the minimum angle, θ, that we can see with our telescope. For present purposes, we rearrange this to

$$D = \frac{114}{\theta} \text{ [mm]}$$

   giving us the aperture required by Dawes to resolve the targets in our experiment.

2. Do you have any feeling for how big an arcsec really is? Most of us don't. Maybe this will help. Obtain a penny and measure its diameter, which we'll call h. Now let $\theta = 1$ arcsec in the first formula above and calculate l, the distance at which the penny would subtend an angle of 1 arcsec. Convert your answer to kilometers. Does this help you appreciate how small an angle an arcsec really is? To give you a few landmarks, the resolving power of your unaided eye is about 1 arcmin or 60 arcsec; the diameter of the full Moon is 30 arcmin or 1800 arcsec; when Mars is closest, its diameter is 26 arcsec.

The Astronomical Telescope I Worksheet

Name: ____________________________ **Date:** ________________ **Section #:** ________

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

Dawes' Limit for the Resolving Power of a Telescope

One of the objectives of this experiment is to use an empirical formula developed by Dawes to calculate a value for the predicted aperture D of a telescope necessary to resolve (separate) two close objects and compare that value with your own experimental value.

In order to calculate Dawes' Limit for the resolving power of a telescope, we first need to determine two important values. First, how far away is the object we are observing, ℓ? Second, what is the angular size, θ, of the finest detail we wish to resolve at the distance ℓ?

Measure the distance ℓ between the slide and the objective lens of the telescope. (Convert your units to millimeters)

$$\ell = \underline{\hspace{3cm}} \text{ mm}$$

We can calculate θ by using the actual distance to the object, ℓ, and the actual size of the object, h. For this lab, h is the actual physical separation between the two canals and between the double stars on the slide, and are given to you in units of millimeters:

Object	**Separation (mm)**
Canals	0.132 mm
Double Stars	0.154 mm

Calculations

Calculate the angular size of the distance between these objects, θ, for both the double stars and the canals, using this angular size approximation (show your work!):

$$\theta = 2.063 \times 10^5 \left(\frac{h}{\ell}\right) \text{ arcsec}$$

$\theta_{\text{canal}} =$ ______________ $\theta_{\text{double star}} =$ ______________

Now that you have determined the angular size, θ, for both the canal and double star, you can determine the predicted aperture of the telescope that will be needed in order to let you see that detail.

The Dawes' predicted diameter of aperture for the resolution, θ, is defined as:

$$D = \frac{114}{\theta} \text{ mm}$$

$D_{\text{canal}} =$ ______________ $D_{\text{double star}} =$ ______________

These predictions using the Dawes' Limit approximation will be relatively close to the actual diameter you measure in your observations

Observations

Open the iris diaphragm fully (carefully). Focus the telescope using the adjustment knob near the eyepiece. While looking through the eyepiece of the telescope slowly close the iris diaphragm until you can just barely distinguish a separation between the canals or double stars. Have a partner use a ruler to measure the diameter of the opening at the iris of the telescope. Record this value in millimeters in the tables below. Open the iris diaphragm fully, repeat until you have completed the number of observations required by your instructor for both the canals and double stars.

Trial #	**Measured Diameter of Iris Diaphragm (mm)**
Trial 1	
Trial 2	
Trial 3	
Trial 4	
Trial 5	
Average Measured Diaphragm Diameter	

Data Table 5.1

Trial #	**Measured Diameter of Iris Diaphragm (mm)**
Trial 1	
Trial 2	
Trial 3	
Trial 4	
Trial 5	
Average Measured Diaphragm Diameter	

Data Table 5.2

Comparison

In order to compare your experimental values of D with those value of D predicted by Dawes' Limit you can calculate the percentage difference between the two using the typical formula, given below:

$$\%\ \text{error} = \left| \frac{D_{\text{avg}} - D_{\text{Dawes}}}{D_{\text{Dawes}}} \right| \times 100$$

What is your percentage error between the diameter of the telescope aperture predicted by the Dawes approximation and the actual average measured value for the canals?

$$\%\ \text{error}_{\text{Canals}} = \left| \frac{D_{\text{avg}} - D_{\text{Dawes}}}{D_{\text{Dawes}}} \right| \times 100 =$$

$$\%\ \text{error}_{\text{Double Stars}} = \left| \frac{D_{\text{avg}} - D_{\text{Dawes}}}{D_{\text{Dawes}}} \right| \times 100 =$$

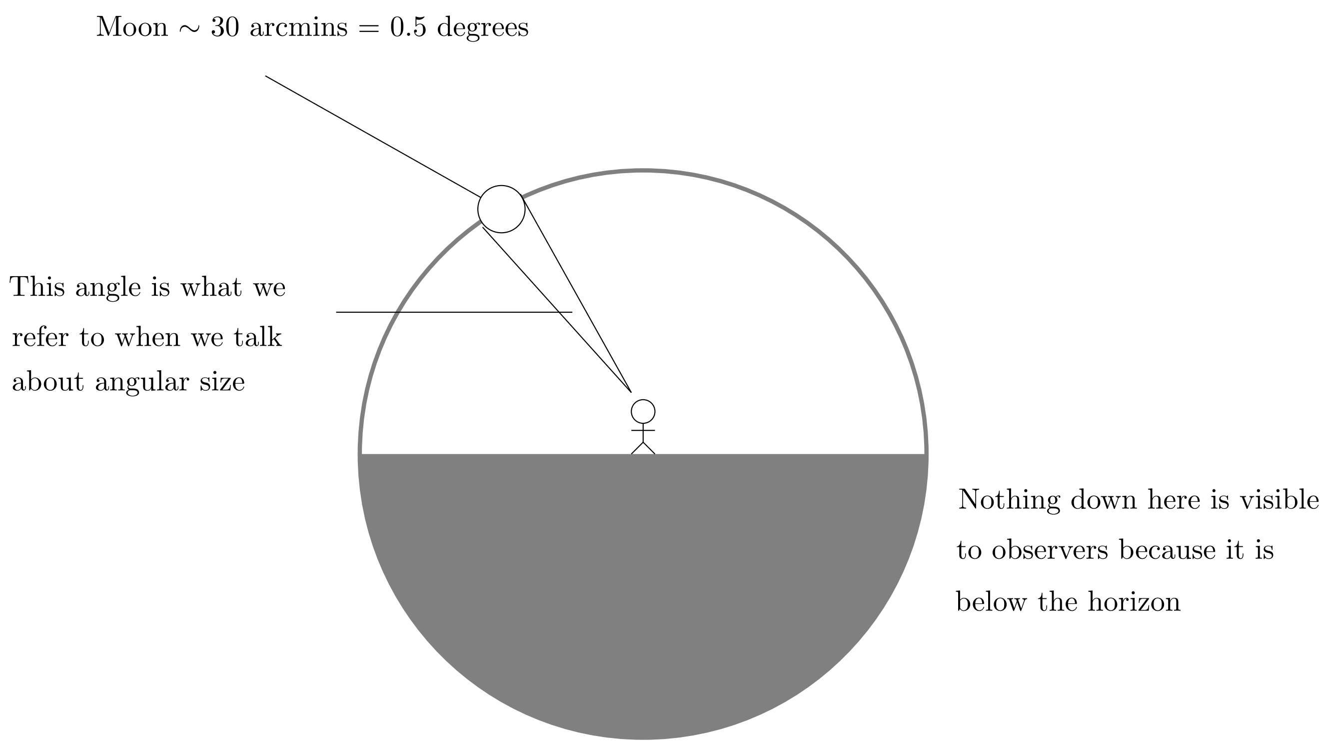
Can you think of any possible errors that may have caused the differences? Please list some and explain them

Understanding the arcsecond

The arcsecond is the smallest basic unit of angular measure on the sky. It is also a useful reference as one arcsecond is the approximate limit of resolution for a simple ground-based telescope due to atmospheric conditions. If the telescope is space-based, then physics and optics come into play, and the resolution of the telescope is limited merely by the size of the aperture and the quality of its components.

Let's get some intuition on just how small one arcsecond is.

We see the sky as one half of a circle, stretching from horizon to horizon. In a complete circle there are 360 degrees, so from horizon to horizon we see about half of that. Only around 180 degrees of sky are visible at one time. The moon has an angular diameter of about 0.5 degrees, or 30 arcminutes. Converted to arcsec the moon's diameter is about 1,800 arcseconds!



Here is a quick exercise to help you better understand the size of one arcsecond. Let $\theta = 1$ arcsecond, this is our observed resolution. Let the actual size of the observed object, h, be the diameter of a penny measured in millimeters.

$$h = \underline{\hspace{3cm}} \text{ mm}$$

Use the resolution relation to determine the distance, ℓ, from an observer for which a penny will have a $\theta = 1$ arcsecond angular resolution

Recall the resolution relation and solve for ℓ:

$$\theta = 2.063 \times 10^5 \left(\frac{h}{\ell}\right)$$

What is your value for ℓ in millimeters?

$$\ell = \underline{\hspace{4cm}} \text{ mm}$$

Convert your value for ℓ from millimeters to kilometers, a much more reasonable way to think about that distance (Recall that there are 1,000 millimeters in one meter and 1,000 meters in one kilometer).

$$\ell = \underline{\hspace{4cm}} \text{ km}$$

Lab 6: The Astronomical Telescope II

Purpose

The purpose of this experiment is to acquaint you with the system astronomers use to describe the brightness of stars. A second objective is to demonstrate why a telescope can allow you to see stars much fainter than you can see with the unaided eye, and why you can see more stars with a large telescope than with a smaller one.

Introduction

All of you have seen the night-time sky. You know that the sky is filled with myriad of stars (about 5000 are visible to the naked eye), and that they show a wide range of brightnesses. Now imagine that you want to make a catalog (list) of stars, or a realistic map of the sky. It soon becomes obvious that you need some way to describe the relative brightnesses of the various stars you are listing or mapping.

This problem was faced - and solved - by early astronomers. Around 134 B. C. the Greek scientist Hipparchus compiled a catalog of about 850 stars. He not only listed their positions, but described their brightness by a system of "magnitudes." The brightest he called "stars of the first magnitude," while the faintest he could see with the naked eye were designated "stars of the sixth magnitude". The other stars were assigned magnitudes between 1 and 6. Hipparchus' catalog was immortalized by another Greek scientist, Ptolemy, who lived between 100 and 200 A.D. Ptolemy republished Hipparchus' catalog and added 170 more stars in his famous *Almagest*, which became the dominant text in astronomy for centuries.

With the advent of telescopes (circa 1610) estimates of star brightnesses gradually became more scientific and thus more accurate. In the latter half of the 18^{th} Century, the great English astronomer and telescope builder Sir William Herschel concluded from measurements made with various telescopes that a 1st magnitude star radiates about 100 times as much light as a 6^{th} magnitude star. Subsequent and increasingly accurate work by others confirmed this ratio, and in 1856 the Oxford University astronomer Norman Pogson proposed that the magnitude scale be defined by making 5 magnitude steps equal to exactly 100. Thus was born the brightness scale we use today.

You might ask, why is a difference of five magnitudes equal to a brightness difference of 100 times? The original scale was based on qualitative measurements by eye. Our eyes, however, do not perceive brightnesses linearly; for example, if someone were to shine a flashlight at you, adding another would not double the brightness that you perceive. Several more flashlights would be required to "double" the brightness. For this reason, the steps Pogson created to fill in the brightness ratios are not linear, they are logarithmic.

Figuring out the brightness ratios is still a relatively straight forward process. Since five steps of magnitude is a difference of 100, and we want five evenly-spaced values (in logarithmic-space), a one-magnitude step is equal to the fifth root of 100, or $\sqrt[5]{100}$, which is 2.512. Each brightness ratio

Magnitude Difference	Approximate Brightness Ratio
1	2.5
2	6.3
3	16
4	40
5	100

Table 6.1: Brightness ratios for the difference between two magnitudes. Note that these values are approximate

can be calculated exactly by using the following formula

$$\text{Brightness Ratio} = 100^{\Delta m/5} = 10^{\Delta m/2.5}$$

where Δm is the difference in magnitudes. This equation is often written in base 10 (right-most portion of the equation) as it is more widely used than base 100. As a quick reference, the approximate results of this equation are shown in Table 6.1.

As you can see, the magnitude scale has its roots in antiquity. If modern astronomers were to start all over, they would almost certainly come up with something quite different, probably based on absolute energy units. However, the traditional magnitude scale is so deeply rooted in the astronomical literature, both amateur and professional, that it is unlikely to go away, and thus it is important to understand it.

After Galileo first turned a telescope on the heavens in 1609, astronomers could see stars much fainter than the 6^{th} magnitude, so the scale was extended in the same way to higher numbers. The 30-inch telescope at our research observatory, Rosemary Hill, has photographed stars as faint as 22^{nd} magnitude, 2.5 million times fainter than the faintest star you can see with your unaided eyes! Similarly, there are objects brighter than 1^{st} magnitude stars, so the scale has to be extended in the other direction as well. The planet Venus gets as bright as -4; the full Moon is near -13; and the Sun is about -26.

We have now illustrated the second reason astronomers incessantly lobby for ever larger telescopes. Not only do the big instruments have superior resolving power; they are also capable of detecting much fainter objects. Needless to say, there are many more faint objects in the sky than bright ones. With the unaided eye you can see about 5000 stars, but with binoculars, you could detect over a million! Figure 6.1 illustrates how larger and larger telescopes reach fainter and fainter magnitudes. This figure shows the faintest stars visible in telescopes of various apertures.

Laboratory Procedure

You are provided with a small telescope mounted on a stand. The aperture (i.e., the diameter of the objective lens) can be varied by means of an iris diaphragm like that used in cameras. You also have an illuminated target that should be set up about 3.5 meters from the telescope. The experiment is best conducted in a darkened room.

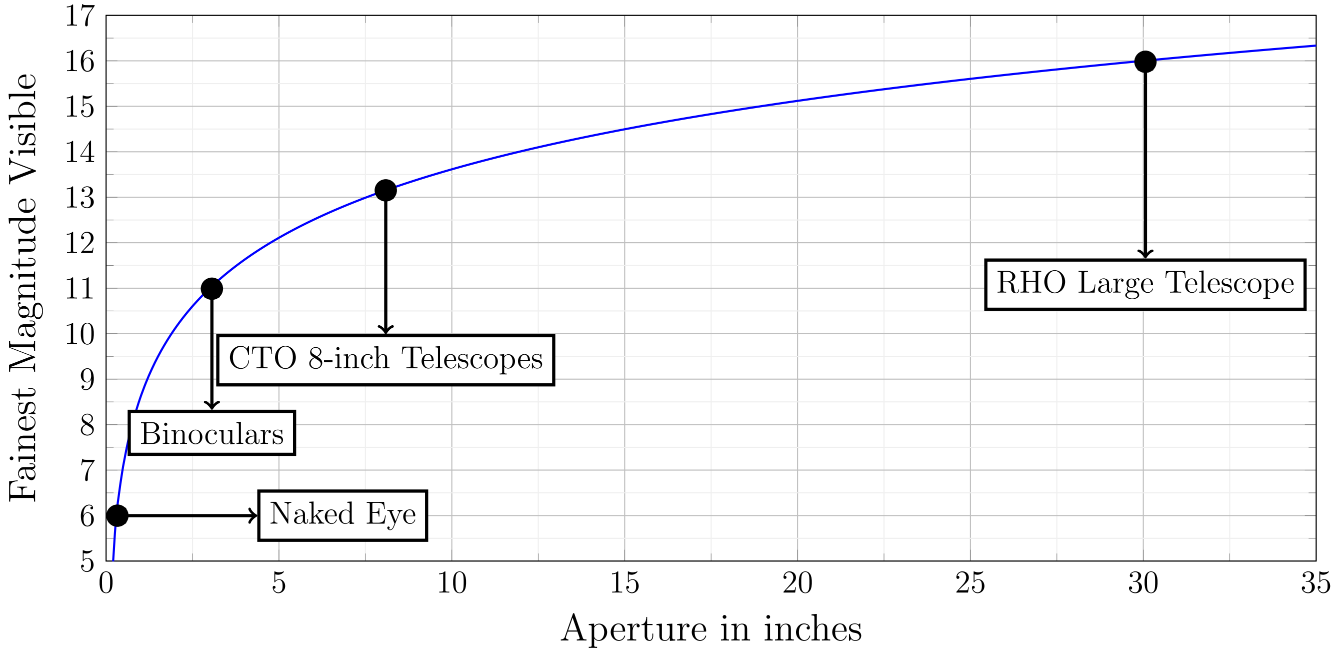


Figure 6.1: Relationship of aperture size versus magnitude visibility

Carefully aim the telescope at the target and center it in the field of view. While you are doing this, the iris diaphragm should be at its maximum opening (notice that a scale on the telescope tube tells you the opening or aperture in millimeters). Do not force the diaphragm; turn it gently! You should see a vertical row of six "stars" of diminishing brightness, like in Figure 6.2. Focus the telescope by slowly turning the knob on the eyepiece tube until the image is at its sharpest; it is quite possible that different observers will need to adjust the focus for their own eye. If you wear glasses, experiment to determine whether the image is better with or without the glasses.

Your instructor will have adjusted the illumination in the projector so that the faintest of the six stars is at the limit of normal vision. You may have to allow a little time for your eyes to become dark-adapted before you can see it. This star then corresponds to a 6^{th} magnitude star in the night sky. The star adjacent to it is 5^{th} magnitude, the next is 4^{th}, and so on to the brightest, which is of 1st magnitude. The group of six stars, in other words, represents the range of naked-eye stars as first defined by Hipparchus over 2000 years ago. If you study the group and retain some

Figure 6.2: Diagram of the 6 pinholes on the slide you will observe

impression of it, it will help you to estimate the brightnesses of various stars in the real night-time sky.

Now concentrate on the 6^{th} magnitude star and slowly close the iris diaphragm until the star just disappears; record the aperture at which this occurs. You should probably do this two or three times to obtain the best result. Yes, there is some subjectivity in deciding just when the star vanishes! Such decision-making is quite characteristic of many kinds of visual observations; perhaps you will understand why there is often controversy about such observations. Repeat the procedure for each of the remaining five stars, being careful to record the iris setting at which each disappears. Each student should run through the procedure independently. Comparison of the various results will prove interesting.

Note for the curious: Your 6-star target was prepared by drilling 6 tiny holes, all the same size, in a thin sheet of brass. The hole representing 1^{st} magnitude is unobscured. Behind each of the other holes was cemented a neutral density optical filter, a colorless, absorbing piece of plastic. Each filter has a density 0.4 greater than the filter over the preceding hole. Since a density of 0.4 decreases the light by 2.5 times (density is a logarithmic quantity), there is a 1-magnitude step between each of the holes.

The Astronomical Telescope II Worksheet

Name: ______________________ **Date:** ____________ **Section #:** ______

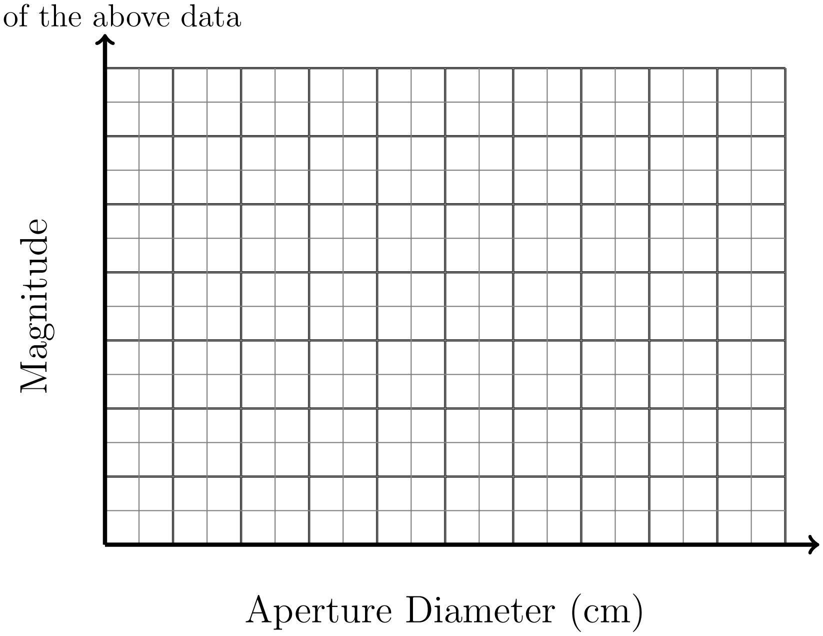
This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

1. Make a table of your data (aperture versus magnitude). Specify units.

Magnitude	**Aperture Width**
1	
2	
3	
4	
5	
6	

Data Table 6.1

2. Make a plot of the above data



Graph 6.1

3. At its brightest, Mars has a magnitude of -2. What is the magnitude difference between Mars and a star of magnitude +1? How many times brighter is Mars than the star of magnitude +1? (Hint: use Table 6.1)

4. The 30-inch A.G. Smith Telescope at UF's Rosemary Hill Observatory (RHO) has an aperture of 76 cm. Your eye has an aperture of about 8 mm. How many times more photons (particles of light) can the telescope gather compared to your eyes? Recall that the light gathering power is directly proportional to the area. Compare them as a ratio, resist the urge to subtract!

$$\text{Area} = \frac{\pi \ (\text{aperture})^2}{4}$$

5. The <u>small</u> telescope at RHO has an aperture of 18-inches. What is the faintest magnitude you'd expect to see? (Hint: you can interpolate this directly from Figure 6.1)

6. What is the formula for magnification? Calculate the magnification that you can obtain with the 8-inch Alvan Clark refracting telescope at the Campus Teaching Observatory if you are using an eyepiece of 15 mm focal length. The telescope has a focal length of 2,920 m.

7. What are some sources of error in this experiment? Are they random or systematic? (Remember that errors here do not refer to “mistakes”)

8. Based on what you learned in this experiment and the Astronomical Telescope I, what are the advantages of building telescopes with larger apertures?

Extra Credit: Another way to answer question 5 is to use the equations given in the introduction to this lab and calculate the faintest magnitude that can be see with the 18-inch (46 cm) telescope. You can assume that the faintest magnitude seen with the unaided eye is +6. Make a comparison between your results and the result of reading the faintest magnitude from the plot on Figure 6.1. To get credit, clearly show how you use the equations and show your work.

Here are some hints:

- You will have to calculate the ratio between the area of the mirror of the telescope and the area of the human eye.
- Also remember that the ratio of the brightness (b_1/b_2) is proportional to the ratio between the area of the lens and the area of the eye.

$$\frac{b_1}{b_2} = \frac{A_1}{A_2}$$

- Use the equation

$$m_1 - m_2 = 2.5 \log_{10} \left(\frac{b_1}{b_2} \right)$$

to compute the difference in magnitudes and assume that the limit of magnitude of the dark-adapted unaided eye is +6.

Astronomical Telescope I and II

Synthesis Questions for Double Formal Report

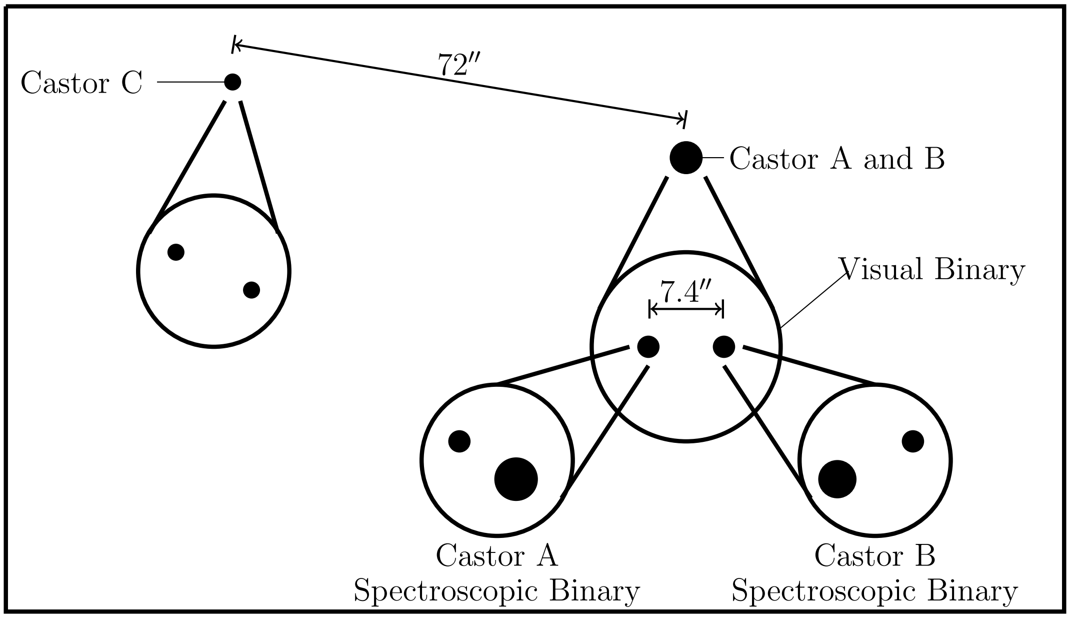


*Image not to scale

1. One of the deep sky objects frequently shown at the Campus Teaching Observatory in the spring is Castor (α Geminorum), in the constellation Gemini. Our telescope can resolve Castor into 2 components, so it is usually presented as a binary – but it is actually a sextuple system! Above is a schematic (not to scale) of the various components and how they all orbit each other.

   a) In 1907, the angular separation of Castor A from Castor B was only 2 arcseconds. Today it is about 7.4 arcseconds. The CTO's 8-inch (∼20 cm) telescope can resolve Castor A and B at their current separation. How big of a telescope would you have needed to resolve Castor A and B back in 1907? Would the CTO's 8-inch telescopes have sufficed? Use Dawes' Limit

$$D[\text{mm}] = \frac{114}{\theta[\text{arcsec}]}$$

b) The Albireo system (Beta Cygni) in the constellation Cygnus The Swan is a very popular multiple-star shown at the Campus Teaching Observatory (CTO) during the fall. Telescopes at the CTO resolve Albireo into two stars, one yellowish-orange (Albireo A, an unresolved binary) and the other blue (Albireo B). Locals sometimes call Albireo "The Gator Star" because of its components' colors. Using the apparent magnitudes given in the table below and the equation

$$\frac{b_2}{b_1} = 10^{(m_1 - m_2)/2.5}$$

(pay attention to the subscripts!), compute the brightness ratio brightness between the two stars. You can assume that m_1 is the fainter star

Star	**Apparent Magnitude**
Albireo A	+3.2
Albireo B	+5.2

2. The most recent Public Policy Polling survey on conspiracy theories estimates that about 7% of Americans still think the Apollo Moon landings were faked. Many cite the inability of Earth-based telescopes or even the Hubble Space Telescope to see the equipment left behind (never mind all the photos from the Lunar Reconnaissance Orbiter, LRO). The landing stage of the Lunar Module from Apollo 11, 12, and 14 through 17 are all still on the Moon. If the larger dimension of the landing stage of the Lunar Module is 9.4 meters, how big of a telescope would you need to resolve it at the typical Earth-Moon distance of 384,000 km? Ignore here the distortion caused by the terrestrial atmosphere. Consider only the theoretical resolution or the diffraction limited resolution. Follow the steps below to find out.

   Step 1 – Use the resolution relation to compute the angular size of the Lunar Module. Remember that h and ℓ must be in the same units.

$$\theta[\text{arcsec}] = 2.063 \times 10^5 \left(\frac{h}{\ell}\right)$$

   Step 2 – Plug that answer into the Dawes' Limit formula and convert your answer to meters

$$D[\text{mm}] = \frac{114}{\theta[\text{arcsec}]}$$

   Step 3 – The largest single mirror telescope is the Gran Telescopio de Canarias (GTC) with an aperture of 10.4 meters. The Hubble Space Telescope has an aperture of 2.4 meters. Based on your result, should either of these two telescopes be able to resolve the Lunar Module?

Use and Applications of the Astronomical Telescope

Guidelines for Writing the Report

In this report, you will summarize the results from "The Astronomical Telescope I" and "The Astronomical Telescope II" experiments, and will synthesize what you learn regarding the two main properties of a telescope. You will apply what you learned to elaborate and answer some questions regarding the use and applications of telescopes.

You must submit <u>your own work</u>. You can collaborate and exchange ideas with your lab partners, but do NOT copy and paste, your work must be entirely your own. Your submissions will be checked by Turnitin.

In "The Astronomical Telescope I", the key concepts you learned about were:

- The concept of angular resolution
- Dawes' empirical formula to compute the angular resolution and how to use it
- How varying the other parameters in the formula affects the angular resolution
- An application for the size of an arcsecond

In "The Astronomical Telescope II", the key concepts you learned about were:

- The relationship between telescope aperture (diameter) and its light gathering power
- The relationship between the aperture (diameter) of a telescope and the magnitude of the dimmest stars visible through it
- The magnitude system to classify stars according to their brightness
- The formula to convert between a difference in magnitude and a brightness ratio

Your report should contain all of the following sections, in this order, with **headers**

1.	Abstract	(5 points)
2.	Introduction	(10 points)
3.	Discussion of Physical Concepts	(10 points)
4.	Methods and Purpose	(20 points)
5.	Data	(10 points)
6.	Discussion	(20 points)
7.	Conclusions	(10 points)
8.	Applications – Synthesis Questions	(10 points)
9.	Original Data Sheets attached	(5 points)
Total		100 points

Since this report compiles different labs, read through this lab guide carefully. If you're unsure of the requirements of this report, please ask your instructor for clarification as soon as possible.

How to Address Each Section:

Abstract (5 points)

An abstract is just a brief overview/summary of the work. This section should be a very brief overview of the what we're doing and what we achieved. In general, this section should be ∼150 words, but I won't hold you to exactly that number. Be succinct and get your point across.

Use numbers as a method of discussing results in the abstract very sparingly. Instead, opt for a more generalized discussion of the results. For example, instead of listing data points describe the trend they follow (linear, exponential, etc..)

Introduction (10 points)

Give an introduction into the history of telescopes and their relevance to astronomy. Discuss how each experiment performed showed the importance of telescope design in observational astronomy.

The introduction offers more context on the reason we're doing this experiment and answers some basic questions about what we're studying: Why should your reader care about a telescope? What does a telescope do for an astronomer? How long have people been using telescopes? How do telescopes link-up with rest of "big picture" of astronomy?

Discussion of Physical Concepts (10 points)

The Discussion sections purpose is to help is visualize the purpose of the experiments in terms of the concepts introduced during lab. The physical principles are what motivate the experiment. What are we trying to gain more information about? How would we get this information from the following equations?

Write out the equations, define the variables, and give an explanation for what the equation means and how it is used for each of the following (as applicable).

- Angular Size
- Dawes' formula
- What is the magnitude system and its relation to an object's brightness? How is it related to a telescope's light collecting area?
  - Note: an equation is not necessary to explain the magnitude system, but it might be useful to describe the mathematical relationships between the brightness that magnitudes represent.

Methods and Purpose (20 points)

Describe the procedures of the experiments, detailing what you and your group did (i.e. this should not just be a paraphrase of the lab manual instructions). Also explain the purpose of each experiment - what did the experiment reveal about telescopes? Think about why you did each experiment (not just that you had to do them because the manual said so).

- What supplies/tools were used?
  - Include units and physical sizes as necessary (i.e. for “Impact Craters” - there were 8 spheres used, their sizes were 20.66mm, 19.05mm, etc...)
- What predictions were made prior to observation?
- What was measured? How many times were things measured?
- What were you looking for to make a measurement (i.e. what was each experiment about)?

Data (10 points)

Type/computer generate all tables and plots with the data collected during class. Make sure you are using the appropriate plot type (scatter) for the given data and that your data points are actually represented on the plot (not just a line). Also be careful that your tables are carefully <u>labeled with the correct units</u>.

Tables

1. (Astronomical Telescope I) Canals on page 3.6
2. (Astronomical Telescope I) Double Stars on page 3.6
3. (Astronomical Telescope II) Question 1 on page 4.7

Plots

1. (Astronomical Telescope II) Question 2 on page 4.7

Discussion (20 points)

<u>Error Analysis</u> (10 points):

- Discuss how closely your values followed the Dawes limit and how well your magnitude vs. diameter plot matches Figure 7.1. Discuss the percent error of your calculations.

- What are possible sources of error in these experiments? Remember to consider the tools and techniques used for the experiments. Errors are not math mistakes/rounding precision, nor is it (typically) valid to suggest the rulers/lab equipment are manufactured incorrectly.
- Other errors that you can think of...

Questions (10 points total):

These are the questions that you will be responsible for in this report. Any other questions in the lab manual can be answered if you're interested, but these are the required items to complete the report.

1. (3 points) Explain why the resolving power of a telescope built on the ground is not limited by diffraction.
2. (1 point) Discuss the size of the arcsecond, referring to your calculations with the penny - how far would the coin have to be to take up one arcsecond in the sky?
3. (4 points) The larger of the two telescopes at our Rosemary Hill Observatory (RHO) has an aperture of 30 inches (76 cm). How much more light does it collect than your unaided eye (diameter of 8mm)?
4. (2 points) Why are telescopes today built with mirrors instead of lenses (i.e. reflectors vs. refractors?).
5. If you attempted the extra credit question #5 in Astronomical Telescope II, indicate that here and make sure you show your work on the original WS.

Conclusions (10 points)

The conclusion section is a general overview of the entire lab. You might find it useful to think of this as similar to the abstract, except now you can expect that your reader knows more about the experiments conducted. Results in numerical form are common in the conclusion.

Applications - Synthesis Questions (10 points)

Attach the Synthesis questions from the back of the lab manual (see last pages). These questions should be answered in full and with the solutions clearly marked. Don't forget to show your work!

Attach Data Sheets at the End (5 points)

- (Astronomical Telescope I)
- (Astronomical Telescope II)

Lab 7: Modern Photometry and Astrometry

Purpose

This exercise will familiarize you with some of the techniques that are employed by modern astronomers who often perform digital photometry and astrometry on star clusters to investigate the origins and the life histories of the stars. This experiment's purpose also is to acquaint you with the type of detector that is now in actual use on the telescopes of nearly all professional astronomers and even many advanced amateur astronomers. You will be working with the image of a real star cluster, as well as an artificial laboratory image, and you will gain experience in using a star chart to identify individual stars.

Introduction

The first practical system of photography was announced by the Frenchman Louis Daguerre in 1839. Within a year the first astronomical photograph, of the Moon, had been taken by an American, Dr. John Draper. For the next 140 years the photographic plate reigned supreme as the detector of choice for most astronomical problems. The popular image of the astronomer peering into their telescope long has been largely a myth; as a detector the human eye is simply too unreliable, too transient, and above all unable to record the faintest details. During the 1980's the photographic plate began to be challenged by a variety of electronic recording devices roughly analogous to TV cameras. By 1990, the electronic cameras clearly were winning, and the photographic plate began to fade. Five years later, in 1995, ordinary photography had virtually disappeared from professional observatories.

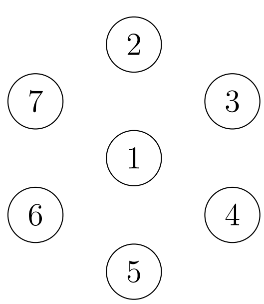


Figure 7.1: Illustration of the artificial cluster analyzed in this lab

The type of electronic detector that is currently in widespread use by astronomers is known as the charge-coupled device or CCD. In simplest terms, a CCD is a mosaic or checker-board of tiny light-sensitive "picture elements" or pixels coated on a silicon chip. Megapixel to gigapixel cameras are common today. Given that typical individual pixels are tiny, approximately 1 micrometer across, the chips themselves are only still then approximately $1 - 10$ centimeters across.[1]

When light strikes a CCD, the pixels act as tiny photocells. Each pixel acquires an electrical charge that is proportional to the amount of light it has received. The light image has been converted to an invisible image in electric charges. To render the new image, the charges are read off pixel by pixel, row by row, onto an electronic storage device, generally the memory of a computer. Once this has been done, the computer can reconstruct the image and display it on its monitor. Here we see one of the advantages

[1]Many personal cameras today, such as the ones in cell phones, use CMOSs or complementary metal oxide semiconductors, not CCDs, for technical and economic reasons. They do still detect light using pixels but a more technical description of the differences is beyond the scope of this class.

of the CCD: instant gratification. If we don't like the image we can delete it and try again very quickly. An even greater advantage is sensitivity, technically referred to as "quantum efficiency". The fastest photographic films have quantum efficiencies of about 1%, meaning that 99 of every 100 photons of light that strike the film are not recorded/detected! On the other hand, the best CCDs, have efficiencies exceeding 90%.

Your experiments will involve measuring the magnitudes ("brightnesses") of the stars in a clusters, both artificial (Figure 7.1) and real (Figure 7.2). This is an illustration of photometry (literally meaning "measuring light"), an application for which the CCD is especially well adapted and widely used by present-day astronomers. Much of what we know about stellar evolution and the lifetimes of stars is derived from photometry of star clusters, which are compact groups of stars born at nearly the same time in a small volume of space.

A second part of the experiment illustrates astrometry, the measuring of positions. Until modern times astronomy consisted largely of astrometry, recording the positions and movements of stars and planets. For example, this is important for measuring the orbits of these celestial bodies, which then enables the calculation of other fundamental quantities, such as masses. The CCD also provides an accurate way to measure the relative positions of stars in a cluster.

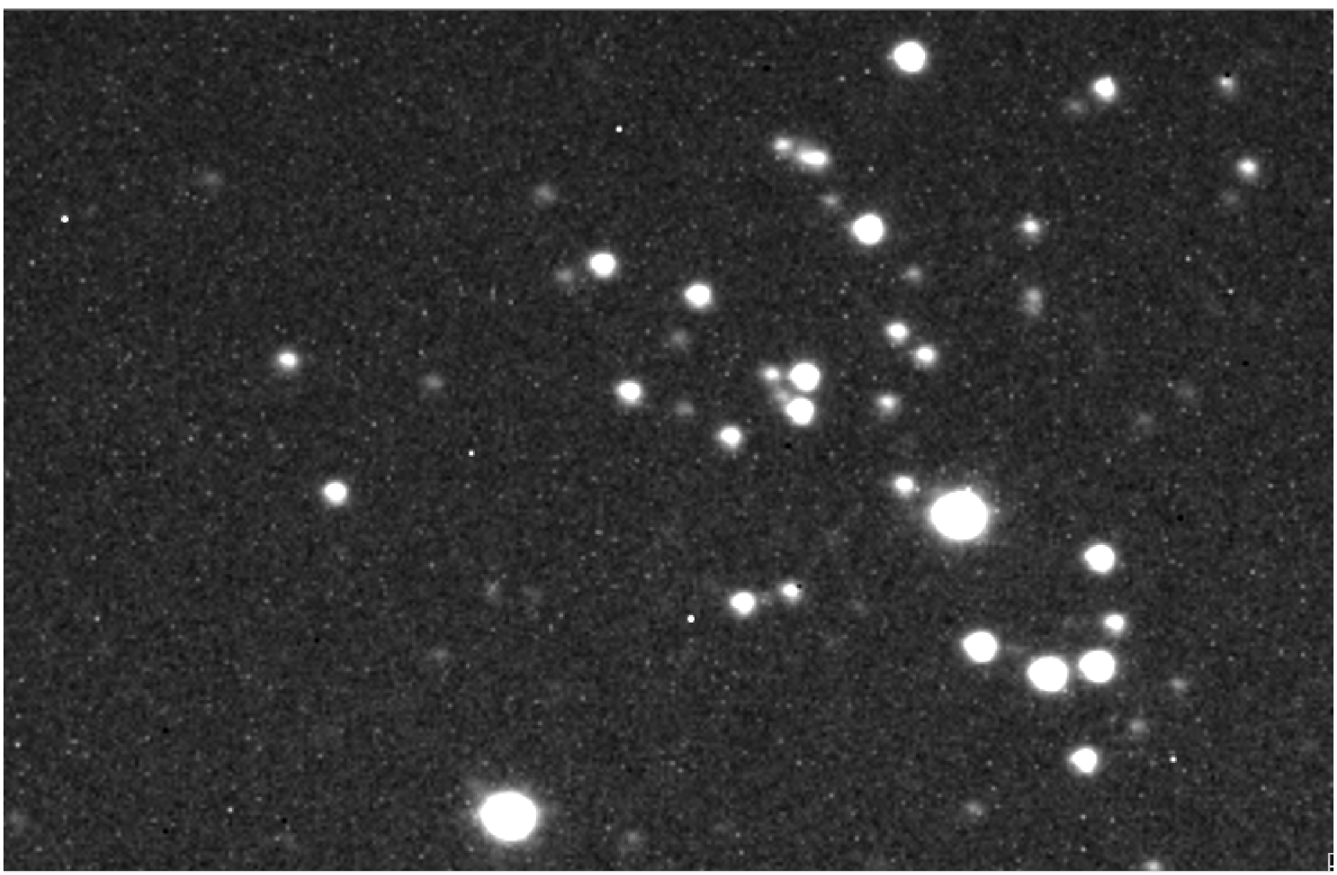


Figure 7.2: This is an optical image of the H-Cluster that we'll be using for our analysis.

Laboratory Procedure

Please DO NOT modify, create, or delete any files on the computers unless EXPLICITLY told to do so by your instructor

For your reference, use Table 7.1 on the different keyboard shortcuts. Please read all of the instructions below thoroughly, but use this as a reference as you're working.

Shortcut	Function
`B`	Set background magnitude
`+`	+0.1 Magnitudes
`-`	-0.1 Magnitudes
`Shift +`	+0.01 Magnitudes
`Shift -`	-0.01 Magnitudes
`S`	Set 0 position

Table 7.1: Quick-look keyboard shortcuts

Artificial Cluster

The purpose of this portion of the lab is to get you acquainted with CCDOps, the analysis software used by research astronomers, before moving into a more complex example with real stars. The cluster that you'll see is from a plate that we have created for this lab and is not a real cluster of stars.

Photometry

Here are the steps to working with the photometric data and getting values for the magnitudes of the 6 stars of interest in our artifical cluster:

1. Start the computer and launch the CCDOps software.
2. Click on `File` and then `Open`.
3. You should see the file `FKCLUST.st6`, open this file (the .st6 file extension is easily read by CCDOps). You will see an elaborate screen listing data for the exposure. Click anywhere on this box to proceed.
    - If the directory manager is not pointing to the `FKCLUST` directory (i.e. you don't see the file), click on `Look-In` and select the root directory `C:`. Within that directory you should be able to find the `FKCLUST` folder with `FKCLUST.st6` inside. If you still cannot find it, ask your instructor for help.

4. You should see a window with the image and another window called `Contrast`.
5. (Optional) To change the size of the image, go to the menu bar at the top of the screen and click `Utility`, choose `Resize > Resize Utilities` and select `Enlarge Image x2` or `Reduce Image x2` (this process can be repeated several times to get an even larger image, but likely won't need to be)
6. If the box called `XHair` is not already on your screen, go to `Display` and select `Show Crosshair` to bring up the `XHair` analysis window.
7. The CCDOps photometry program measures the brightness of a star by adding up the electrical charges on all the pixels that comprise the image of the star. To do this, you need to tell it how many pixels to include, which is governed by the `Boxsize` option at the bottom of the `XHair` analysis window; a `Boxsize` of 5×5 or 7×7 pixels is usually optimum.
   - A box that is too large will actually reduce accuracy by including too much background or "sky," which adds "noise" to the data.
   - A box that is too small obviously will not catch all of the charges that represent the star image.
8. Two steps are necessary to calibrate the software:
   - First, you need to tell it how much background to subtract to correct the image. Use the mouse to drag the cross-hair to a blank area of the "sky". Click with the left mouse button to position the box and press the `B` key (B for "background"), and you should see the Absolute magnitude reading in the analysis box change to 99.0.
   - Second, you to set the magnitude value of a known star; for convenience we will use the central star in the cluster (Star 1). Drag the cross-hair and carefully center it on Star 1 and click with the left mouse button. You can use the arrow keys to improve the centering of the star. Use the `+` and `-` keys to adjust the Absolute magnitude reading to 0. (Trick: by depressing `Shift` along with `+` or `-`, you can refine your magnitude setting to 0.01 magnitude.)
9. You are now ready to measure the magnitudes of the 6 "unknown" stars in the cluster, numbered 2 through 7 in Figure 7.1, which turns out to be quite simple once the system is calibrated. Center the cross-hair (accurately!) on the image of each star, and read its magnitude from the Absolute magnitude line in the analysis box. Record your results in Data Table 7.1
   - Assuming that your centering is always good, the values are generally repeatable to one or two hundredths of a magnitude. When you're measuring a real cluster in the sky, later in this lab the procedure will be (virtually) identical.

Astrometry

The CCDOps software that operates your camera also allows you to measure angular separations and position angles. The software assumes that the focal length of the telescope that made your image has been properly entered when the image was taken and recorded in the image parameters.

The program then gives you the angular separation of objects on the screen in arcminutes and arcseconds and the rotation angle in degrees.

- If the `XHair` window is still present, go directly to the next step. If the `XHair` window is not present, click in `Display` and select `XHair`
- The center star will again act as your reference star. Carefully center the cross-hair on the reference star and press `S` on the keyboard. The values of "Sep" and "Angle" under `Geometry` in the X-hair window should be updated. Both of these values should change to zero. You are now "calibrated" and ready to measure these two parameters for the rest of the stars.
- Now set the cross-hair on the first of the 6 "unknown" stars. Note that you obtain a Separation and Angle reading for this star. Press the `P` key (for "Position") and notice that your readings change slightly. This is because the computer has improved your setting by reading the centroid, a kind of "center of gravity," of the pixels within the box. Record the Separation (in seconds of arc) and angle of the star in Data Table 7.2.
  - The angle is what astronomers term the position angle, with respect to the reference star. An object due north (top of the image) of the reference has, by definition, a position angle of 0°, with the angles increasing clockwise up to 360°; due south is of course 180°. This system of separations and angles evolved from the necessity of recording thousands of observations of double stars
- Proceed to make the same measurements for the remaining 5 "unknown" stars.

Real Cluster

Now that you've accrued experience working with the software, we'll now move on to a more complex example of what modern photometry looks like in a real star cluster.

You will be provided with an image of a star cluster. The image was taken at the UF Campus Teaching Observatory using a 12-inch reflector telescope and a CCD camera. The cluster is one of the two clusters known as the Double Cluster in the Perseus constellation. It is known as the h cluster (NGC 869). It is located at a distance of 7,500 ly in the Milky Way galaxy. It has a mass of about 4,700 solar masses. You are also provided with a "finding chart" (as it is called) for the cluster on the last page of this lab. On this chart the individual stars are identified by numbers assigned by an earlier investigator.

We will only be doing photometry on this cluster. The procedure for calibrating the image is very similar the same as it is for the artificial cluster, save for two changes:

- The file you'll be looking at now is `H1125A.sf6` in the `H1125A` directory.
  - If the directory manager is not pointing to the `H1125A` directory (i.e. you don't see the file), click on `Look-In` and select the root directory `C:`. Within that directory you should be able to find the `H1125A` folder with `H1125A.sf6` inside. If you still cannot find it, ask your instructor for help.

- Additionally, instead of setting the magnitude of the reference star to 0, you will set it to the value given in the Finding Chart (last page of the lab).

In this section, we will observe an "open" (or "galactic") cluster with relatively few stars, so that identification is reasonably easy. "Globular" clusters, another type, are extremely crowded, with hundreds of thousands of stars and a circular symmetry that often makes identifications difficult even for professionals. We provide you with a Finding Chart on the last page of the lab to guide your identification.

Once you are confident that you can identify the cluster stars, you can begin the photometry. After you have calibrated the software by using the reference star, proceed to determine the magnitudes of all 12 in Data Table 7.3 of stars in the cluster. **Repeat each measurement three times** and use the average as the best value for the magnitude. Be sure to tabulate your measurements carefully as you make them!

Modern Photometry and Astrometry Worksheet

Name: ______________________ **Date:** ______________ **Section #:** ________

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

Artificial Cluster

Photometry

Star Number	Magnitude 1	Magnitude 2	Magnitude 3	Avg. Magnitude
2				
3				
4				
5				
6				
7				

Data Table 7.1

Astrometry

Star Number	Separation (arcsec)	Angle (degrees)
2		
3		
4		
5		
6		
7		

Data Table 7.2

Open Cluster

Reference Star Number = Reference Star Magnitude =

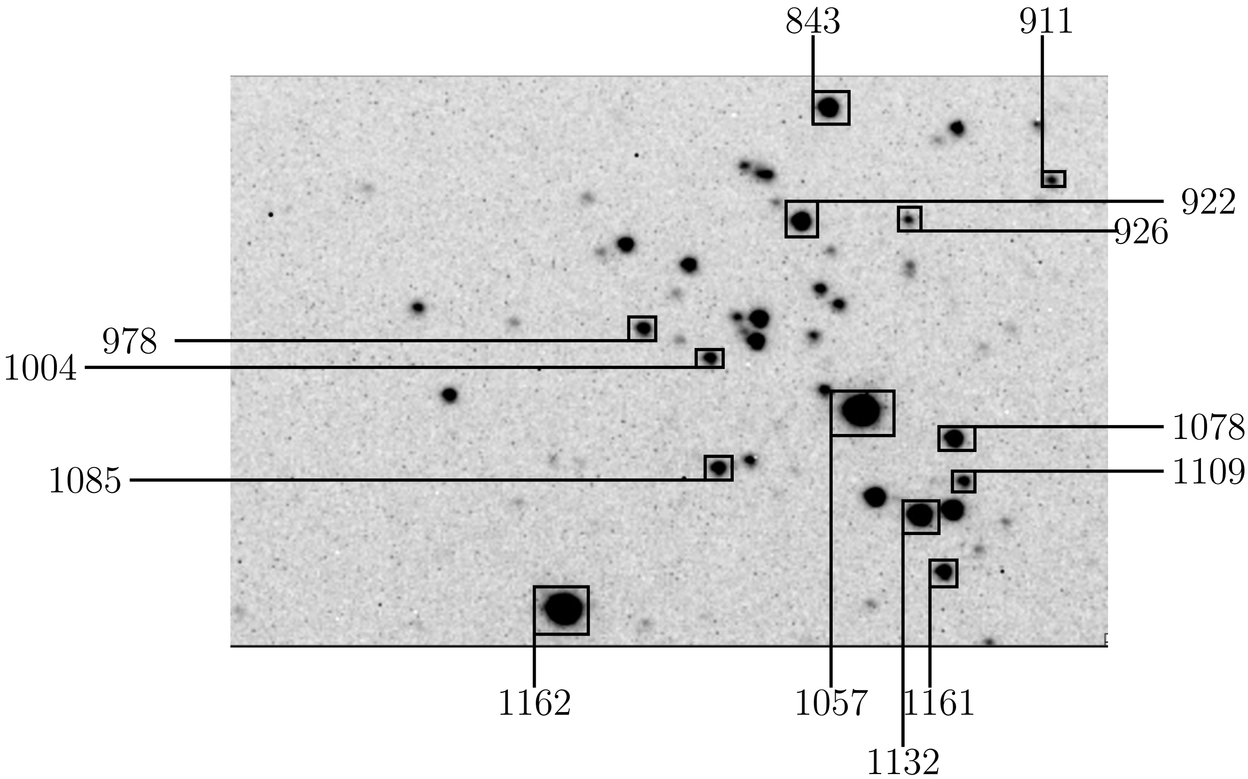
Star Number	**Theoretical Magnitude**	**Magnitude 1**	**Mag. 2**	**Mag. 3**	**Average Mag.**	**% Error**
1162						
1132						
843						
922						
1078						
1085						
1161						
1004						
978						
1109						
926						
911						

Data Table 7.3

1. Did the errors increase or decrease as the stars got fainter? Why might this be?

2. What are some possible sources of error?

Finding Chart



Reference Star: 1057	Magnitude 6.55

File Name	H1125A.ST6
Observation Date	11/12/97, Time: 22:45:12
Observer	Observer's Name
Note	Image taken 11/25/97 at 22:45:12
CCD Parameters	
Camera/image	ST-6/Standard Image
Exposure	20.00 Seconds
Snapshots	1 of 20.00 Sec. Pedestal: 0
Image Size	375 Pixels Wide × 241 Pixels High
Resolution Mode	High
Pixel Sizes	23.0 × 27.0 Microns (2.3 × 2.6 ∧ s)
Exposure State	ABG-Hi Rate, DCS - Yes, ABL - No
Temperature	12.74 Degrees C
Response Factor	300.00, 6.70 Photons/ADU
Telescope Parameters	
Focal Length	80.00 Inches
Aperture	43.0000 Square Inches
Optical Filter	Lunar
Tracking	Unknown

Lab 8: Astronomical Spectroscopy I

Purpose

The purpose of this exercise is to acquaint you with the three types of spectra that astronomers encounter in their research, and to familiarize you with the kinds of tools used in such research. In the process, you will become familiar with the relationship between the colors of light and the wavelengths of the radiation producing these colors.

Introduction

Almost everything we have learned about the Universe comes from studying light. In particular, spectroscopy, the splitting light into its component colors, reveals an enormous amount of information, notably the composition of the Universe. Using the Doppler effect, we also can determine the motions and rotations of celestial bodies by measuring the shifts of spectral features.

When the great Issac Newton used a prism to split sunlight into its component colors in 1666, he became the first spectroscopist. In 1802, with a better apparatus, Wollaston discovered that there are dark absorption lines in the solar spectrum; by 1814, Fraunhofer had mapped 576 of these lines. Around the middle of the 19th century, the spectroscope was being applied to stars, nebulae, and galaxies; modern astrophysics had been born.

Three Laws of Spectral Analysis

In 1859, as the result of many laboratory experiments, Kirchoff announced what have come to be called his *Three Laws of Spectral Analysis*:

1. If a solid or liquid (or even a dense gas) is heated to incandescence, it radiates a **continuous spectrum** (Figure 8.1, top), that is, a solid band of colors like a rainbow, ranging from violet at one end to red at the other. By placing a thermometer beyond the ends of this visible spectrum, Newton showed that radiation extends both ways in regions undetected by our eyes.

2. A gas at low pressure can be excited by heat or electric currents to radiate a bright-line **emission spectrum** (Figure 8.1, middle), consisting of sharp lines on a background. Most importantly, the line pattern is uniquely characteristic of the chemical element (or molecule) that it is emitting the photons.

3. If a cooler gas is placed in front of a continuous source, the gas will absorb a pattern of lines similar to those it would emit if it were incandescent. This produces a dark-line **absorption spectrum** (Figure 8.1, bottom) that is also characteristic of the absorbing material. Certain liquids and transparent solids similarly yield absorption spectra that tend to consist of broad bands, rather than sharp lines.

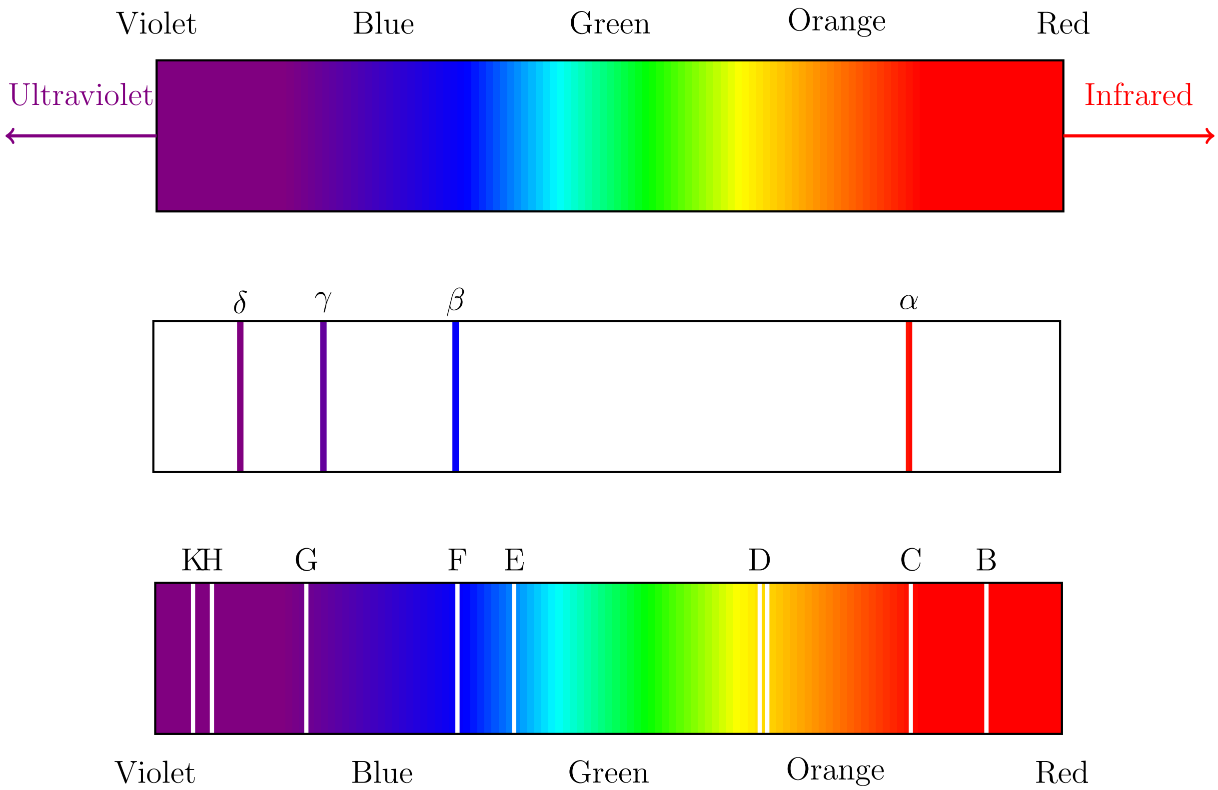


Figure 8.1: **Top:** Continuous Spectrum; **Middle:** Mock hydrogen emission-line spectrum; **Bottom:** Mock absorption-line spectrum for the Sun with some of the Faunhofer lines (white used for higher contrast of the lines).

Laboratory Procedure

Newton and virtually all early spectroscopists used glass prisms to disperse light into its constituent colors. However, large prisms are expensive, heavy, and difficult to mount. Early in the 19^{th} century, Faunhofer invented the *diffraction grating*, a fine pattern of straight lines ruled on a glass or metal surface. Such gratings disperse light through an interference phenomenon described in elementary physics texts. Initially, gratings were also expensive because of the difficulty of ruling thousands of lines per inch, as required to achieve adequate precision. As modern techniques have allowed manufacturers to mass produce a myriad of inexpensive plastic replicas from a single original grating, the diffraction grating has increasingly taken over from the prism in current instruments. The gratings we will be using have 19,000 lines per inch; they were created using the modern technique of holography.

The Prism

Your instructor will have set up a demonstration of dispersion by a prism, using a slit in a slide projector

Notice that the colors are spread out at the blue end of the spectrum and compressed at the red end; such a non-uniform spectrum is (somewhat curiously) termed *irrational.* Conversely, the colors are more uniformly spaced in the *rational* spectrum of a grating. Note also that yellow, of the familiar colors, is represented by a very narrow band in the visible spectrum

The Grating Spectrometer

The simple instrument you will be using was made in our shop. This piece of equipment is a grating spectrometer. As you can see from Figure 8.2, it consists of a narrow slit to admit rays of light from a source, an inexpensive replica grating, and an illuminated wavelength scale to the right of the slit. The numbers on the scale represent the wavelength in hundreds of nanometers (nm); for example, the number 4 on the scale represents 400 nm.

Continuous Spectrum

Your source will be an incandescent tungsten lamp, commonly called a "light bulb". Looking off to the right in your spectrometer, you should see a bright continuous spectrum poised above the wavelength scale. Now move your eye and look off to the left. You will see a similar spectrum in that direction. Diffraction gratings disperse light in both directions. If you look far enough to the right and left, you may even see part of a dimmer "second-order" spectrum. For this lab, you will only be concerned with the "first-order" spectrum to the right above the wavelength scale.

Bright Line Emission Spectrum

Your sources will be glass tubes filled with various low-pressure gases. Neon signs are familiar examples of similar tubes. The gases are excited to radiate by electric currents driven by very high voltages. The tubes also get hot. For both reasons, keep your hands away from the tubes which the power supply is switched on! The tubes are fragile, so please handle them with care when changing them, and to extend their lives, switch them on only while you are making observations. To insure the best results, see that the source is illuminating the slit of your spectrometer as brightly as possible.

A) Hydrogen

Since 90% of the atoms in the Universe are Hydrogen, it appears that prominently in astrophysical spectra. Figure 8.3 depicts the Bohr model of the Hydrogen atom, in which its one electron orbits like a planet around a nucleus consisting of a single proton. Normally the electron stars in the innermost orbit (Also known as the "ground state"), designated by the quantum number $n = 1$. A collision or other event can excite the electron into one of the outer orbits. The electron quickly drops back to the ground state, emitting one or more photons of radiation to make up for the energy it is losing.

Hydrogen radiates several series of bright lines, depending on the orbit to which the electron falls. The lines you will see in the visible spectrum belong to the *Balmer* series, which terminates on the second orbit, designated $n = 2$.

With the hydrogen tube mounted in with the power supply, turn it on and line it up with the slit of the spectrometer. When you look into the instrument, you should see three emission

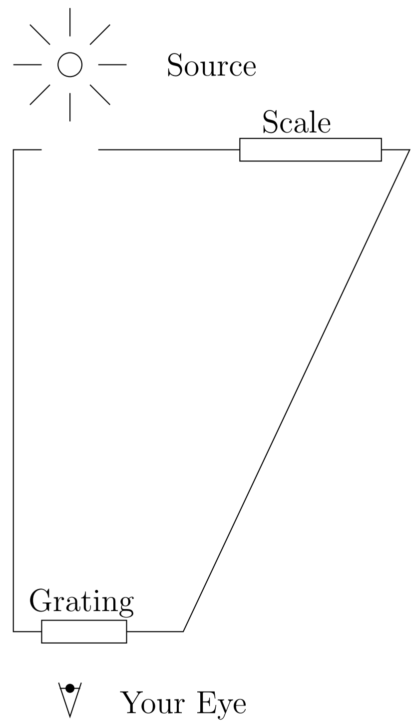


Figure 8.2: The Grating Spectrometer

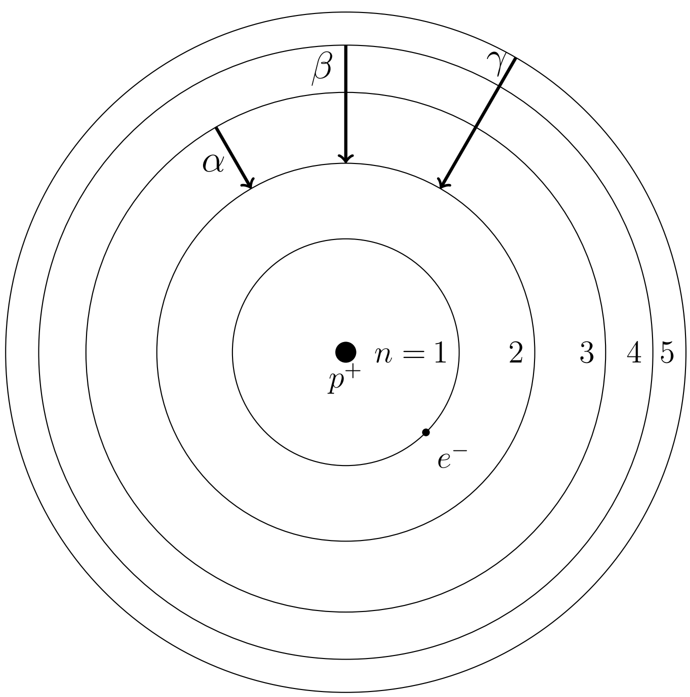


Figure 8.3: Energy levels of the hydrogen atom

lines, which are designated Hα, Hβ, Hγ (shown on the drawing in the previous pages) – you may even see the fourth, Hδ, if you have very good eyesight.

B) Mystery Gas

Your instructor will provide you with another spectrum tube that is unlabelled. Sketch the spectrum that you see and estimate the wavelengths of the lines. Now, compare your sketch and your wavelengths with the spectra on charts available in the lab. Can you identify your unknown gas? The process you are going through is quite analogous to the methods astronomers use to determine the compositions of stars (including the Sun), nebulae, and galaxies.

Absorption Spectrum

If we place a cool gas in front of a continuous light source, such as the incandescent light bulb, we will see an inverted view of the emission line spectrum which is called an absorption line spectrum. Since it is time-consuming and perhaps even hazardous to generate absorbing gases, we will instead view absorption through a broad filter typical of many filters that astronomers use to isolate particular regions of the spectrum for study. In order to view this, your instructor will set up your spectrometer with the filter in front of the incandescent light bulb used in the **Continuous Spectrum** section of this lab.

Astronomical Spectroscopy I Worksheet

Name: ______________________ **Date:** ____________ **Section #:** ______

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

The Prism

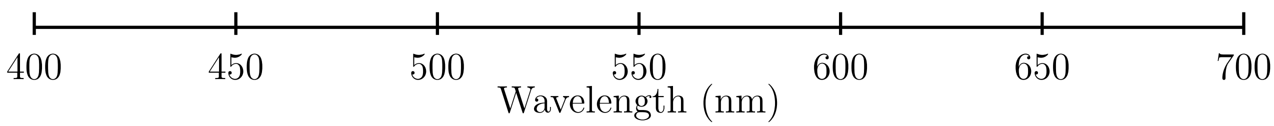
1. Make a quick sketch of the spectrum that you see below:

2. Which type of Kirchoff Spectrum do you see? Based on this, what type of source is the light in the projector?

3. List, in order, the spectral colors that you see

4. Which color is bent (refracted) the most by the prism? Which is the least?

Continuous Spectrum



Graph 8.1

5. Which color is dispersed or "bent" the most by the grating? Which is the least? How does this compare with what you observed with the prism?

6. The visible spectrum is usually described as extending from 400 to 700 nm. What is the shortest wavelength *you* can see? The longest?

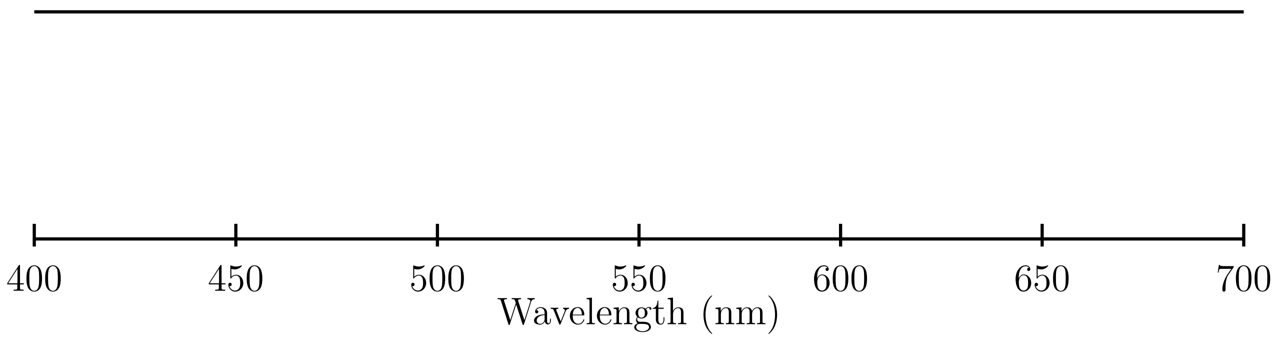
7. A normal human eye has its greatest sensitivity at about 555 nm. What is the color of light at this wavelength? Can you think of any reason why our eyes might have evolved this way?

8. Construct a table of all the colors you can distinguish in the spectrum and write down the wavelength limits of each of these colors.

9. Where, relative to the wavelength scale, would *ultraviolet* radiation be located? Where would *infrared* radiation be located? Label these locations on your sketch

Hydrogen Emission Line Spectrum

Draw a sketch of the spectrum and label the lines with the appropriate Greek letters. Remember that bigger electron jumps correspond to more energetic photons, and that more energetic photons have shorter wavelengths



Graph 8.2

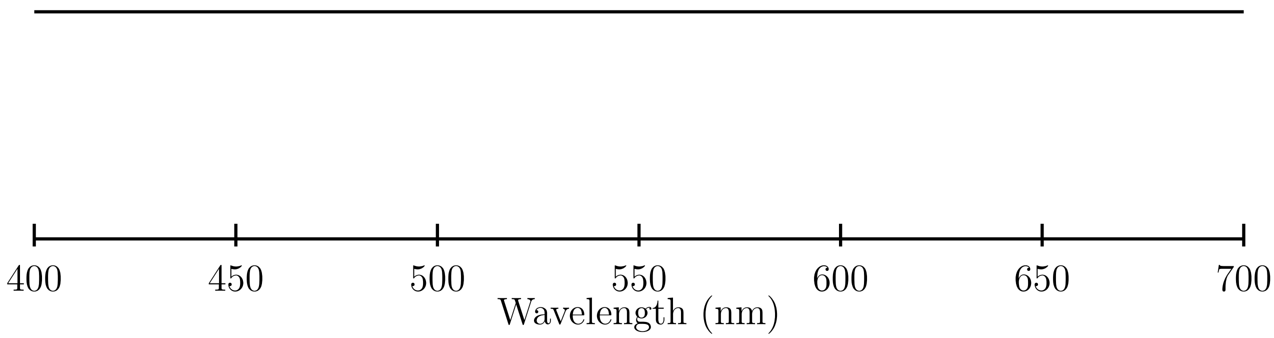
10. How many lines do you see? If you have excellent violet vision, you might glimpse Hδ, a fourth line of the Balmer series occurs near the short-wavelength extreme visible spectrum.. Can you see it? If so, add it to your sketch and estimate its wavelength

11. Estimate the wavelengths of the lines from the wavelength scale. Compare your estimates with the accurately measured wavelengths available from your instructor. How did you do?

12. Why do glowing gases in space, such as in a region like the Orion Nebula, appear certain colors? What key piece of information can astronomers learn by looking at such glowing gases?

Mystery Gas Spectrum

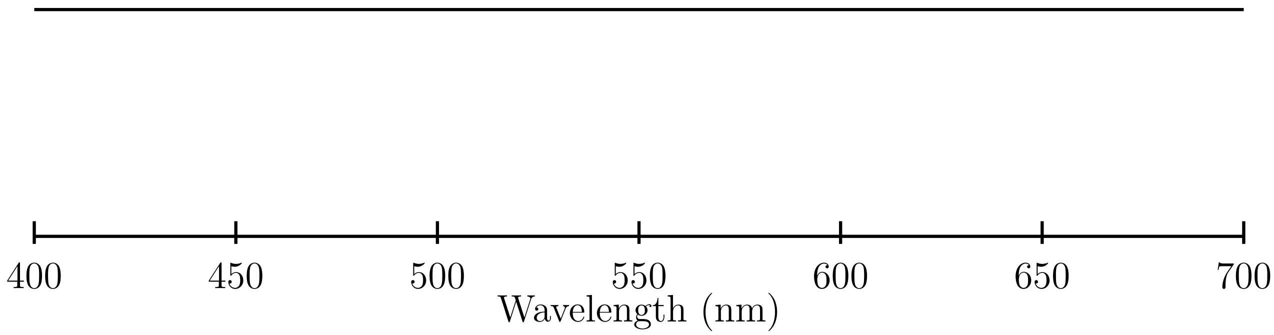
Sketch the spectrum of the mystery gas



Graph 8.3

13. Now, compare your sketch and your wavelengths with the spectra on charts available in the lab. Can you identify your unknown gas?

Absorption Spectrum



Graph 8.4

14. What region of the spectrum does this filter transmit?

Lab 9: Astronomical Spectroscopy II

Purpose

Now that we know what spectroscopy is, let's look at an application within the Sun. The Sun is composed mainly of hydrogen and helium, but astronomers have identified nearly all the chemical elements found on Earth in the atmosphere of the Sun. Helium itself was discovered on the Sun in 1869, 27 years before it was isolated on Earth; the name *helium* was in fact derived from the Greek work for the Sun, *helios*. How is it possible to perform chemical analysis on a body that is 150 million miles away? The answer is that the light from the Sun is analyzed by a spectroscope, an instrument that splits light into its constituent colors or wavelengths.

Introduction

Fraunhofer Lines

The use of spectroscopy began with Issac Newton around 1666. Newton admitted a sunbeam into a darkened room through a round hole. When he passed the beam through a glass prism, the white light was split into a rainbow-like spectrum. Because he used a round hole, his spectrum had low resolution and he saw no details in it. Many years later, in 1802, Williams Wollaston used a narrow slit to define the beam. He noticed four dark lines running across the colored bands. Unfortunately, Wollaston though that the lines were merely boundaries between different colors, and he attached no importance to them. Shortly therafter, in 1814, the noted Munich optician Joseph Fraunhofer not only saw the lines, but made a careful map of 576 of them, assigning letter designations to a dozen of the most conspicuous of them.

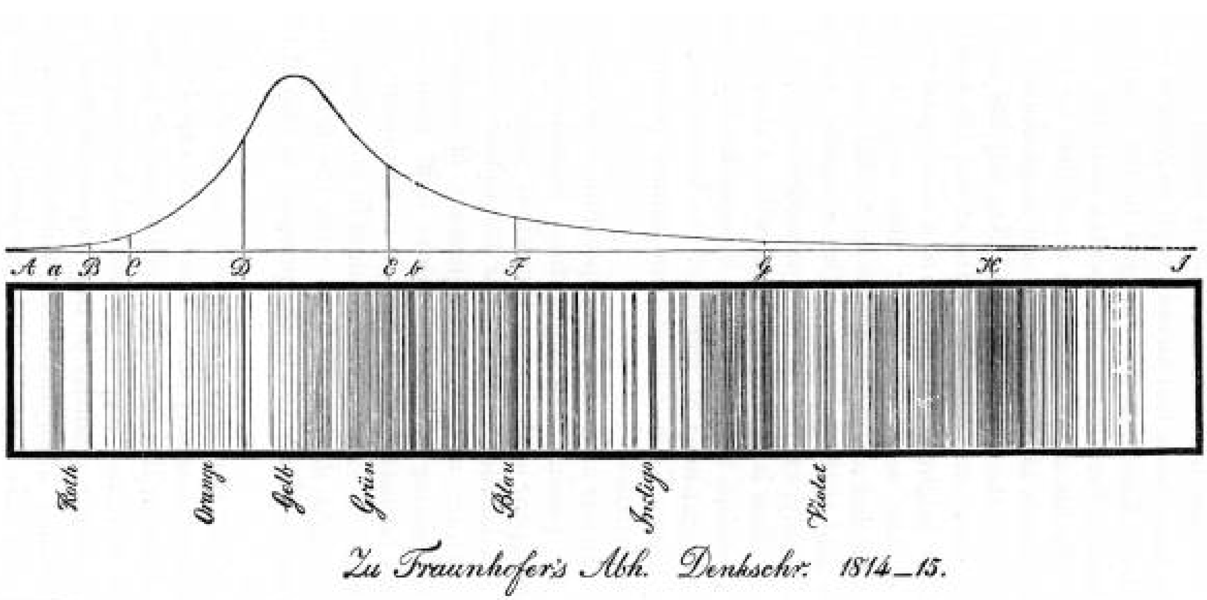


Figure 9.1: Fraunhofer's historic sketch of the solar dark absorption lines, 1814. The curve above is his estimate of the response of the human eye to the various colors.

Thus Fraunhofer achieved the immortality that Wollaston had side-stepped, since the dark lines in the solar spectrum have been known ever since as the *Fraunhofer lines*. Figure 9.1 reproduces one of Fraunhofer's maps, with his letter designation above the lines. Notice that the longer red wavelengths are at the left and the shorter, violet wavelengths are to the right.

The explanation of the dark lines was given in 1859 by Gustav Kirchoff of Heidelberg, Germany. Kirchoff showed that dark lines are produced when an absorbing gas lies between the spectroscope and the source of a continuous spectrum. The continuous spectrum, an unbroken band of rainbow colors, can be produced by an incandescent solid or liquid, or even a gas – at high enough pressure. Kirchoff further demonstrated that the dark absorption lines are characteristic of the chemical elements in the intervening gas. He showed that Fraunhofer "D" line coincides with the wavelength with the yellow emission line of sodium in the lab; ergo, the atmosphere of the Sun must contain the metal sodium. The laboratory spectrum of iron is extremely complex, and Kirchoff succeeded in identifying no less than 60 of Fraunhofer's solar lines with iron. He was similarly able to show the presence of some half-dozen other terrestrial substances in the Sun. It is fair to say that this work in the middle of the 1800's marked the birth of modern astrophysics.

Blackbody Radiation

As you've seen in "Astronomical Spectroscopy I", there are two different types of radiation: absorption and emission. All objects absorb and emit radiation to varying degrees. What governs how much an object absorbs and emits?

For absorption, we define an object's albedo as the fraction of light it reflects. Albedos range from 0 to 1, where an albedo of 0 means that 0% or none of the incident light is reflected, and an albedo of 1 means that 100% or all of incident light is reflected. You probably have intuition about this very effect. If you've ever tried to read a book outside on a nice, sunny day, you've probably noticed that the pages are very bright to look at without sunglasses. Yet, looking at the grass and ground around you, it appears less bright. This is because white paper has a very high albedo (0.7), it reflects most of the incident light, while grass and soil have low albedos (0.25 and 0.17, respectively).

When an object emits light only due to its internal heat and absorbs 100% of the incident light on it (i.e. an albedo of 0), we call that object a perfect blackbody (often referred to as simply a blackbody). "Perfect" indeed implies an idealized construct. There are no such objects in nature. However, some are very close so that referring to them as blackbodies is quite useful. In fact, any opaque object glowing because of its internal heat can be well-described by a blackbody: you, your pet, the Earth, stars, this page, etc.

Figure 9.2 shows the spectrum of a blackbody, the brightness as it continuously varies with wavelength. Notice that the blackbody spectrum peaks in brightness at a certain wavelength. The position of this peak depends only on the temperature of the object. The relationship between the peak emission and temperature is known as Wien's displacement law:

$$\lambda_{\max} = \frac{b}{T}$$

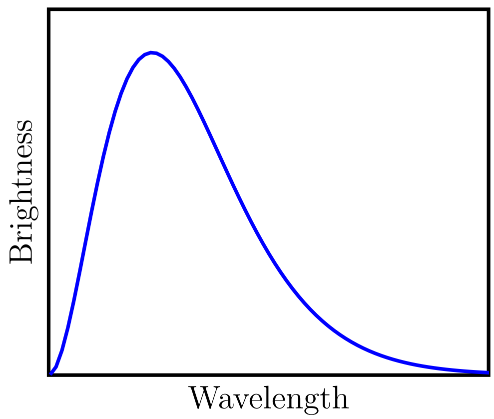


Figure 9.2: Blackbody spectrum sketch

where b is just a constant of proportionality. Because temperature is inversely proportional to the peak wavelength, hotter objects have blackbodies with shorter peak wavelengths. In other words, hotter objects are "bluer".

Since blackbody radiation effectively tells us about the temperature of an object based only on its color, it is particularly useful when applied to stars. For example, the surface of the Sun has a temperature of approximately 5800 K. The peak emission of this blackbody occurs around the green part of the spectrum at a wavelength of around 500 nm.

Interestingly, the curve sketched above the spectrum in Figure 9.1 is Fraunhofer's approximation for the human eye's responsiveness to the different colors. This resembles the blackbody of the Sun through our atmosphere because we have evolved to use this available light, albeit imperfectly.

Light from the Sun

Figure 9.3 shows the basic structure of the Sun. The light energy that we see is generated in the core by fusion reactions, when hydrogen is combined into helium stably under intense pressure. The light then very slowly makes its way out by first scattering or bouncing its way through the radiative zone before being carried through the convection zone in hot rising blobs of plasma (ionized gas) to the photosphere. Since the photosphere of the Sun is the point at which it transitions from opaque and transparent, this is the surface of the blackbody we see.

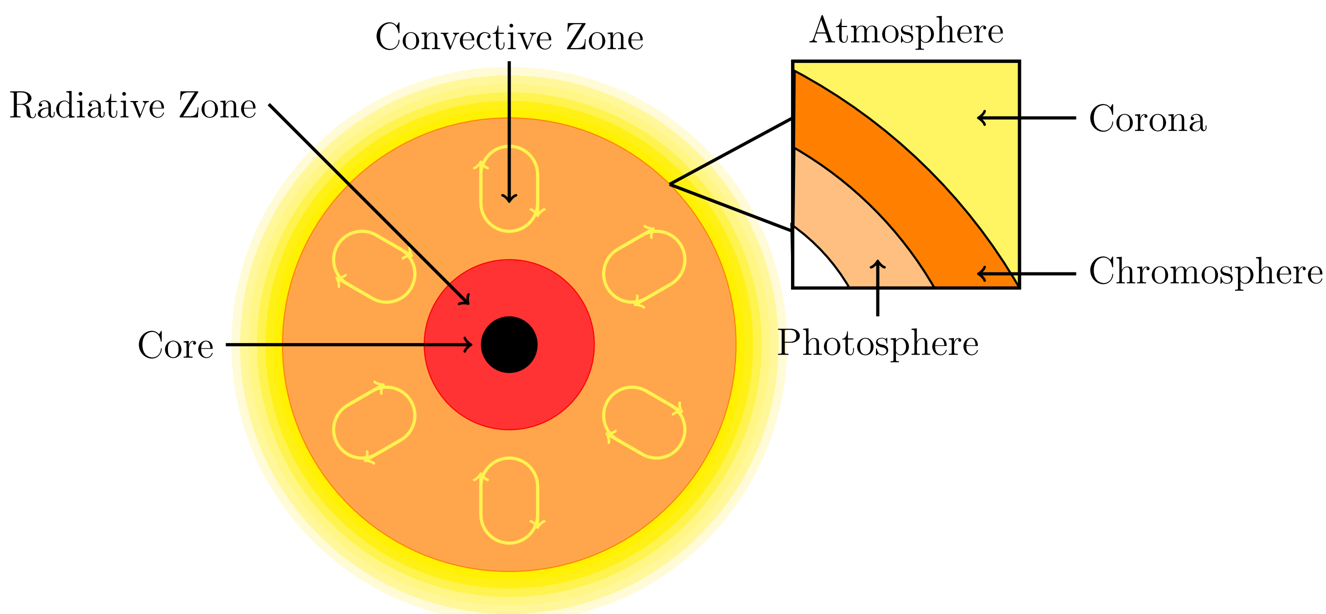


Figure 9.3: Model of the Sun (not to scale)

The Sun's blackbody spectrum must then travel through its atmosphere, which has two layers, the chromosphere and the corona. The corona, the outermost layer, so tenuously extends far out into space that it is rarely noticed (e.g., during a solar eclipse or by a special solar telescope). However, like the atmosphere of the Earth, the chromosphere absorbs some of this light, forming the absorption lines of the Fraunhofer spectrum.

In the same manner as you did for "Astronomical Spectroscopy I", we can use these absorption lines to determine the chemical composition of the Sun!

Laboratory Procedure

Identifying Fraunhofer Lines

Using the reference table below, you will be able to match the wavelength of the absorption lines in the solar spectrum.

Using the lab software:

- Simply press `Generate Spectrum` to see an example of a mock spectrum of the Sun. You will be able to identify a few absorption lines and identify the chemical elements that produce these lines.
- You can click-and-drag over a specific region to zoom in and double-click to zoom out

Write down the wavelengths of each of the lines that you are able to identify. Using the information in Table 9.1, write down the Fraunhofer identification of those lines and the elements that produce those lines.

Wavelength (nm)	**Element or molecule**	**Comment**
393	Ca	Fraunhofer's K Line
397	Ca	Fraunhofer's H Line
410	Hδ	
423	Ca	
431	Fe	Fraunhofer's G Line
434	Hγ	
438	Fe	
486	Hβ	Fraunhofer's F Line
517	Mg	A triplet line
527	Fe	Fraunhofer's E Line
590	Na	Fraunhofer's D Line
656	Hα	Fraunhofer's C Line
686	O_2	Fraunhofer's B Line

Table 9.1: A listing of the more conspicuous Fraunhofer lines, together with the chemical elements or molecules from which they arise

Blackbody Radiation

In this experiment, we will determine the blackbody spectrum by matching curves of different temperatures, a simplified approach to the way real astronomers can determine such temperatures.

Using the lab software:

- Input the desired wavelength into the box at the top of the page. Press `Plot` and a blackbody radiation curve corresponding to that peak wavelength will appear in the plot.
- Use the slider to adjust the green curve to find the temperature that best fits the blackbody emission that you just generated.
- Rinse and repeat for all the desired wavelengths.

Absorption Spectra

As you learned from the "Astronomical Spectroscopy I" experiment, photons can be absorbed by an electron in an atom only if they have the right energy to make the electron jump from its original level of energy to one of the discrete higher levels.

In this experiment you will be sending photons of different energies (given in electron volts or eV) through a gas. Depending on their energies, the photons can pass through the gas or can be absorbed by the atoms in the gas.

Remember that the energy of a photon E_{photon} is related to the wavelength λ. For each value of energy of a photon there is an associated wavelength. The exact relationship is:

$$E_{\text{photon}} = \frac{hc}{\lambda}$$

(h is 6.626×10^{-34} J/s, c is the speed of light 3×10^8 m/s).

Important Note: In order to successfully convert from electron volts (eV) to nanometers, you first need to convert the energy to joules! There are 1.602×10^{-19} Joules in 1 eV.

Using the lab software:

- Your instructor will assign you a mystery gas, use the menu to select which one the simulation uses.
- Use the slider to set the photon energy to 1.6 eV.
- Input the number of photons to send through the gas (we recommend you use 15-20). Keep the number of photons constant for the rest of the experiment. Click on `Start!`. Once the simulation ends for the 1.6 eV energy, record in the provided table the energy, color, wavelength and number of photons detected.
- Increase the energy of the photons by 0.1 eV to 1.7 eV and repeat the simulation. Continue with the process increasing the energy in steps of 0.1 eV until you complete the table.

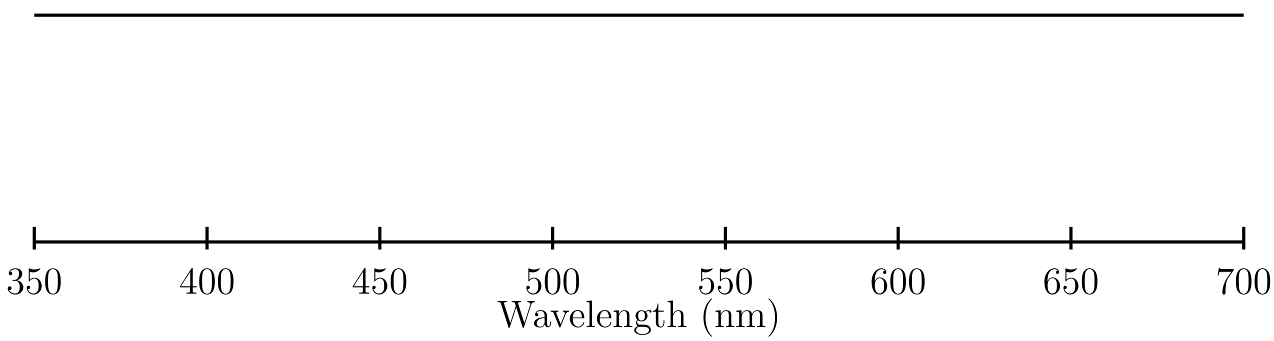
Astronomical Spectroscopy II Worksheet

Name: ______________________ **Date:** ____________ **Section #:** ______

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

Identifying Fraunhofer Lines

1. Use the blank spectrum outline below to draw in the Fraunhofer lines that you can identify, being careful to place them at the appropriate wavelengths. Write the wavelenghts on the drawing.



Graph 9.1

2. Table 9.1 has a listing of of the more prominent Fraunhofer lines, with their chemical identification. Using the table, identify each of the lines that you draw, writing their chemical symbol

3. Where on the Sun does the continuous spectrum arise? Why?

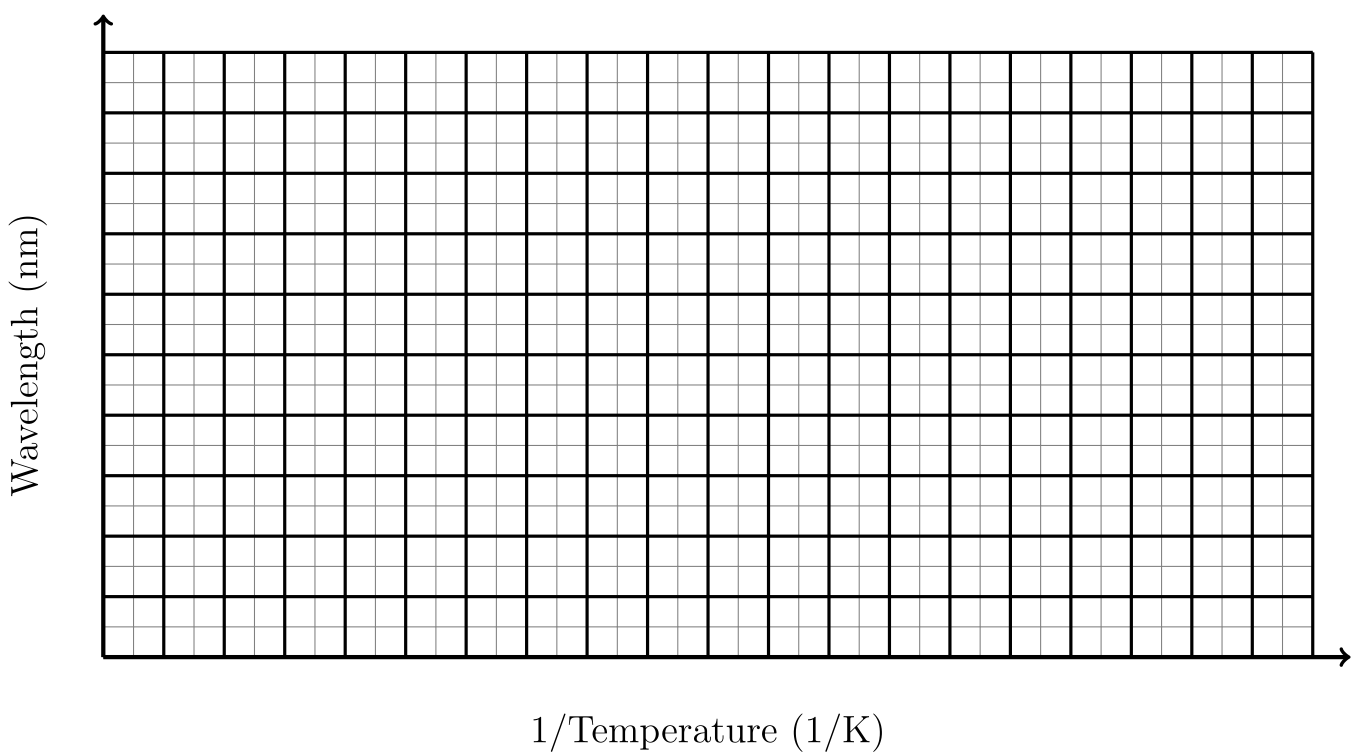
4. Where on the Sun do the Fraunhofer lines arise? Why?

Blackbody Radiation

For this next experiment, we will reconstruct Wien's Law

Data Table 9.1

Wavelength (nm)	**Temperature (K)**	**1/Temperature (1/K)**
300		
350		
400		
450		
500		
550		
600		
650		
700		



Graph 9.2

5. Draw a best-fit line for the data points. What is the slope, using rise over run ($\Delta y/\Delta x$), of this best-fit line?

6. Ask your instructor for the actual value of b from Wien's Law. Calculate the percent error of b to ascertain the accuracy of the best-fit line. What is a potential source of error?

7. Numerically solve for the peak wavelength of the Sun (given that temperate of the photosphere of the Sun is 5,800 K) using the true form of Wien's Law.

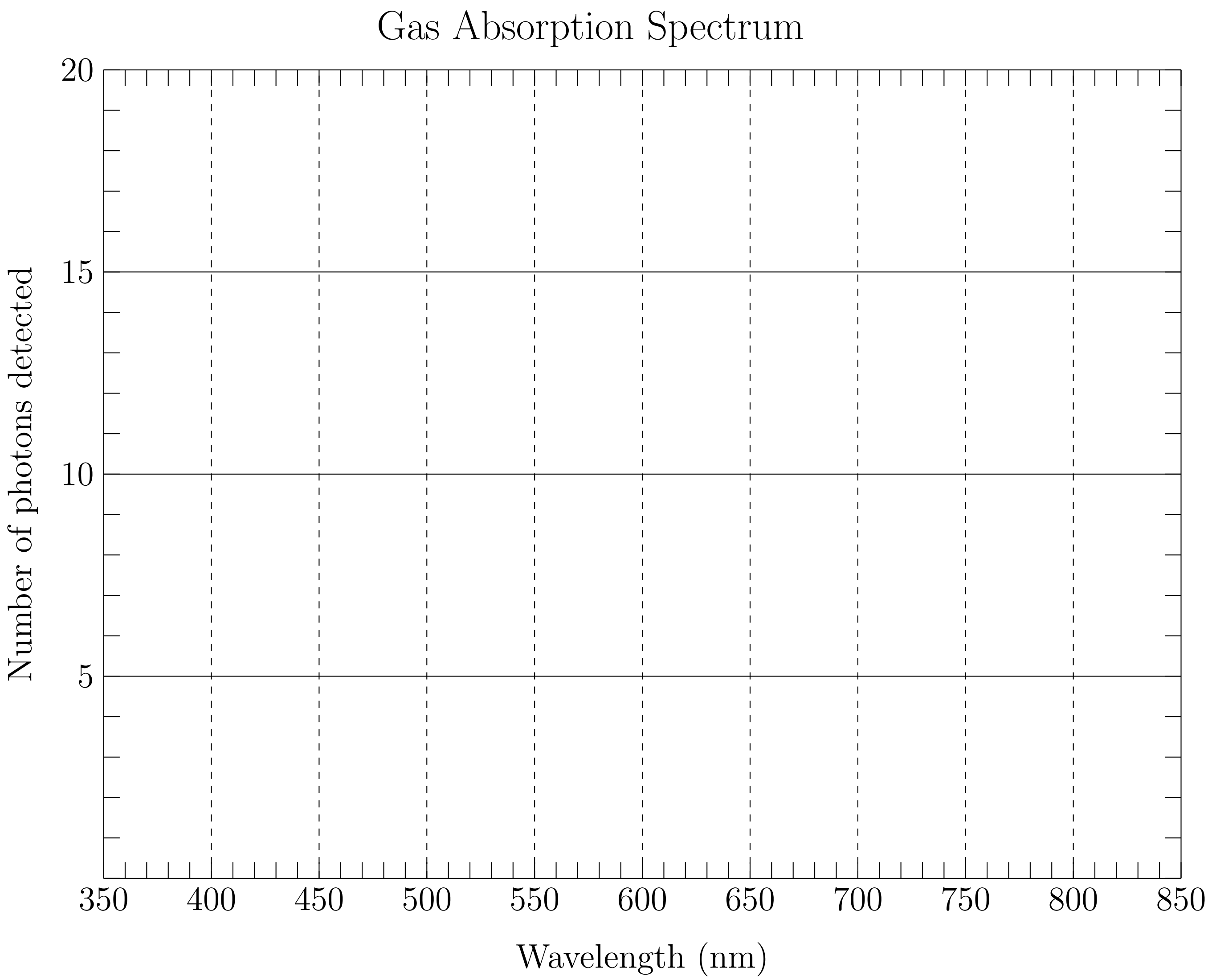
Absorption Spectra

For this next part, we'll be examining the absorption lines that are produced by a cool gas being backlit. Select whichever element you like, but make sure the denote which element you used.

Mystery Gas Used: ______________

Data Table 9.2

Energy (eV)	**Energy (J)**	**Wavelength (nm)**	**Color**	**Photons Detected**
1.6				
1.7				
1.8				
1.9				
2.0				
2.1				
2.2				
2.3				
2.4				
2.5				
2.6				
2.7				
2.8				
2.9				
3.0				
3.1				
3.2				
3.3				
3.4				
3.5				



Graph 9.3

8. Look at the spectra for the mystery gases. What is your mystery gas?

Applications of Astronomical Spectral Analysis

Guidelines for Writing the Report

In this report you will summarize the results from two experiments dealing with spectroscopy: “Astronomical Spectroscopy I” and “Astronomical Spectroscopy II”. An important part of this report is applying what you learned from these two experiments and also making use of concepts we learned from other experiments to explain how you will solve the related problem proposed at the end of these instructions.

You must submit your own work. You can collaborate and exchange ideas with your lab partners, but do NOT copy and paste, your work must be entirely your own. Your submissions will be checked by Turnitin.

In “Astronomical Spectroscopy I”, the key concepts you learned about were:

- Learned about the basic principles of spectroscopy, including Kirchoff’s Laws, and applications of spectroscopy in astronomy, like identifying elements based on their emission lines.

In “Astronomical Spectroscopy II”, the key concepts you learned about were:

- Applied the concept of spectral line identification to identifying absorption lines in the Sun’s spectrum, which correspond to chemical elements in the Sun.
- Used blackbody curves to reconstruct Wien’s Law, the relationship between the temperature of a body and the wavelength that it emits.
- Learned how photons interact with matter, i.e. that photons of different energies are absorbed by a gas of a particular element, which explains why certain emission lines occur uniquely for each element.

Your report should contain all of the following sections, in this order, with **headers**

1.	Abstract	(5 points)
2.	Introduction	(10 points)
3.	Discussion of Physical Concepts	(10 points)
4.	Methods and Purpose	(20 points)
5.	Data	(10 points)
6.	Discussion	(20 points)
7.	Applications – Design an experiment	(10 points)
8.	Conclusions	(10 points)
9.	Original Data Sheets attached	(5 points)
Total		100 points

Since this report compiles different labs, read through this lab guide carefully. If you’re unsure of the requirements of this report, please ask your instructor for clarification as soon as possible.

How to Address Each Section:

Abstract (5 points)

An abstract is just a brief overview/summary of the work. This section should be a very brief overview of the what we're doing and what we achieved. In general, this section should be $\sim$150 words, but I won't hold you to exactly that number. Be succinct and get your point across.

Introduction (10 points)

Specify that this report is about the concepts and applications of spectroscopy we learned about in the three labs. Focus on the big picture of spectroscopy - what are some cool astronomy problems that can be solved using spectroscopy (exoplanet detection, stellar composition, etc). Then introduce the reader to the basics of spectroscopy. Leave the specifics to the summary of physical concepts section.

Discussion of Physical Concepts (10 points)

Discuss the concepts introduced and lab and explored within the experiments. I don't expect equations for these concepts, but explain the concepts in the context of what we learned about in class.

- What are the three Kirchoff's Laws? Give some examples of objects that would have spectra classified by each law.
- What is blackbody radiation? How is it related to a continuous spectrum?
- What is Bohr's model of the hydrogen atom? How is it related to emission and absorption lines?

Methods and Purpose (20 points)

Explain the methods your group used during the experiments. This should not be a paraphrase of the lab manual procedures. Explain the purpose of each experiment - what did the experiment reveal about spectroscopy? Think about why you did each experiment (not just that you had to do them because the manual said so).

- What instruments were used in each lab (i.e. prism/spectrometer/computer, types of lamp and filters, method of wavelength/color identification)?

- What kinds of spectra did you view and what kind of information did you record about the various spectra?
- How did you run the photon experiment and what did it model?

Data (10 points)

Type/computer generate all tables and plots with the data collected during class. Make sure you are using the appropriate plot type (scatter) for the given data and that your data points are actually represented on the plot (not just a line).

Tables

1. (Spectroscopy I) Table of hydrogen lines observed with the spectrograph. Include names (i.e. Hα), measured wavelength of the emission line (nm), actual wavelength of the line (nm), and percent error comparing measured with actual wavelength.
2. (Spectroscopy II) Table of absorption lines in the solar spectrum. Include the measured wavelengths of the absorption lines, Fraunhofer denominations of the lines, the chemical element producing the lines, the accepted wavelengths of the lines, and the percent error of the measured wavelengths.
3. (Spectroscopy II) Table of energies, wavelengths, colors, and number of detected photons for the absorption spectra.

Plots

1. (Spectroscopy II) Wavelength versus the inverse of temperature for Wien's Laws
2. (Spectroscopy II) Plot the # of photons detected vs. photon energy or wavelength.

Discussion (20 points)

Error Analysis (10 points):

- How accurate are your wavelength measurements? Discuss the percent error of your calculations.
- What are possible sources of error in these experiments? Remember to consider the tools and techniques used for the experiments. Errors are not math mistakes/rounding precision, nor is it (typically) valid to suggest the rulers/lab equipment are manufactured incorrectly.

Questions (10 points total):

1. (4 points) Explain, in terms of Kirchoff's Laws, how the Sun has absorption lines on top of a continuous spectra. Consider how each component of the spectra (continuous and absorption lines) are produced by the Sun.
2. (2 points) What is the difference between the dispersion of light by a prism and the dispersion of light by a diffraction grating? What color is dispersed the most/least by each method?
3. (2 points) Why does each element (like hydrogen, sodium, neon, etc.) have a unique spectra, different from any other element?
4. (2 points) The normal human eye is most sensitive to light with wavelengths around 555 nm. Why?

Applications – Design an experiment (10 points)

With our understanding of telescopes, CCD cameras, and spectroscopy in hand, we are now equipped to do real science. In this section, we will design an experiment to determine the chemical composition of a star with an apparent magnitude of +14. Describe the procedure by which you will accomplish this, justifying the tools and methods used. Use the following points to guide your thinking, but be sure to extend your thinking beyond these points.

- Considering the brightness of this star - can we see it with our eyes?
  - What is the minimum size aperture we need to view this star and collect its light?
- What is a method to identify the chemical composition of a star from its light?
  - What tool(s) can we use to achieve this?
- How can you identify the various features of a spectrum and the elements responsible for those features? Is there some sort of calibration you can do with our detector prior to the experiment?
- What are some potential problems you can run into with your experiment design?

Conclusions (10 points)

Summarize the basic principles of spectroscopy and why spectroscopy is important in astronomy. Discuss how the experiments you conducted gave you an understanding of spectroscopy and how the basic activities done during class can be expanded into actual research being done.

Attach Data Sheets at the End (5 points)

- (Spectroscopy I) The 5 spectra diagrams that you've sketched

- (Spectroscopy II) The diagram of the solar spectrum with Fraunhofer labels
- (Spectroscopy II) Wien's Law Table
- (Spectroscopy II) The diagram of wavelength versus the inverse of temperature from the blackbody curves
- (Spectroscopy II) Absorption Spectrum Table

Lab 10: Measuring The Hubble Constant

Purpose

This exercise is a computer simulation that is intended to give you a feeling for the operation of a computer-controlled spectrometer attached to a large telescope. It will provide experience in the use of a computer for scientific purposes, and it will familiarize you with the parameters and problems involved in the measurement of one of the most important quantities in all of astrophysics. You, too, can be a cosmologist!

Introduction

In 1931 the American astronomer Edwin Hubble announced what many feel is the greatest discovery in modern astrophysics. Now known as Hubble's Law, the discovery states that the external galaxies are receding from the Earth with speeds that increase with distance; if a galaxy is twice as far from us, it is receding twice as fast. This discovery is the basis for the concept of the expanding Universe, and indeed for all modern cosmology – that is, theories of how the present Universe came into being. To refine such theories, we need to know the Hubble Constant, which is simply the relationship between distance and speed; how fast is a galaxy at a given distance running away from us? The most powerful tool for answering this question is the Doppler shift, the change in the apparent wavelengths of the lines of a spectrum due to the velocity of the source relative to the observer.

In Figure 10.1, we are seeing mock spectra of light which emulate some taken from a spectrograph (see "Astronomical Spectroscopy"). As you learned in Lab 4: Light is A Wave, photons emitted by a source are just electromagnetic waves flying through space at the speed of light. As the light

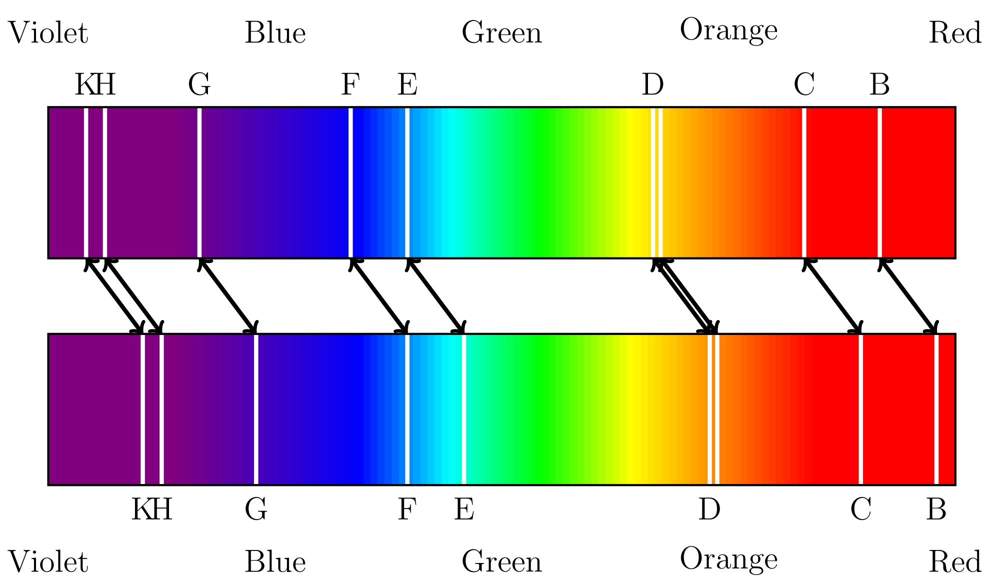


Figure 10.1: Mock Spectrum demonstrating the redshift effect

travels, it encounters many things: dust, gas, nebulae, etc. These structures are cold regions of gas being back-lit by some source.

Once the light encounters cold gas regions these regions, some light corresponding to the specific wavelength is absorbed by the atom (this is because the energy needed to excite atoms is quantized – it must be a specific, discrete value). This is what we see the in the top panel of the diagram. Most of the light that is incident on us from the galaxy has traveled through these regions without being absorbed, but a significant amount that could have been absorbed were. Now, because this physics works in all places of the universe, we can know what wavelength of light is necessary to excite specific atoms through lab tests (extremely similar to what you did in Lab 8: Astronomical Spectroscopy I). Therefore, we can observe spectra from distant galaxies and learn about the chemical composition!

There is a small wrinkle in this whole process though - when we observe distant galaxies, none of the lines are where we would expect them to be. In fact, they have all shifted over by the same amount towards redder frequencies. This is a direct consequence of Hubble's measured expansion of the universe. As the photons travel immense distances throughout space, space itself is expanding causing the wavelengths of the photons to expand as well. This effectively makes the photons appear "redder" than they originally would and causes the effect demonstrated in the bottom panel of Figure 10.1.

This effect is known as redshift and is a highly useful tool for astrophysicists in describing how far away distant objects are from our galaxy. In this lab, we will be investigating this very effect and measuring the distance to some real galaxies in a nearby cluster in order to estimate the expansion rate - as well as age - of the universe!

Laboratory Procedure

This exercise is a computer simulation of the operation of a spectrometer attached to a major telescope in taking and measuring the spectra of distant galaxies.

Determining the Recession Speeds of Galaxies

In Figure 10.2, we can see a real spectrum of the galaxy M31 (more commonly known as the Andromeda Galaxy). There are two big dips in the relative intensity at two different wavelengths. The H line is the one on the right and the K line is on the left. You will use the ALEX Labs software to examine these different atomic lines in distant galaxies. When you are performing your analysis, you should notice that these lines are redshifted over by a certain amount! (Note: in Figure 10.2, the lines are actually *blue*-shifted because the Andromeda Galaxy is moving towards us!)

Once you have the wavelengths of the H and K lines for several galaxies. How do you convert these to speeds? The laboratory wavelengths (wavelengths at rest) of the H and K lines are, respectively, 3969 and 3934 Angstroms. Subtracting the laboratory wavelength from your galaxy wavelengths will give you the shift in wavelength, $\Delta\lambda$, of each of the two lines.

With this shift in wavelengths, you can obtain something that looks similar to an error calculation for the wavelengths: $\Delta\lambda/\lambda_{\text{lab}}$. The ratio $\Delta\lambda/\lambda_{\text{lab}}$ is what astronomers refer to as "the redshift". For some reason, this quantity is always designated by the letter z.

To obtain the speed of recession v we use the following relation:

$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda_{\text{lab}}}$$

where v is the recession speed, c is the speed of light (3×10^5 km/s), $\Delta\lambda$ is the shift in wavelength, and λ_{lab} is the laboratory wavelength. In addition to calculating v, also calculate z for each of your galaxies. At this point, you now have the speeds of recession for the galaxies you measured.

Determining Distances of Galaxies

Determining how distances to far away galaxies represents the greatest uncertainty in determining the Hubble Constant. For this reason, our understanding of the Hubble Constant has changed dramatically over time. In fact, Hubble himself first calculated the value to be around 500 km/s/Mpc, which is almost 10 times as fast as the modern accepted value!

Take the absolute magnitude of each galaxy as -20 (note that this is a crude approximation). In the previous step, you were given the apparent magnitude of the galaxy as well. Having both the apparent and absolute magnitude of an object will give you a clue as to its distance. The

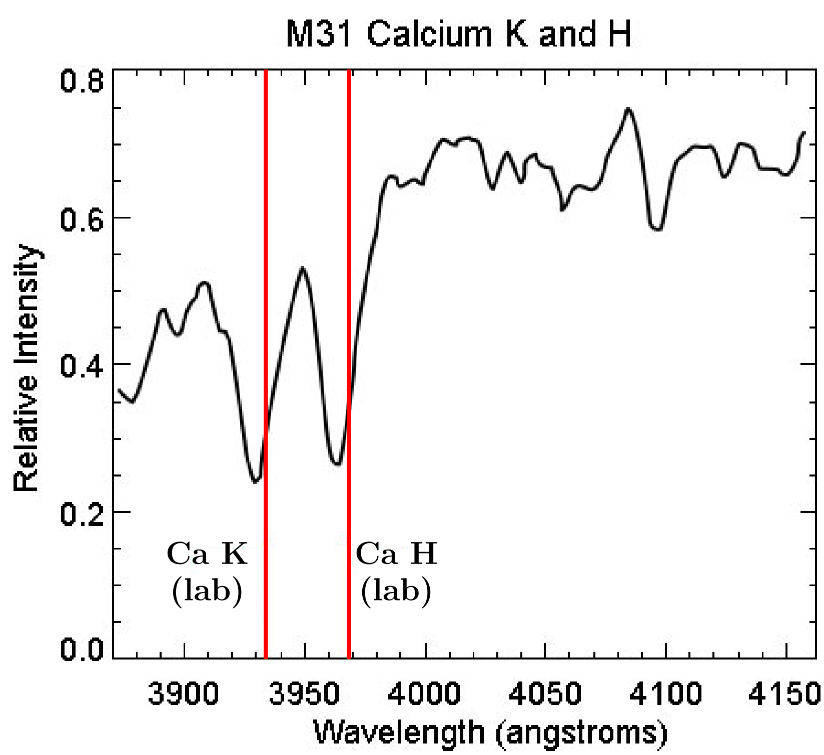


Figure 10.2: Example spectrum of M31 galaxy, courtesy of NASA Goddard Space Flight Center (slightly modified)

mathematical relationship (often called the "distance modulus") can be written as

$$\log d = 1 + (m - M)/5$$

where d is the distance in parsecs (one pc = 3.26 light-years, for scale), m is the apparent magnitude, and M is the absolute magnitude. If you have trouble with the log, your instructor will show you how easily it can be handled on a simple hand-held calculator. You now have the distance and speed of recession for each of your galaxies.

Calculation of the Hubble Constant

As we noted earlier, the Hubble Constant H is simply the relationship between speed and distance:

$$H = \frac{v}{d}$$

You measured v in the first part and calculated d in the second part. Perform the necessary division of one by the other, and voila! have a value for the Hubble Constant (note: you should obtain values for each cluster).

Measuring The Hubble Constant Worksheet

Name: ____________________ **Date:** ____________ **Section #:** ______

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

Through all of these calculations, take the speed of light to be $c = 3 \times 10^5$ km/s.

Observational Data

Data Table 10.1

Name of Galaxy			
Apparent Magnitude m			
λ_K of K line (left line)			
λ_H of H line (right line)			
Integration Time (seconds)			

Calculation of Velocity

Data Table 10.2

Name of Galaxy			
$\Delta\lambda_K = \lambda_K$-3934			
$\Delta\lambda_H = \lambda_H$-3969			
Redshift K: $z_K = \Delta\lambda_K/3934$			
Redshift H: $z_H = \Delta\lambda_H/3969$			
Velocity K: $v_K = cz_K$			
Velocity H: $v_H = cz_H$			
Avg Velocity: $(v_K + v_H)/2$			

Calculation of the Hubble Constant

Data Table 10.3

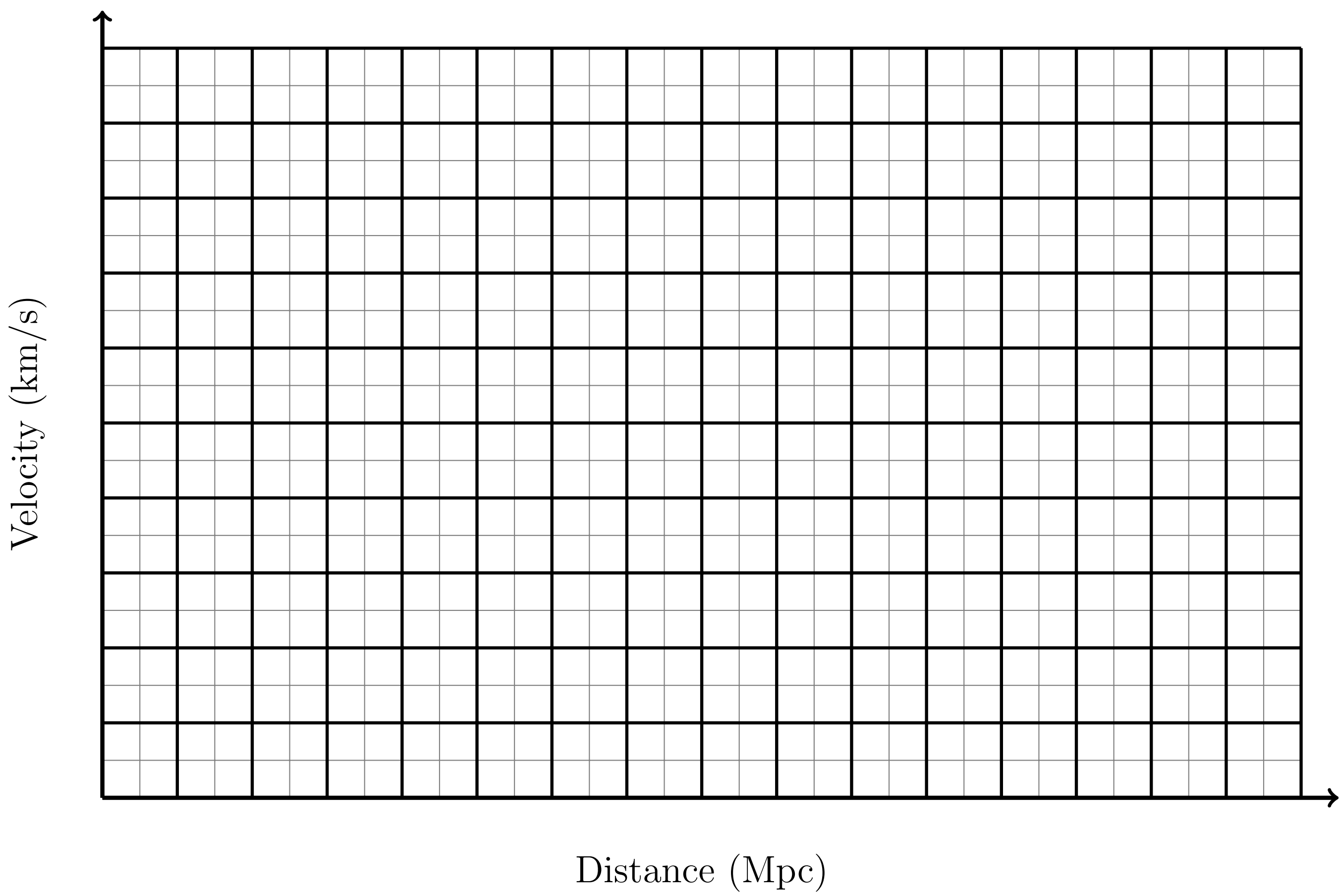
Name of Galaxy			
Apparent Magnitude m			
Absolute Magnitude M	-20	-20	-20
$m - M$			
$\log d\ [= 1 + (m - M)/5]$			
d in pc			
d in Mpc			
$H = v_{\text{avg}}/d$ (km/s/Mpc)			

H_{avg}	

Discussion Questions

1. In recent years, various astronomers have argued for values of H ranging from 65 to 75 km/s/Mpc. How does your result for H_{avg} compare with these values? Does it lie within this "accepted" range? Assume an "accepted" value of 70 km/s/Mpc and calculate the percentage error of your experimental value of H_{avg}.

2. Create your own Hubble diagram below. Note that for $d = 0$ you can assume $v = 0$. Does your diagram look reasonable? Do your points lie more or less on a straight line? Calculate the numerical value of the slope. How does it compare with the value obtained for H_{avg}?



Graph 10.1

Extra Credit: We know how fast the galaxies are receding, and how far apart they are now. If we imagine time running backward, it is evident that at some time in the past all the galaxies must have been jammed together at one location in space. The moment at which the recession began is referred to as the "Big Bang". How long ago was this?

Surprisingly, this age of the Universe is simply equal to the reciprocal of H, or $1/H$! Use your value of H to calculate the age of the Universe in years (Hint: be very careful with units!)

Lab 11: You Can Weigh Jupiter

Purpose

How can we measure the masses of such distant bodies? The answer is that we really have only one method of "weighing" astronomical bodies; we must observe the gravitational effect with some other body. When we weigh ourselves on a bathroom scale, we are actually measuring how hard the scale has to push on our body to hold it in place against the Earth's gravity!

The objective of this computerized experiment is to acquaint you with the way in which astronomers determine the masses of remote bodies such as planets and stars.

Introduction

Let's consider a planet orbiting the Sun. The orbit is stable only because the the Sun's gravity redirects the object from otherwise moving in a straight line (Newton's first law of motion). If the planet were to stop, it would immediately fall toward the Sun! If the Sun were more massive or if the planet were closer to the Sun, the planet would have to orbit faster to resist the increased force of gravity. This implies a relationship between the mass of the Sun, the size of the planet's orbit, and the planet's speed in that orbit.

Orbital Motion

Johannes Kepler was the first to give a mathematical form to this relationship. Kepler came up with his three laws of orbital motion. His third law, formulated in 1618, related the distance of a planet to the Sun, a, to the time it takes to complete one orbit, T (also known as the orbital period). Kepler found the following relation where T is expressed in years and a is expressed in astronomical units (AU – defined by the Earth's average distance to the Sun):

$$T_{\text{years}}^2 = a_{\text{AU}}^3$$

Kepler's third law was purely empirical - that is, it was based on fiddling with the parameters until something worked out. A half-century later, the great Issac Newton used his laws of motion and gravitation to derive a far more general version of Kepler's harmonic law that was now based on physical understanding of the problem. Because Newton's version included the mass, M, of the central body, the law could now be applied not only to planets orbiting the Sun, but also to satellites orbiting the planets, and even stars orbiting each other. Let's go through a quick sketch of a Newtonian argument for Kepler's Third Law:

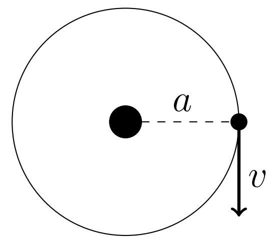


Figure 11.1: Circular orbit

The distance that an object traveling in a circle (sketched in Figure 11.1) moves is just the circumference of the circle, given by $C = 2\pi a$ (where a is the radius), therefore we know that the velocity, v, which is distance over time, can be expressed as the total distance for one orbit divided by the period of the orbit:

$$v = \frac{2\pi a}{T}$$

Additionally, from any introductory physics course, we know that the centrifugal force exactly balances the force of gravity in circular motion:

$$F_{\mathrm{grav}} = \frac{GMm}{a^2} = F_{\mathrm{c}} = \frac{mv^2}{a}$$

We can combine these two equations by seeing that the distance between the two objects in the force equations is just a in our diagram. Then, we can substitute in the velocity:

$$\frac{GMm}{a^2} = \frac{m(2\pi a)^2}{T^2 a}$$

Solving for T we obtain our desired expression:

$$T^2 = \frac{4\pi^2}{GM} a^3$$

As a matter of brevity, Newton's Law is often written as the following, with M typically being expressed in unit of solar masses:

$$T^2 = \frac{a^3}{M}$$

Newton himself used this to estimate the masses of Jupiter, Saturn and the Earth, the only planets known at the time to have satellites. Due to the poor quality of the available measurements, his results were not very accurate. Hopefully, we can do better.

We will use Newton's equation to measure the mass of the giant planet Jupiter, a mass so large that it greatly exceeds the masses of all the other solar system planets combined. The key to our experiment lies in the fact that Jupiter has four moons that are so bright they can be glimpsed with a good pair of binoculars. These satellites were discovered by the Italian scientist Galileo in January of 1610, soon after he turn the first astronomical telescope on the heavens.

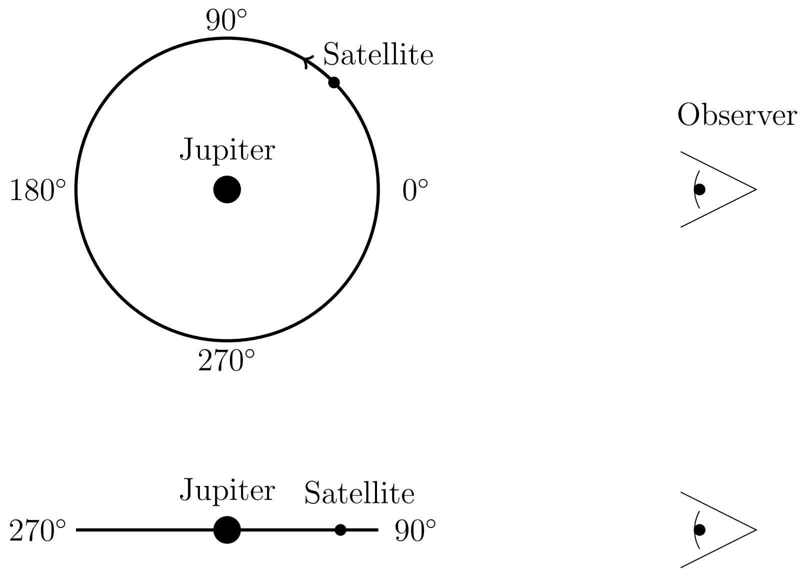


Figure 11.2: Two visualizations of the orbit of a moon of Jupiter. The top is seen from above, and the bottom is an edge-on orientation.

Sinusoidal Motion

We, as observers, are nearly in the plane of the satellite orbits, we see each moon oscillating from one side of Jupiter to the other, almost in a straight line (see Figure 11.2 for two different perspectives of the single orbit). The apparent distance, a, of the moon from the center of Jupiter follows a sinusoidal curve as illustrated on the second figure. ("Sinusoidal" is from the Latin *sinus*, meaning a bend or semicircular fold.) When the moon is in front of Jupiter (0°), $a = 0$. As the moon moves from 0° to 90°, a increases steadily from 0 to 1. Then a decreases smoothly as the moon moves from 90° to 180° where $a = 0$ again. Between 180° and 360° the curve simply repeats itself, but in the opposite direction. Many natural phenomena follow sinusoidal curves: sound waves, vibrating musical strings, radio waves, electrical currents and voltages, oscillating springs, etc. An example sine curve is show in Figure 11.3 with the inner regions of the orbit not filled in as the moon passes behind Jupiter during this time.

Laboratory Procedure

Please DO NOT modify, create, or delete any files on the computers unless EXPLICITLY told to do so by your instructor

In this section, we will detail how the steps necessary in completing this lab. Your instructor will also provide you with guidance.

1. Navigate to the ALEX Labs "You Can Weigh Jupiter" link.
2. You should see a page with the orientation that the planets will be in during our observation window. This orientation is known as opposition, where the two planets are on the same side

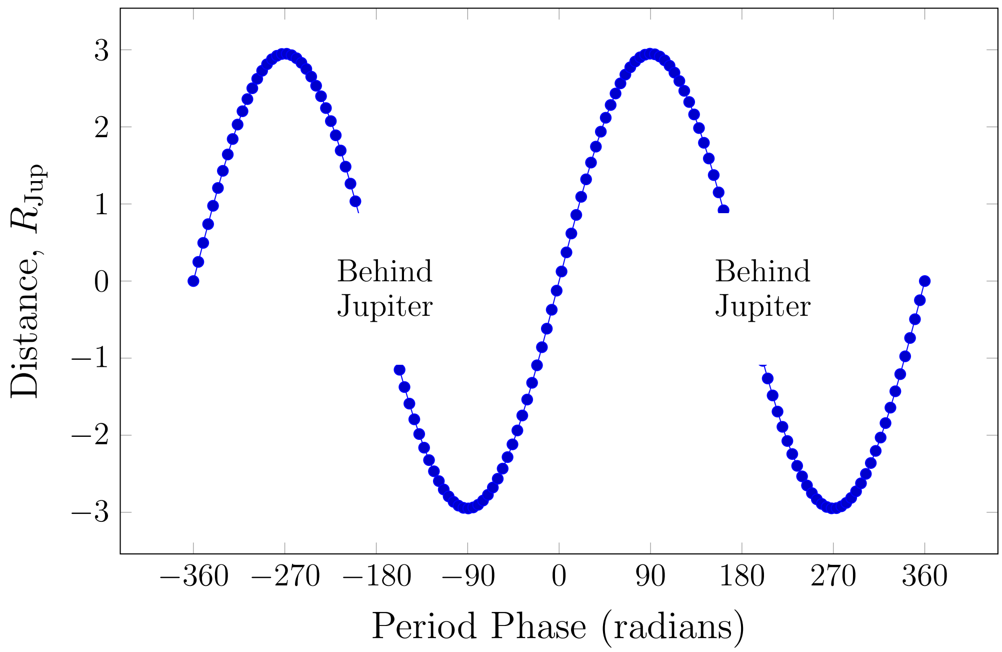


Figure 11.3: Example fine-resolution curve of what an observer would see for an edge-on inclination of the orbit of a moon around Jupiter. The reason there are no data points between -1 and 1 is because the moon is behind the planet during this phase of its orbit.

of the sun. Once you've figured out how far apart the two planets are, click on the `Start!` button.

3. You are now on a page with information regarding all four of the Galilean moons of Jupiter. Your instructor will assign you moon(s) to examine during this activity. As you read about the moons, note the colors as they will appear in the simulation.
   - Io is orange
   - Europa is red
   - Ganymede is green
   - Callisto is blue
4. Navigate to the bottom of the webpage and select `Start!`
5. We're now almost ready to take data. Based on Table 11.1, use the top slider to set the time-step of the observations

Moon	**Recommended Time-step** (hours)
Io	3
Europa	5
Ganymede	10
Callisto	22

Table 11.1: Recommended time-steps for the four Galilean moons. **Note:** You may deviate slightly from these if you so choose, but doing so lead to not obtaining a full period in your data or fine enough resolution!

6. Using the second slider, you can zoom into the picture for more accurate data-taking.

7. You are now ready to collect data! To get the positions of the moon, all you need to do is click on it in the picture and it should populate the **bottom of the screen** with the X-position on the picture in arcseconds, with respect to the center of the image.

    - The positions from Jupiter have either positive or negative. The sign simply denotes which side of Jupiter the moon is on, left being negative.

8. Once you've recorded the first data point into Data Table 11.0, you can advance the simulation to the next time-step by simply pressing the `Next Timestep` button. Continue to do this until you run out of spaces in your table. If you miss a position, simply press the `Back One Timestep` button to go back.

9. Once Data Table 11.0 is completely filled in, create the sine-curve graph corresponding to the moon(s) you observed. From this, and some simple unit conversions, you can estimate the mass of Jupiter.

You Can Weigh Jupiter Worksheet

Name: ______________________________ **Date:** ________________ **Section #:** ________

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

Introductory Questions

1. When Jupiter and Earth are in opposition (as they are for data collection in this lab) how far away are they in AU? What about in meters?

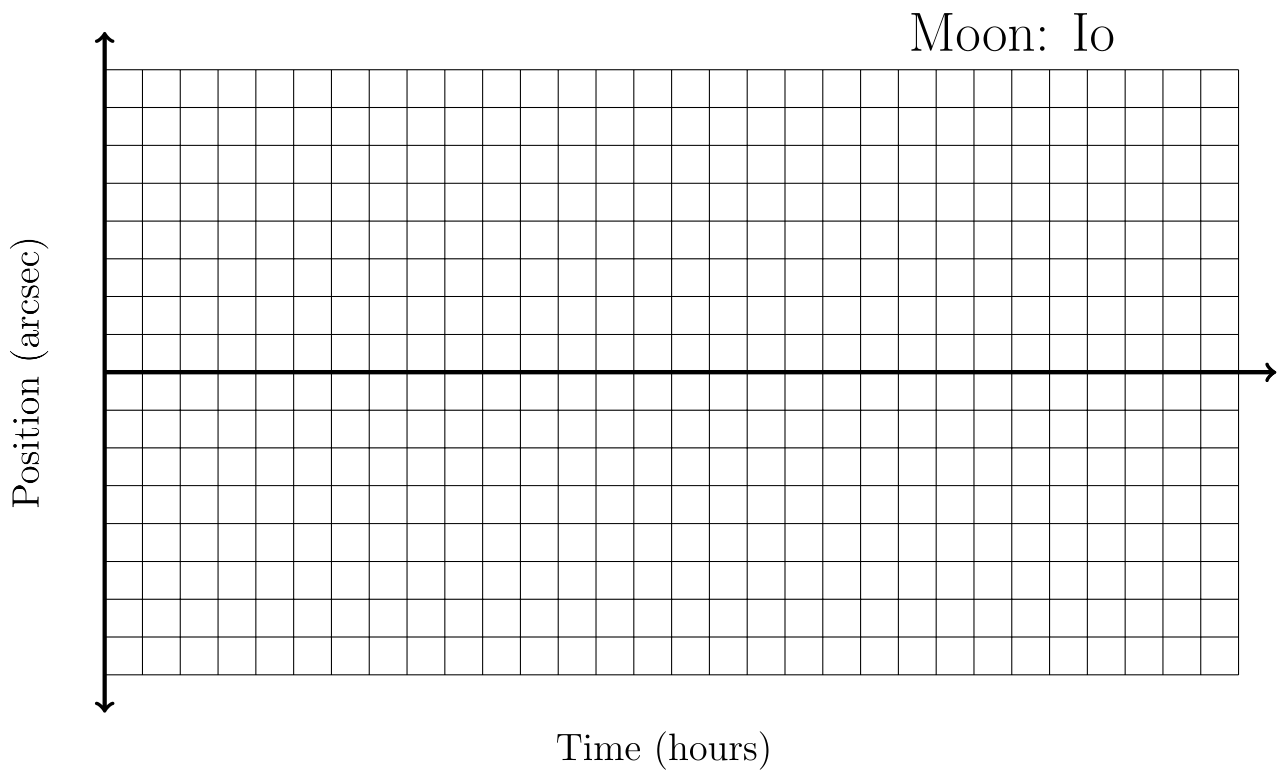
2. Given this distance and the fact that the radius of Jupiter is 7.149×10^7 m, what is the *angular* size of Jupiter as seen from Earth, in arcseconds? (Hint 1: drawing a right triangle may help you recall which trigonometric relation to use) (Hint 2: be careful with units)

3. If an object has an angular size of $50''$ and is 10 AU away from us, what is the *physical* size of the object in AU? What about in meters?

Data Collection

Data Table 11.0

(1) Time	(2) Io	(3) Europa	(4) Ganymede	(5) Callisto



Graph 11.1

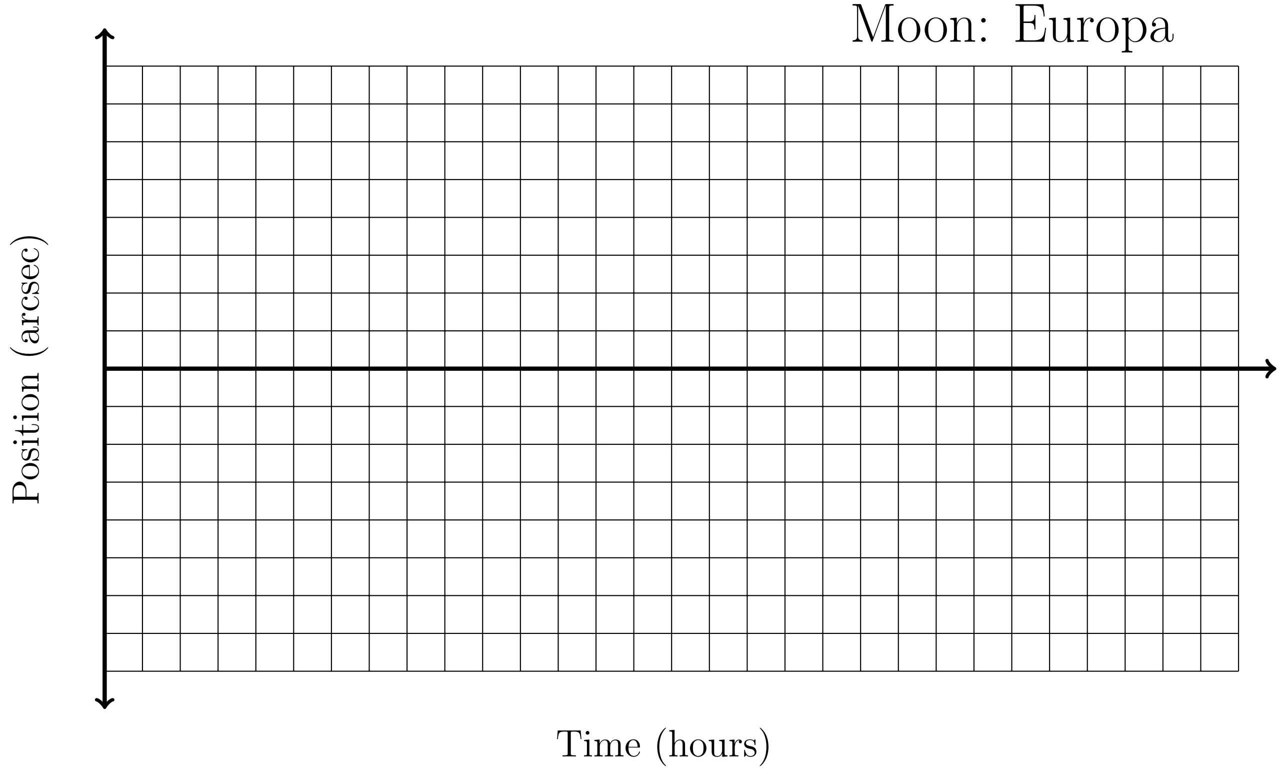
Period (hours)		Semi-major Axis (arcsec)	
Period (years)		Semi-major Axis (m)	
		Semi-major Axis (AU)	

Data Table 11.1

Compute the mass of Jupiter from Kepler's Third Law, where T is in years and a is in AU, your answer will be in terms of $M_\odot$, solar masses.

$$M = \frac{a^3}{T^2}$$

Moon: Europa



Graph 11.2

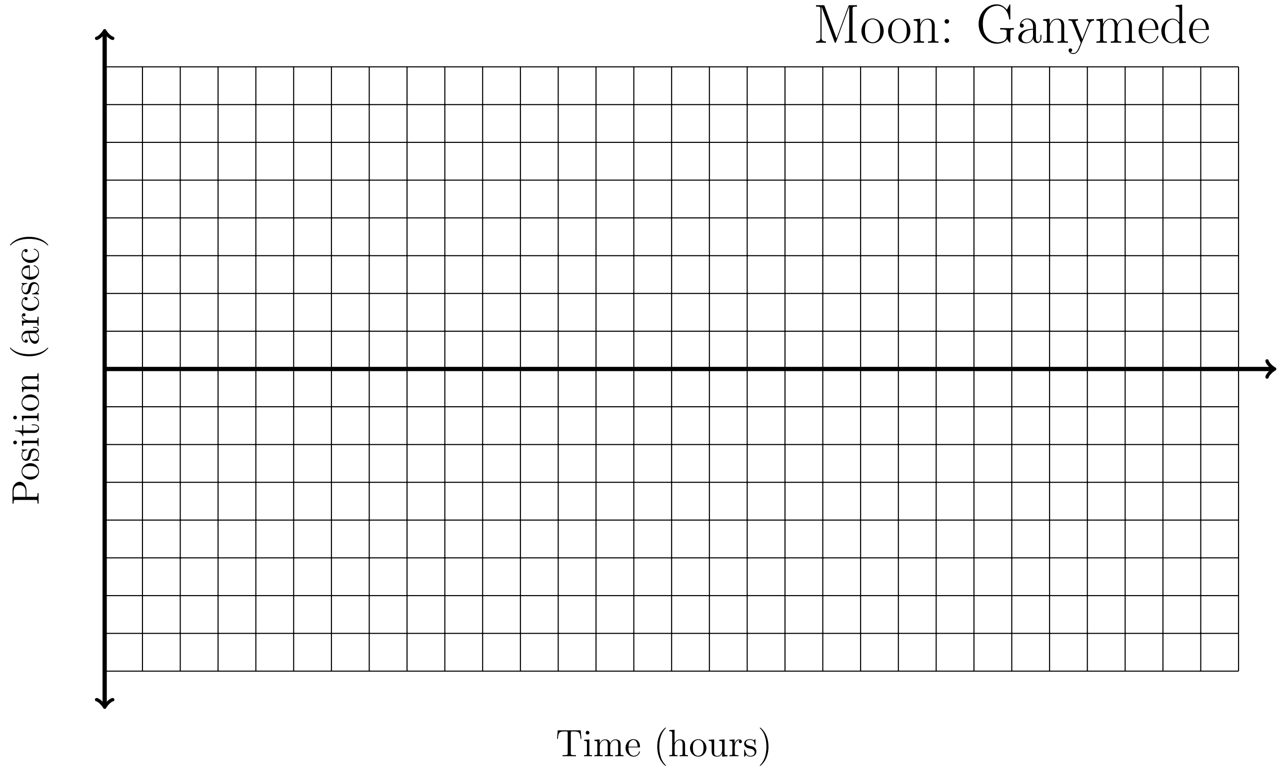
Period (hours)		Semi-major Axis (arcsec)	
Period (years)		Semi-major Axis (m)	
		Semi-major Axis (AU)	

Data Table 11.2

Compute the mass of Jupiter from Kepler's Third Law, where T is in years and a is in AU, your answer will be in terms of $M_\odot$, solar masses.

$$M = \frac{a^3}{T^2}$$

Moon: Ganymede



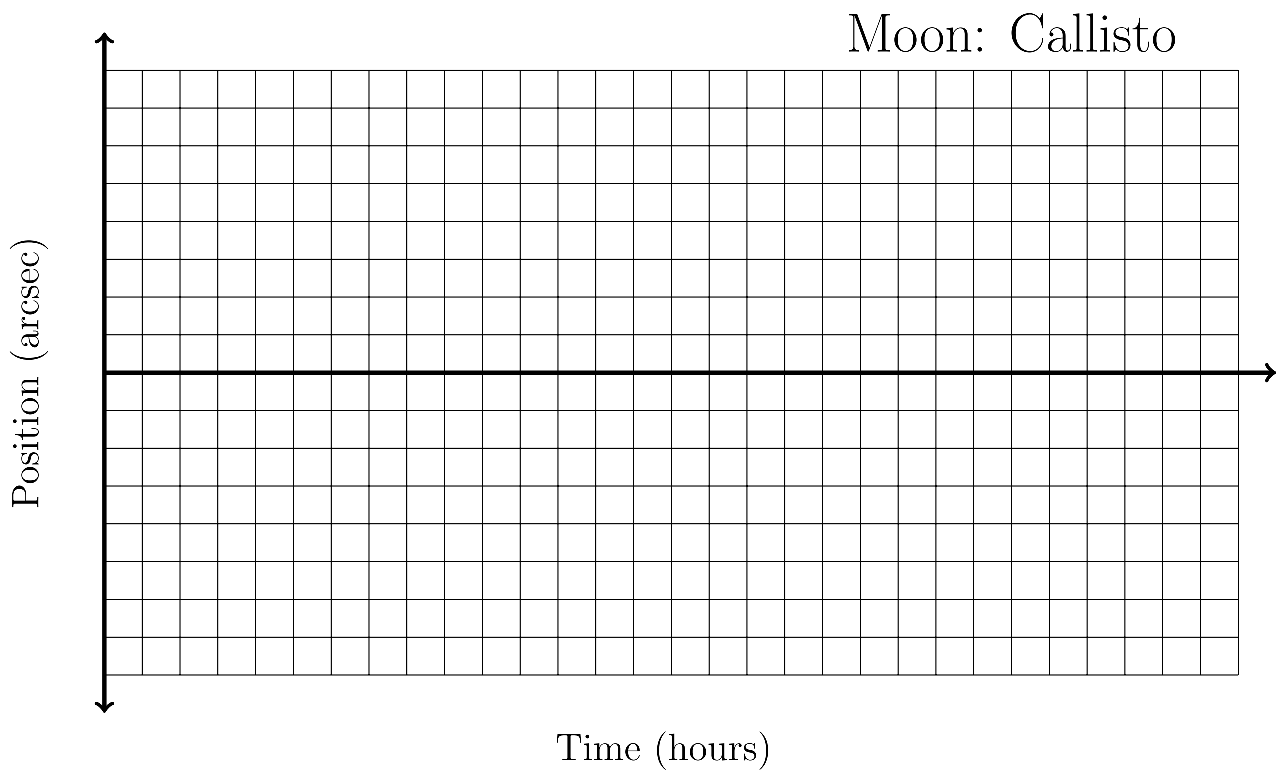
Graph 11.3

Period (hours)		Semi-major Axis (arcsec)	
Period (years)		Semi-major Axis (m)	
		Semi-major Axis (AU)	

Data Table 11.3

Compute the mass of Jupiter from Kepler's Third Law, where T is in years and a is in AU, your answer will be in terms of $M_{\odot}$, solar masses.

$$M = \frac{a^3}{T^2}$$



Graph 11.4

Period (hours)		Semi-major Axis (arcsec)	
Period (years)		Semi-major Axis (m)	
		Semi-major Axis (AU)	

Data Table 11.4

Compute the mass of Jupiter from Kepler's Third Law, where T is in years and a is in AU, your answer will be in terms of $M_\odot$, solar masses.

$$M = \frac{a^3}{T^2}$$

Analysis

4. Compute the mass of Jupiter in grams (1 $M_{\odot}$, solar mass, is equivalent to 1.992×10^{33} grams) for all the moons you observed. If you observed multiple, are your answers consistent?

5. Calculate the percentage error of your calculated value for the mass of Jupiter, given that the accepted value for the mass of Jupiter is 1.9897×10^{30} grams. What are some sources of error for this calculation?

6. The mass of the Earth is 5.975×10^{27} grams. Using your prior knowledge of Jupiter and Earth, does your answer to question 4 seem reasonable? Why or why not?

7. Density is defined as the mass within a fixed volume. The volume of a sphere is given by the following, where r is the radius of the sphere:

$$V = \frac{4}{3}\pi r^3$$

Given that the radius of Jupiter is 7.149×10^9 cm, use the following equation to compute the average density of Jupiter in g/cm^3 (use your measured mass of Jupiter)

$$\rho\ [\text{grams/cm}^3] = \frac{m\ [\text{grams}]}{V\ [\text{cm}^3]}$$

8. How does the mean density of Jupiter compare with the mean density of Earth ($\sim$5 g/cm^3)?

9. Some typical densities for different materials are shown below:

Material	ρ [g/cm^3]
Water	1
Ice	$\sim$0.9
Rock	$\sim$3
Metal	$\sim$5

From spectroscopy, we can determine that Jupiter is about 90% Hydrogen and 10% Helium. Given this information and your result from the previous problem, what would you infer about the composition and structure of Jupiter?

Lab 12: Observe The Moon

Purpose

You will be given the opportunity to observe the Moon through a small telescope at the Campus Teaching Observatory. You will be asked to sketch the moon and identify several important types of features on the lunar surface.

Introduction

Galileo was the first scientist to use the telescope to view the heavens, and the Moon was an obvious target. His telescopes were scarcely as good as a modern pair of binoculars, as the sketch should suggest, but Galileo nevertheless discovered and described the mountains and craters that are the principle surface features (Figure 12.1). He even calculated the heights of several of the lunar mountains by measuring the lengths of their shadows.

By way of contrast, Figure 12.2 is a modern digital CCD photograph of the Moon made with one of the telescopes at our Campus Teaching Observatory. The tremendous increase in detail is obvious! To establish the scale of the photograph, the magnificent walled plain Clavius (near the upper right-hand corner) is approximately 150 miles in diameter, while the smallest visible details are one or two miles in size.

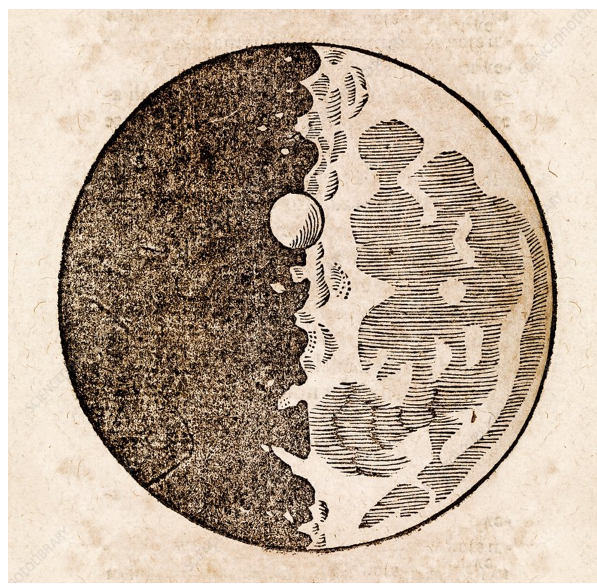


Figure 12.1: Sketch published by Galileo in 1610 in *The Sidereal Messenger*

Galileo's seminal work was quickly followed by other observers who developed the field of selenography, as the mapping of the Moon is called, after the Greek word for Moon, *Selene*. In 1647, Hevelius published a map assigning names to nearly 250 features. Mountains were named after terrestrial analogs such as Alps and Apennines. The large dark areas, the only naked-eye features, were erroneously called "seas" (*maria*, in Greek), and were given fanciful designations such as Mare Tranquillitatis (Sea of Tranquility), Mare Crisium (Sea of Crises), Mare Serenitatis (Sea of Serenity), and so on.

Hevelius also assigned various names to numerous craters. Only four years after Hevelius' work, the Italian Riccoli published a competing map with different nomenclature, on which the craters were named after prominent astronomers and mathematicians. Oddly, Hevelius' names for the seas and mountains have survived on modern maps, while Riccolo's system of naming crates was retained. One must marvel at the patience of cartographers such as the Germans Beer and Madler who, in 1834, after 600 nights of observations, produced a lunar map 3 feet in diameter.

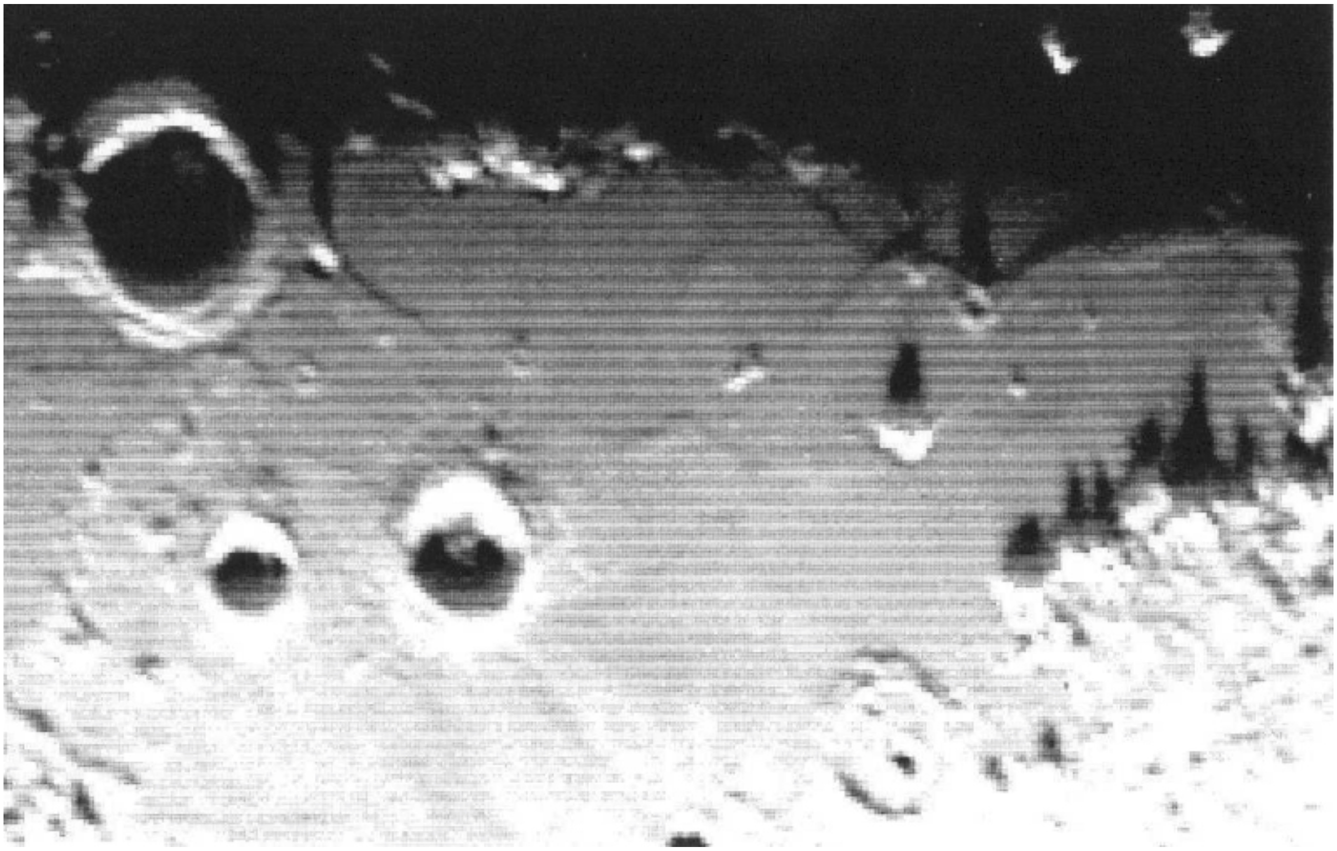


Figure 12.2: Enlargement of a section of a digital photograph of the Moon made by A. G. Smith with the University's 30-inch telescope at the Rosemary Hill Observatory, March 16, 1997.

The advent of photography, of course, revolutionized selenography. What took weeks to draw could be recorded on a photographic plate in a fraction of a second! The first recognizable photo of the Moon was made in 1850 by William Bond at Harvard College, and by the end of the century extensive photographic atlases of the Moon were published. Today, we take digital photos of the moon using our CCD cameras, like in Figure 12.2. The modern tendency is to produce hand-drawn and airbrushed maps by transferring details from numerous photographs. Huge, detailed maps of this kind have been sponsored by U.S. government agencies. An example is displayed in the laboratory room.

Laboratory Procedure

Completing your Data Sheet

Before beginning your observations, fill out the data sheet that is attached to this write-up. Your instructor will give you the Right Ascension (RA) and Declination (DEC) of the Moon for the current night. These coordinates are much like latitude and longitude on the Earth. They enable an astronomer to locate an object on a map of the sky, or to set a properly equipped telescope on an invisible object. Because the Moon moves among the stars, its RA and DEC are continually changing. The instructor will also explain how to estimate the Altitude and Azimuth of the Moon as seen from the Observatory. These are "practical" coordinates that tell you where to look for an object; they will change with time as the sky rotates throughout the evening. The age of the Moon in astronomical parlance is the number of days that have elapsed since New Moon; it has a major effect on the features that are visible.

Visual Observations

Viewing the Moon for the first time through a good telescope is, for many people, a memorable experience. You will be assigned to one of several small telescopes on the piers outside the Observatory. Your telescope is an expensive piece of equipment that is easily damaged; please treat it with care. Do not try to point it on your own. Do not use the small "finder" telescope or the eyepiece as handles; they break quite easily. If you have any doubt or any difficulties, *consult your instructor!* A damaged telescope is then unavailable to students in the laboratories that follow yours.

The Data Sheet includes a list of types of lunar features. How many of these you will see depends, to some extent, on the age of the Moon. Using a camera and TV, your instructor will help you locate, observe and check-off as many of these types as you can find. Record the focal length of the eyepiece you are using, and the overall magnification of the telescope with this eyepiece. Figure 12.2 shows many examples of craters without central peaks, and a few with central peaks. A very large crater with relatively low walls is referred to as a "walled plain". "Rays" are most visible at Full Moon, when most other features are nearly invisible due to the absence of shadows. The most difficult features on your list are probably the "rilles", which are linear cracks or crevices in the surface. Conversely, the easiest features at any age of the Moon are the Maria, which look like dark patches ("the Man in the Moon" pattern) to the naked eye, and as very smooth, level areas with few craters in the telescope.

Observe The Moon Worksheet

Name: ______________________ **Date:** ____________ **Section #:** ______

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

Local Time		Age of The Moon (days)	
Moon's R.A.		Moon's DEC	
Moon's Altitude		Moon's Azimuth	
Sky Conditions		Focal Length of Eyepiece (mm)	
Focal Length of Telescope (mm)		Magnification	

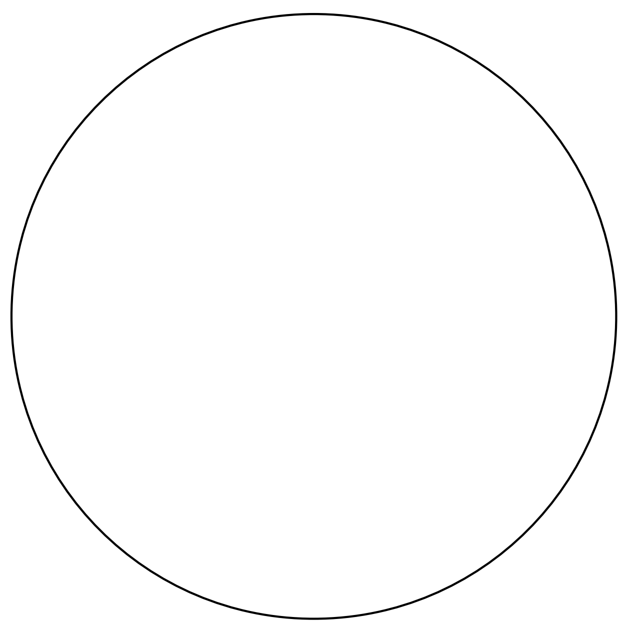
Data Table 12.1

Types of Lunar Features

Check all of the following that you see:

Maria	
Craters with Central Peak	
Craters without Central Peak	
Rayed Craters	
Walled Plains	
Mountain Ranges	
Isolated Peaks	
Rilles	

Data Table 12.2



Graph 12.1: Make your sketch in this circle, which represents the field of view of the telescope, not the moon itself

Lab 13: Observe The Planets

Purpose

You will have the opportunity to make visual telescopic observations of the planet(s) that appear in the evening sky. You will be asked to sketch the planet and its satellites.

Introduction

The word "planet" is derived from the Greek word for *wanderer* because the five naked-eye planets seemed to wander about the fixed stars. With the invention of the telescope, around 1610, came the discovery that the planets were further distinguished from the stars by showing discrete disks on which could be seen, at least in some cases, intricate markings like the canals on Mars seen in Figure 13.1.

Mapping these markings proved to be one of the most challenging kinds of astronomical observations, placing a premium on the excellence of the telescope, the steadiness of the atmosphere, and the eye of the observer. Quite a few dedicated astronomers spent major segments of their careers on planetary observations; names such as the American Lowell and Frenchman Dollfus come to mind. Unlike most branches of astronomy, photography was not the solution to recording planetary details. A photographic plate was unable to compete with a skilled eye in resolving the fine detail glimpsed during brief moments of good "seeing" when the atmosphere, for a second or two, stopped trembling.

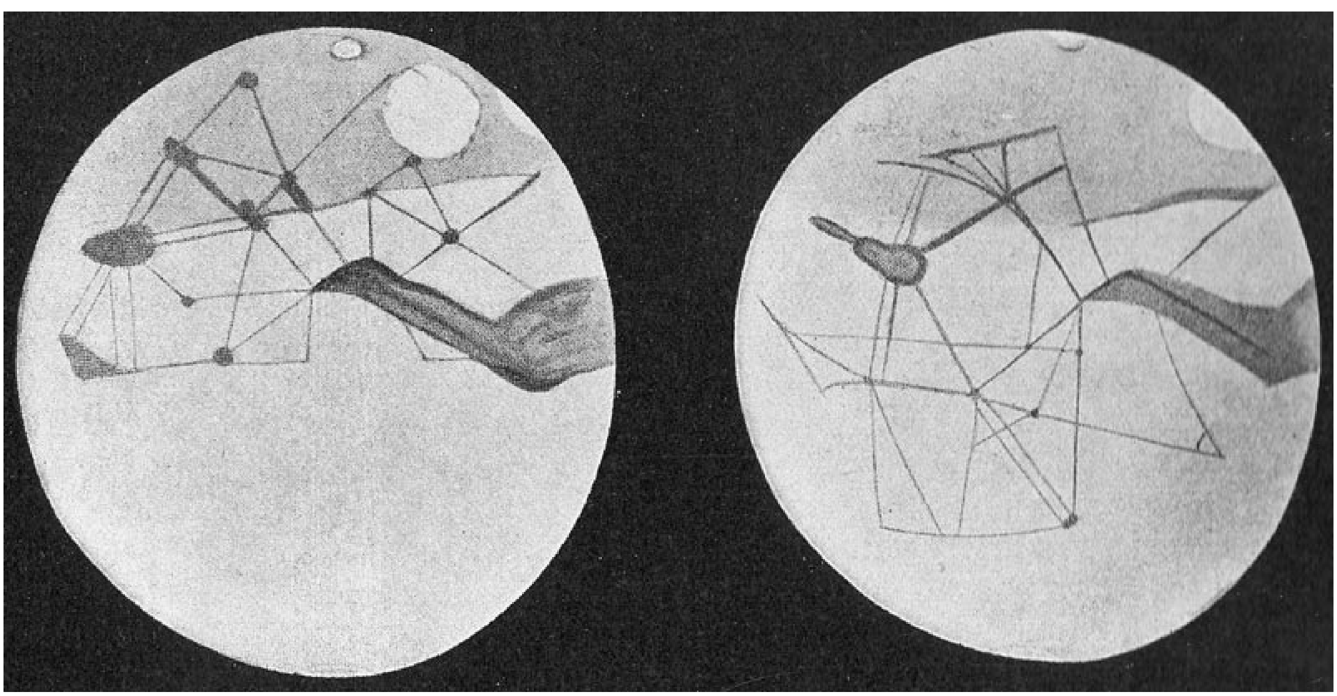


Figure 13.1: Sketch of Martian Canals from *Mars and Its Canals* by Percival Lowell (Macmillan & Co. 1907)

The real break-through, of course, came with the advent of spacecraft that could fly to the planets and take close-up photos or – in a few instances – even land on their surfaces to record detailed landscapes. The spacecraft's photographs, radioed back to Earth, exceed, by many orders of magnitude, the detail in the best Earth-based observations. Thanks to this new technology, we now have maps of other bodies rivalling maps of the Earth itself.

We provide two diagrams for the scale of the solar system, the first (Figure 13.2) shows the distance that each of the planets orbits around the sun (note that the size of the planets are <u>not</u> to scale). The second (Figure 13.3) shows the relative sizes of the planets.

Because planets do wander among the stars, the planets visible in the evening sky will vary from year to year. Following are brief descriptions of the planets, conveying some notion of what you might expect to see through a small telescope. The first five are "naked-eye" planets (named since you can see them with your eyes in the night sky), which have been known since antiquity. Asking who discovered them first is like asking who discovered the Moon?

Mercury

Circling the Sun in only 88 days, Mercury moves so rapidly among the stars that it was named after the swift "messenger of the gods". Typically, it will appear in the evening twilight about three times per year, and an equal number of times in the pre-dawn twilight. Since it never gets over 28° from the Sun, it cannot be seen high in a dark sky, It is said that the great Copernicus went to his grave regretting that he had never seen Mercury

To the naked-eye, Mercury resembles a first magnitude star. In the telescope, it displays phases like those of the Moon; when it is furthest above the horizon, the phase resembles a quarter-Moon. Other than the phase, you are unlikely to see detail on the disc, which at best is only 13 arcseconds in diameter – for reference the Moon is 1800 arcseconds in diameter. Only a handful of dedicated observers claimed to have mapped surface detail on this difficult object, and much of that proved to be illusory.

Venus

Venus is conspicuous for several months at a time as either a "morning star" or an "evening star" (The Greeks knew it by two names because of this: Phosphorus and Hesperus). Venus can be brighter than any celestial object, except for the Sun and Moon. At such times, it can be seen in broad daylight, if you know where to look and can properly focus your eyes. It occasionally gets reported as a UFO in situations like this.

As an *inferior planet* (closer to the Sun than the Earth), Venus, like Mercury, shows phases that are easily observed in the telescope. One of Galileo's triumphs was his little telescope, scarcely more powerful than modern binoculars, was the discovery of the phases of Venus. There have been even claims of detecting the crescent phase with the naked eye. When it is nearest Earth, at "inferior conjunction", the disc is as large as 65 arcseconds, greater than any other planet and at least theoretically within the resolving power of our eyes.

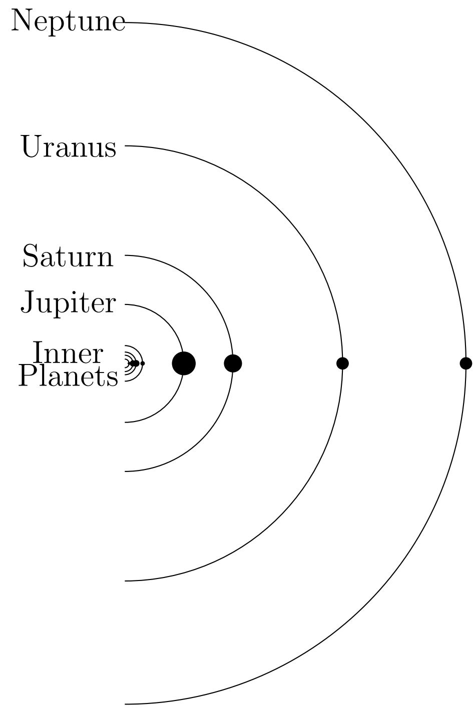


Figure 13.2: Relative distances of planetary orbits (size of planets not to scale)

Unfortunately, Venus is perpetually shrouded in dense white clouds. Structure can be seen in the clouds in infrared radiation, but in visible light they are virtually featureless. Because of her brilliance, Venus tends to bring out the worst in any telescope – internal reflections, false colors and so on.

Mars

Because of its striking red color, Mars was named after the Roman god of war. Much earlier, the Babylonians called it Nergal in honor of their god of pestilence and death. Mars has attracted popular attention since the invention of the telescope because it is the only planet whose actual surface can be studied effectively from the Earth. At intervals of 2 years (plus 7 weeks), Mars makes close approaches to the Earth. Termed "oppositions" because the planet is then directly opposite the Sun in the sky, these occasions are by far the best times to study Mars. At a favorable opposition Mars subtends an angle of over 25 arcseconds, whereas when it is furthest from Earth, its diameter is under 4 arcseconds. At opposition, Mars appears to the naked-eye as a very bright red star, brighter than any of the fixed stars.

Mars' most conspicuous feature is usually one or the other of the brilliant white polar ice caps, which alternate with the Martian seasons. Next, you may detect one or more of the dusky areas such as the Syrtis Major; these also change intensity with the seasons, which are rather similar to seasons on Earth since the two bodies have nearly identical tilts of their axes of rotation. It is the totality of these dark "albedo features" that comprise the elaborate maps drawn by skilled observers. If you have a vivid imagination, you might even glimpse some of the linear markings that gave rise to the myth of "Martian canals" dear to the hearts of science fiction writers.

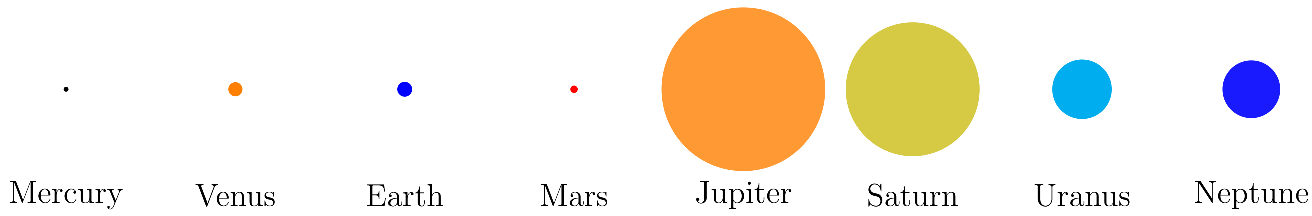


Figure 13.3: Relative sizes of the planets (distances between planets not to scale), ordered by closest to the Sun out (note: the gas giants are presented without their rings)

Jupiter

Named after the Greco-Roman ruler of the gods, Jupiter is usually the most rewarding planet for study in a small telescope. To the naked-eye, it appears as a yellowish star, second only to Venus in brightness. Jupiter is observable throughout most of the year, except for a few months when it is uncomfortably close to the Sun. At opposition, Jupiter is 50 arcseconds in diameter, and it never gets smaller than 31 arcseconds (still considerably larger than Mars).

Since Jupiter is a "gas giant", what we see is the top of a dense, cloudy atmosphere. Except in miserable seeing, the system of alternating dark and light bands (properly called belts and zones) is easily visible in the telescope. You should make an effort to count the number of bands you can see. The ball of the planet is distinctly flattened (elliptical) because of its rapid rotation; the Jovian day is less than 10 hours long. Of the local features, the Great Red Spot (three times the size of the Earth!) is often conspicuous, although its color and contrast vary considerably from year to year, and of course it must be on the hemisphere facing the Earth. Smaller spots and irregularities in the belts aer sometimes visible, as well as wisps extending across zones between belts.

You should, of course, note the Galilean satellites, which can be seen even in binoculars. From time to time, a satellite or its shadow can be seen crossing the disc of the planet.

Saturn

The name "Saturn" is the Roman equivalent of *Cronus*, the Greek god who ruled Olympus. To the naked-eye, Saturn appears as a yellowish first-magnitude star. Like Jupiter, it is visible most of the year (though not always in the evening sky!)

A 19th century author of numerous astronomical texts, Richard A. Proctor, described Saturn as "the most charming telescopic object in the heavens". The striking feature of the planet is, of course, the beautiful ring system, the only such appendage visible from Earth. Every 15 years the Earth passes through the plane of the rings, which virtually vanish since they are thin.

The disc of Saturn varies from 15 to 21 arcseconds in apparent diameter. There are parallel belts and zones you should try to discern, but they are of much lower contrast than those of Jupiter. Spots are rare. The ball of the planet is even more flattened than that of Jupiter, but the rings tend to confuse the eye. If seeing is at all good, you should be able to detect *Cassini's Division*, a black line splitting the ring into a narrow outer band and a broader inner band (ingeniously named Ring A and Ring B). The Division is easiest to see in the *ansae*, the extreme outer ends of the ring. There is a third ring, Ring C, interior to B, known as the Crepe Ring, but it is very faint. Look for the shadow of the rings on the ball, and the shadow of the ball on the rings. Saturn has a retinue of 82 known satellites (as of 2021), of which very few are bright enough to be seen in our telescopes. To identify them, and distinguish them from stars, requires an ephemeris – a book with tables that gives the trajectory of naturally occurring astronomical objects as well as artificial satellites in the sky.

Uranus and Neptune

These are telescopic objects, although Uranus is at times bright enough to be detected, at least in principle, by a keen naked eye. Uranus was discovered accidentally in 1781 by Caroline and William Herschel during a telescopic survey of the sky. The discovery of Neptune was more deliberate. Based on observed disturbances of Uranus' orbit, two mathematical astronomers, Adams and Leverrier, predicted the position of the disturbing body, which was located on September 23, 1846 after a telescope search of only half an hour.

The blue-green disc of Uranus is about 4 arcseconds in diameter, that of Neptune about 2 arcseconds. Although you are unlikely to discern any detail on these tiny discs, the images are noticeably different from those of stars. Neptune's largest satellite, Triton, and two of Uranus' moons should be visible in our instruments, but again an ephemeris is required to identify them.

Dwarf Planet: Pluto

The discovery of Pluto in 1930, by Clyde Tombaugh, resulted from an intensive photographic search inspired by Lowell's mathematical calculations (which are now regarded as fallacious!). Pluto, upon discovery, was given the designation of a planet, but after finding several similarly sized massive bodies it was stripped of its title in 2005 by the International Astronomical Union (IAU). It is now classified as a dwarf planet or a Kuiper Belt Object (KBO). Pluto demands at least a 6-inch telescope to be seen as a faint star-like point of light. The first spacecraft to visit Pluto, the New Horizons Spacecraft, arrived on July 14, 2015 after a nearly 10-year, 3 billion mile journey and took the iconic photo of the planets surface, our first time resolving any such features.

While you shouldn't expect to see surface detail on Uranus, Neptune, or Pluto, you can derive intellectual satisfaction from joining the exceedingly small group of human beings who have seen even one of these remote outposts of our solar system.

Laboratory Procedure

At the start of the lab, your instructor will point out any naked-eye planets that are visible. Make note of these

The instructor will then designate a *Primary Planet* and assist you in locating it in your telescope. Even experienced observers have difficulty in seeing detail on a planetary disc when they first look at it. The detail comes with patient study – with training the eye, so to speak. After you have studied the image for several minutes, begin sketching it in the circle provided on the worksheet. In the cases of Mercury and Venus, there may be little to draw except the incomplete disc, although at times irregularities may appear along the terminator (the line dividing day and night). For Mars, Jupiter, and Saturn, the detail may be limited only by your patience and available time. In drawing Jupiter, don't fail to include the Galilean satellites which, if you look closely, display tiny non-stellar discs.

After the class has complete its sketches, the instructor may use the 12-inch Meade reflector to give you quick looks at Uranus, Neptune, or Pluto when these are well placed for observations. With its rapid "Go-To" capability, the Meade can quickly find such invisible targets. If Uranus and/or Neptune should be the only planet available, the instructor may wish to provide the maps or ephemerides needed to identify the brighter satellites, which can be shown in a sketch.

Observe The Planets Worksheet

Name: ______________________ **Date:** ______________ **Section #:** ________

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

Date of observations	
Time of observations	
Sky Condition	

Planets Observed

	With Naked Eye	With Telescope
Mercury		
Venus		
Mars		
Jupiter		
Saturn		
Uranus		
Neptune		
(Dwarf) Pluto		

Primary Planet

Name	
Constellation	
R.A.	
Dec	
Altitude	
Azimuth	
Aperture of Telescope	
Magnification	

Make your sketch in this circle, which represents the field of view of the telescope. Did you notice any colors? Did you see any satellites? If so, how many? How were you able to identify them?

Lab 14: Observe The Deep Sky

Purpose

You will be given an opportunity to observe and learn about of faint, often diffuse objects in "deep space" beyond our solar system: binary stars, star clusters, nebulae, and galaxies. You will view four deep sky objects, record some basic information about each, and then sketch what you observe.

Introduction

The term "Deep Sky" has no precise definition. Generally, it is understood to mean objects outside of our little Solar System, which is to say objects that are usually fainter than the Sun, the Moon, and at least the brighter planets. Such observations are a challenge at our Campus Teaching Observatory, which is situated in the heart of campus, in an area that suffers severe light pollution. The resulting bright sky makes it difficult to locate and observe the faint objects that comprise the bulk of the Universe.

In our observing sessions we will attempt to observe a sample of several of the following classes of deep sky objects:

Binary Stars

Over half of the stars in our part of the Universe occur in pairs (or higher multiplicities). A few of these "double stars" are merely chance alignments of stars that are actually at quite different distances from us. Real binary stars, however, are gravitationally bound to each other, just as the Moon orbits around the Earth. If the two stars are close together, their orbital periods can be quite short – a few years, down to days or hours. But such close pairs are generally difficult or impossible to observe as separate stars. Binaries far enough apart to be readily observable may have orbital periods of hundreds or even thousands of years. Some of the brighter binaries are very attractive with, for example, a yellow star contrasting with a deep blue star (the human eye, unfortunately, is incapable of distinguishing color in faint objects). Observations of binary stars have been our primary source of information about the masses of stars

Galactic Clusters

There is a strong tendency for stars to be born in clusters in dense clouds of dust and gas. Since these clouds lie in the Milky Way, in the plane of our galaxy, the resulting clusters are called "galactic" clusters. Such clusters are loose, irregular aggregations that range from a dozen to several hundred stars. A few are close enough to be resolved readily by the naked eye; the Pleiades and the Hyades, both in the constellation Taurus, are familiar examples.

Globular Clusters

Roughly spherical in shape, these huge clusters are among the oldest objects in the Universe. In fact, it is embarrassing that some measures suggest that the globulars are older than the Universe itself! Each cluster contains hundreds of thousands of stars. The globular clusters form a halo surrounding the core of our Milky Way galaxy. Seen in a large telescope under good conditions, a globular cluster can be an impressive sight.

Nebulae

A nebula is a mass of dust and gas floating in space. If there are nearby hot stars, the radiation from the stars excites the gas to glow, much like the gas in a neon sign. Such objects are known as emission nebulae. If the gas is not illuminated, the nebula may reveal itself as an opaque mass hiding stars or luminous gas behind it; in this event it is called a dark nebula. The Milky Way (the plane of our spiral galaxy) is rich in both types of nebulae. A third type of nebula is a shell of gas thrown off by a dying star. Because they generally appear as luminous discs or rings, somewhat like the image of a faint planet, these relatively small objects were long ago given the perhaps unfortunate name of planetary nebulae (they, of course, have nothing to do with planets). Bereft of their cooler outer layers, the central stars in planetary nebulae are the hottest known, with temperatures of up to 100,000 K

Galaxies

Formed very early in the history of the Universe, the galaxies are the major building blocks of our Universe. If an alien were to view our Universe from a great distance, the galaxies are what they would notice. A large galaxy like our Milky Way system can contain over 100 billion stars. The forms of most galaxies fall into two categories: spiral and elliptical galaxies. Because of their size and luminosity, galaxies are by far the most remote objects we can observe. They are the deepest of the deep sky objects! In recent decades, it has been discovered that many galaxies have small, bright, highly variable nuclei. These so-called AGN or "active galactic nuclei" are thought to be super-massive black holes. In fact, the first image of a black hole in April 2019 was of the super-massive black hole at the center of M87, a galaxy in the constellation Virgo.

Laboratory Procedure

The objects that are available depend strongly on the time of the year. Presence of the Moon make it more difficult to observe faint objects, although our Observatory site is always so bright that the Moon makes less difference than it would in a better location.

Your instructor will have prepared a list of 4 targets for the evening's work, representing several of the categories described in the preceding section. They will assist you in pointing one of the portable telescopes at each object in succession. We again remind you to NOT attempt to operate the telescope yourself, leave that for your instructor.

Allow a short time to become dark adapted, and then study the object and attempt to appreciate what you are seeing in view of the discussion in the preceding section. Enjoyment of celestial scenery is at least as much intellectual as it is visual! Make a sketch of the object in the circle provided in the worksheet; sketching (as any artist will tell you) is a powerful tool for focusing attention on details. Repeat the procedure for each of the targets on the evening's program.

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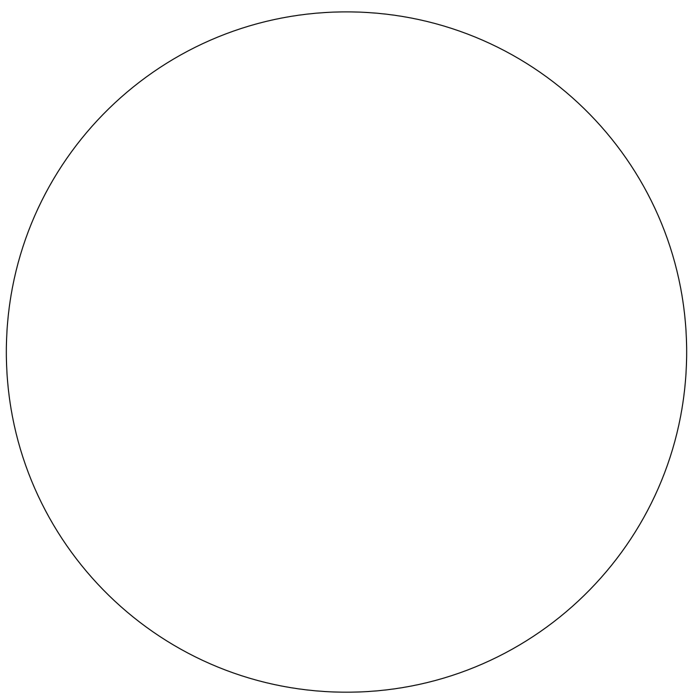
Object 1

Name of Object	
Type of Object	
Time of Observation	
Magnification of Telescope	
Description of Object	

Data Table 14.1

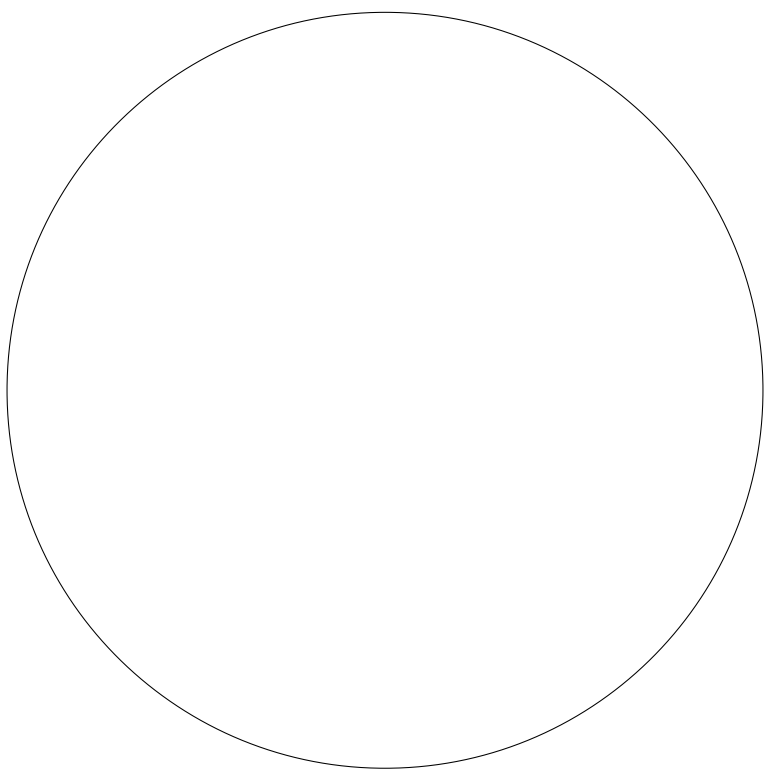


Graph 14.1

Object 2

Name of Object	
Type of Object	
Time of Observation	
Magnification of Telescope	
Description of Object	

Data Table 14.2

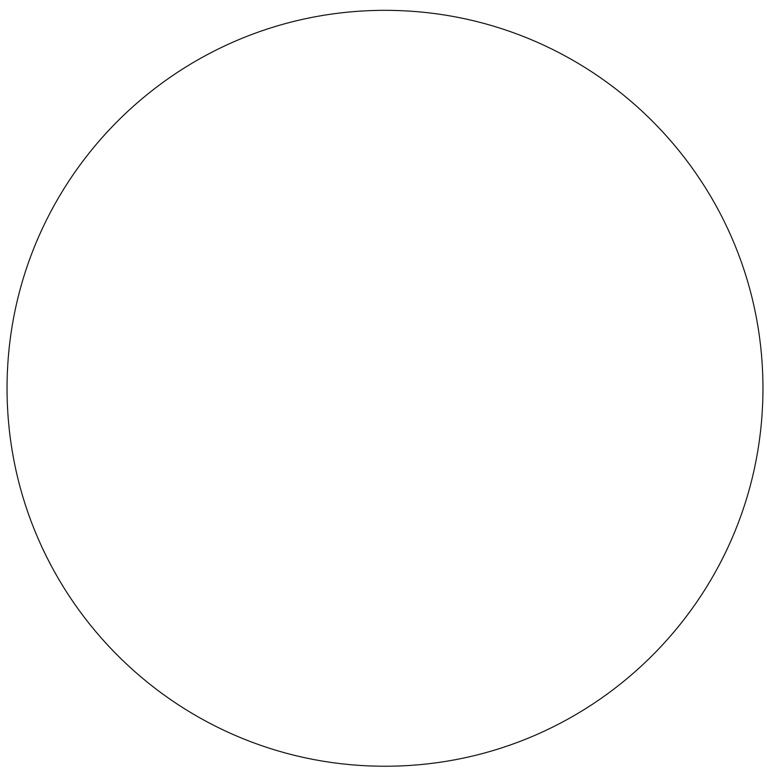


Graph 14.2

Object 3

Name of Object	
Type of Object	
Time of Observation	
Magnification of Telescope	
Description of Object	

Data Table 14.3

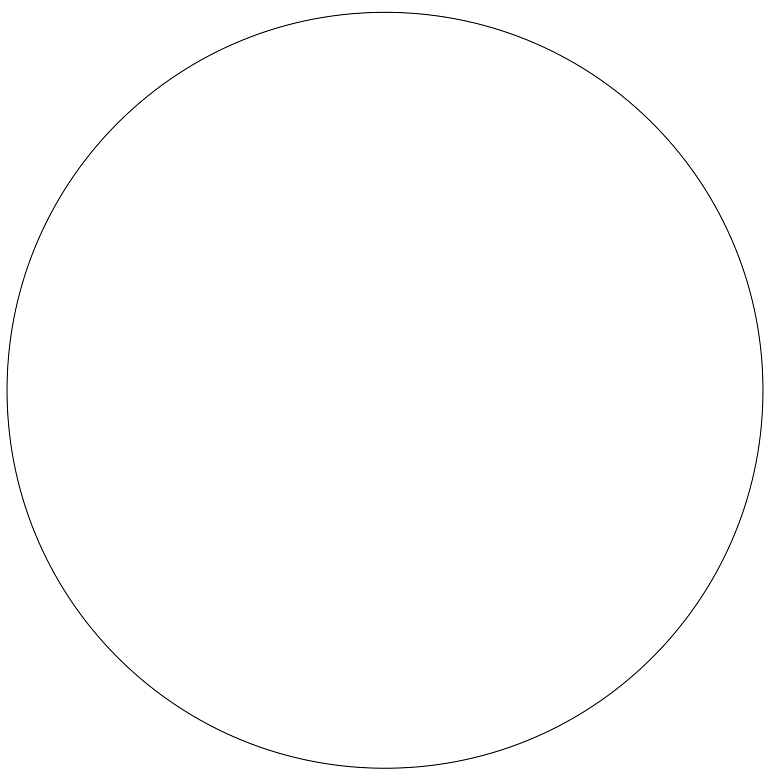


Graph 14.3

Object 4

Name of Object	
Type of Object	
Time of Observation	
Magnification of Telescope	
Description of Object	

Data Table 14.4



Graph 14.4