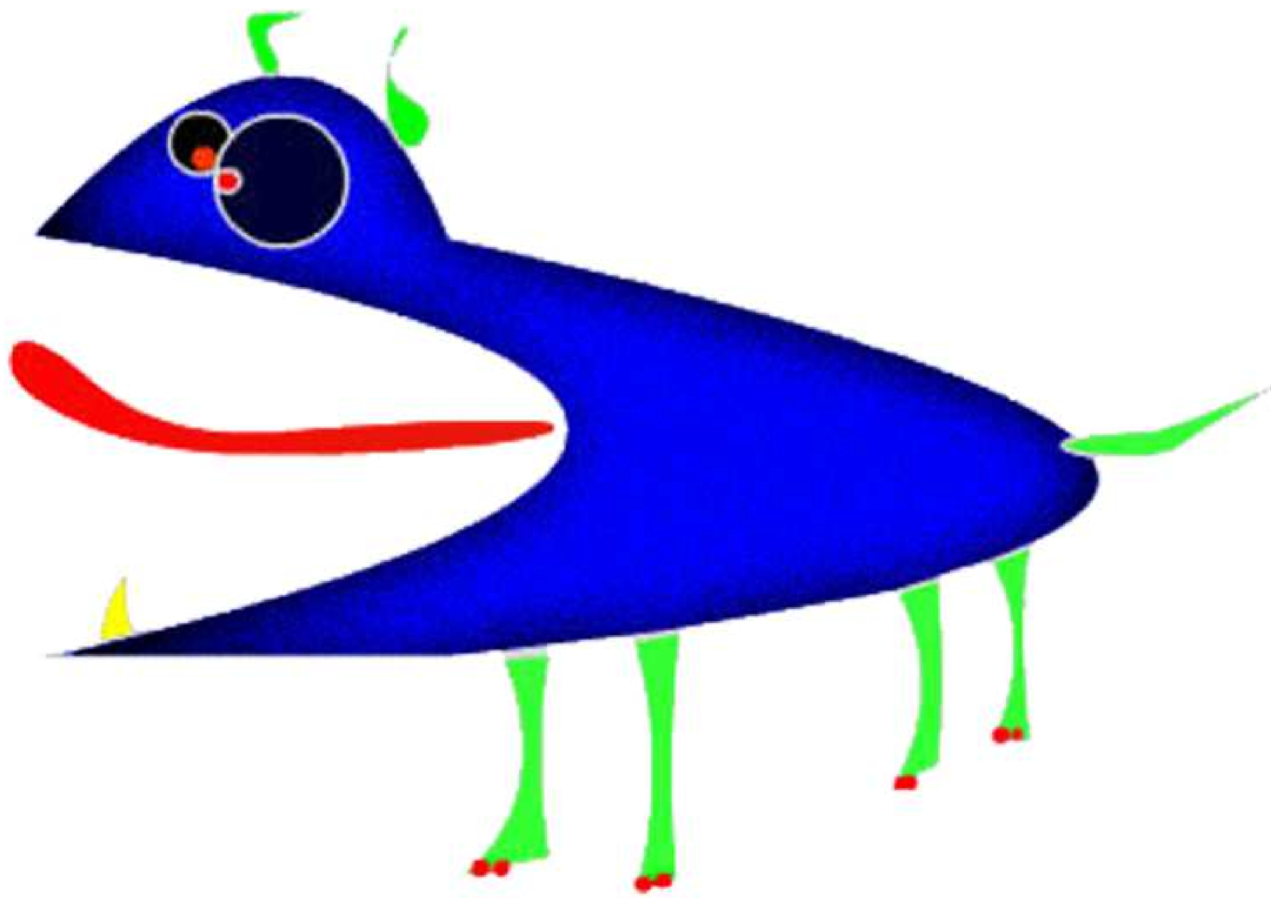
Astronomy Laboratory Exercises
(Instructor Supplement)



2020

ASTR110G Laboratory Exercises (Instructor Supplement)

Lab 1

Fundamentals of Measurement and Error Analysis

1.1 Overview

This first laboratory exercise introduces key concepts and statistical and plotting tools that are used throughout the entire sequence of exercises. It also focuses on the idea of productive scientific experimentation – how to design, conduct, and evaluate an experiment. There are four primary activities: (1) planning and conducting a short experiment with common household items, (2) examining existing data to uncover a basic connection between seasonal changes and the height of the Sun in the sky at noon, (3) analyzing data, including error estimates, and (4) making appropriate conclusions based on evidence.

Students begin by choosing a simple experiment that can be conducted with common household supplies. We provide a list of ten sample experiments and encourage students to select one from the list or to propose a similar experiment to their instructors. The experiments have been designed so that they are non-threatening (it is difficult to be intimidated while tossing marshmallows, or to feel that this is something that one should have paid more attention to in high school), easy to visualize (they involve measuring lengths of time or distance, weights, or counting items), and can produce significantly different results when conducted by different individuals in different environments (the average width of books drawn from a shelf of children's picture books will differ from that for a set of novels). These results of these experiments cannot be "looked up" on Wikipedia or found recorded in scientific texts. Each experiment is described by only a single short sentence (such as "what is the average distance between the pupils of people's eyes?"), leaving students to fill in the blanks and construct an experimental plan of action.

Each student designs their experiment, and submits an experimental design within their laboratory report. They take a small amount of preliminary data, and then evaluate their protocol and their data to determine whether they need to vary the plan (strong winds might make marshmallow tossing untenable outside; a scale designed to weigh humans will not work well for individual pinto beans). They then revise their design, and take a set of 30 measurements. A sample experiment is discussed in the project chapter to provide guidance, and a web-application allows students to vary the number of data points and the precision of measurements in order to determine the effect on derived quantities such as mean values and standard deviations.

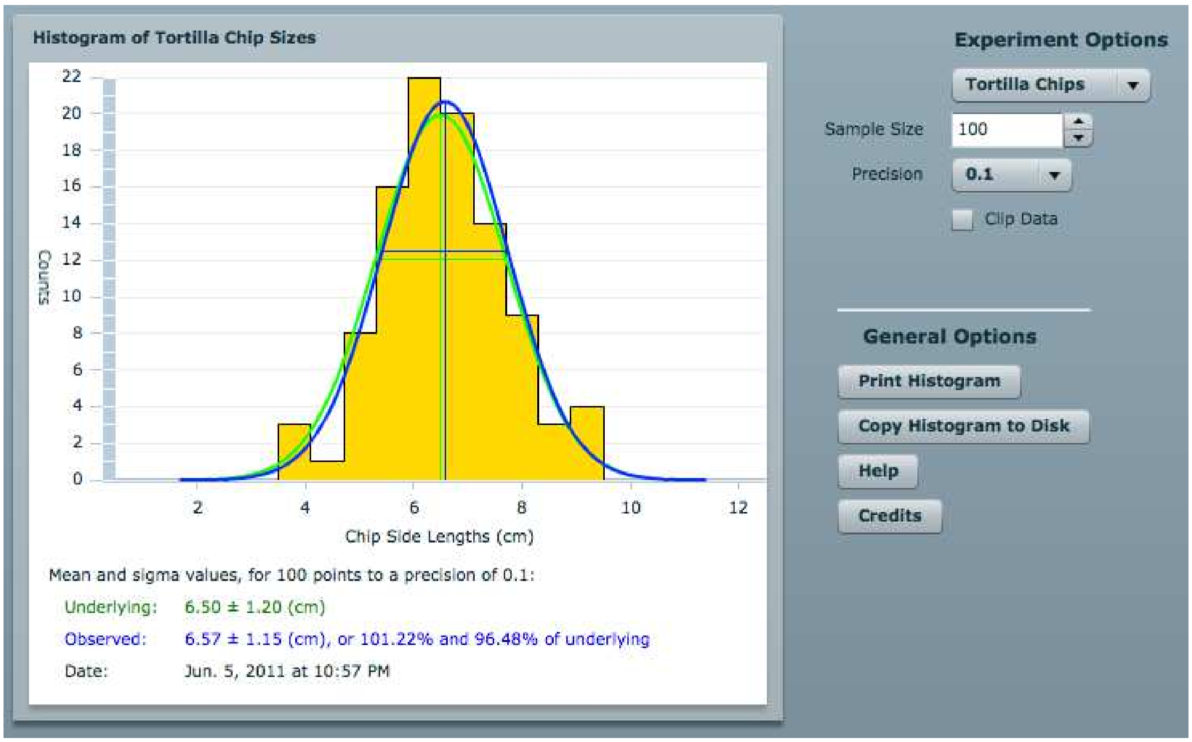


Figure 1.1: A web-application which demonstrates the basic properties of histograms of measurements. Students can choose from a variety of samples drawn from simple hands-on experiments and define a sample size and the precision of modeled measurements. A Monte Carlo simulation presents a set of representative data in the form of a histogram; each simulation run is generated on the fly and differs from previous and future runs (as would real data samples). Mean values and standard deviations are presented for both the underlying complete sample and the simulated finite sample, with differences that illustrate the effect of varying the sample size and the precision of the measurements.

Figure 1.1 is a screen capture of the primary window for this histogram-based web-application. This tool allows students to simulate collecting data for various physical samples such as the lengths of tortilla chips or the weight of pinto beans. By selecting different values for the sample size and the measurement precision, they are able to study the relationship between these factors and the intrinsic scatter in the measured quantity. For example, one might measure the distance that a marshmallow can be thrown to the nearest inch, while needing significantly higher precision to measure the length of a tortilla chip. By repeatedly creating small samples, students can observe how random scatter and sample selection can produce changes in the measured mean values and standard deviations.

All of our web-applications are supported with help screens explaining tool usage and options to either print figures or to save them (in PNG format) as files on local disks. Figures are all date- and time-stamped to the nearest minute. These flash-based applications are fully supported under Windows, Mac iOS, and the Linux operating system, and run within all major browsers.

After completing their experiments, students trade experiment designs with another student. Each student then attempts to reproduce the experiment conducted by their partner, working from just the submitted description of the experiment. The pairs of students are then connected via e-mail. Students use plotting tools to create histograms of their own data. They work together to determine whether their experiments were in agreement or not. Our rule of thumb is that values within two standard deviations of each other do not disagree, differences between two and five standard deviations suggest that it would be good to take additional data and verify experimental set-ups, and differences of more than five standard deviations suggest that there is a significant difference between the two experiments that should be identified. Deficiencies in the descriptions of the experiments come to light quickly as students are frequently forced to guess about critical factors left undefined by their partners and students need to agree on a single set of units in order to calculate and compare mean values and standard deviations.

We have elected to keep this statistical test as simple as possible, to keep it accessible to students with no experience and no intuition for judging data. We make the point separately that larger data sets generally produce better constrained mean values and standard deviations.

Success in the partnering exercise is not defined by whether the students were able to measure similar mean values for quantities, but instead by whether they could discuss and identify differences or agreement in derived quantities and whether they could suggest probable causes for any differences. This activity also prompts of students to work cooperatively in order to succeed, and establishes peer partnerships that students are able to develop further throughout the semester. It also illustrates the need for scientists to communicate their ideas clearly, and to write well enough to describe experiments adequately to their peers.

We introduce three types of "errors" (causes for differences between repeated measurements of a given quantity) to students: (1) natural variation in a population, that produces a range of values that can be measured due to the intrinsic width of a distribution of a property, (2) measurement errors, tied to the precision with which a value is measured, and (3) systematic errors, in which a bias is introduced into a data set (such as a systematic overestimate due to measuring people's heights while leaving their shoes on). These concepts are developed throughout the entire sequence of projects, to build familiarity and comfort.

Additional tools for analyzing data include error bars and fits of particular models to data. We illustrate linear fits, and also show how in some cases a higher-order function can produce a better fit to xy data. The accuracy of various fits is expressed in terms of root mean square deviations from the models. We discuss several sample data sets (using illustrative data sets that will be explored more deeply throughout the semester), and then students work through a plotting and analysis exercise for themselves with worldwide data on surface temperatures and peak solar altitudes at high noon. Because many of our students are unfamiliar with the basic idea of creating and analyzing a plot of data in order to test a hypothesis, we emphasize first the basic skill of reading plots, and then develop the idea of fitting simple models to data.

1.2 Learning Objectives

After completing this laboratory exercise, the student should be able to do the following:

- Design and carry out simple scientific experiments, while guarding against strong biases in sampled populations, selecting a sufficiently precise measurement technique, and sampling a sufficiently large number of times to achieve a desired outcome.

- Comprehend the meaning of natural variance, and measurement and systematic error, and gauge their effects on data.

- Understand how to plot a histogram from repeated measurements, and the meaning and proper use of mean and standard deviation values.

- Explain how to plot two variables against each other, fit a line to them with a slope and y-intercept, and interpret the results in view of associated errors.

- Relate an rms deviation for a fit to a set of (x, y) data to a standard deviation for repeated measurements of a single quantity.

- Connect correlation coefficients to relationships between two variables, primarily in a qualitative sense.

- Compare multiple measurements of a particular quantity, with associated errors, and determine whether the results are in agreement or disagree.

1.3 Teaching Toffees

Teaching toffees are practical tips based on the hard-won experience of fellow instructors.

For all GEAS lab exercises:

Please have students access the list of components for the lab exercise (lab chapter, video tutorial, web applications, report template) directly from the GEAS website so that they use the current version of all tools.

By having them save and share the lab report template, they will have their work backed up automatically and instructors will be able to observe their progress 24/7. This allows instructors to check for appropriate progress towards intermediate goals over a two-week period, and for students and instructors to interact asynchronously through threaded comments placed in the report margins at exactly the point where a question occurs. Note that the Lab #1 video tutorial describes how to work with Google resources, and there is a two-page handout on the lab website as well.

Students sometimes try to complete the lab exercise by skipping over the lab chapter entirely and working from just the report template. This is not an effective learning strategy, nor does it save time. The report template contains only abbreviated forms of the questions with spaces for answers, but none of the context or framework for the questions.

We strongly encourage you to strongly encourage all of your students to watch the video tutorial before beginning to work on the exercise. If a picture is worth a thousand words then a video might be worth a million words. Each tutorial is designed to introduce the scientific concepts that motivate the companion exercise. Because students may be working remotely on their own, it also focuses on the most potentially challenging aspects of each project and walks them through key steps by showing them what they look like in practice.

For Lab #1 in particular:

This lab #1 (Fundamentals of Measurement and Error Analysis) can serve as an effective introductory exercise for laboratory work in any of the scientific fields. It is not specific to astronomy.

The video tutorial for this exercise explains how to create a Google login (for those who may not already have one) and how to copy and save a copy of the lab report template. Students may use the provided Microsoft 365 report template instead if you wish; what is important is that they copy a current report template from the GEAS website and that they share it with you before beginning to work on the lab exercise so that you can observe their incremental progress and intervene if they go off track.

The video also describes how to approach conducting a simple experiment with repeated measurements, emphasizing general guidelines that apply to any experiment. The concepts of mean values and standard deviations for a set of measurements are introduced, and students are shown how to enter measurements into a plotting tool on the GEAS website to create an annotated histogram of their results. Students are then shown how to work with another student to reproduce each other's experiments, and to evaluate their results in doing so. Natural variation, and measurement and systematic errors, are discussed.

The next video topic is the plotting of one variable against another to determine a linear trend, with error bars attached to the dependent variable. A GEAS plotting tool is again used to create an annotated figure. Students are also shown how to save a plot as an image file and then insert it into a lab report.

A common challenge in conducting this laborator exercise is that it is generally placed at the beginning of the semester, and so students who add the class late will need to catch up quickly. Because students perform their own simple experiment and then reproduce another student's experiment, it is important that everyone completes their experiment on time so that they can be paired up and have time to do a second experiment (though note they will need to make only 7 measurements, not another 30) and compare results.

It is helpful to pair students who measure a length-scale for their own experiment with someone who measured something different (such as a weight) for variety, but it is not essential. If anyone weighs light objects which require a kitchen or jeweler's scale, make sure that their partner has access to similar equipment. Sometimes a particular experiment (throwing marshmallows, or measuring tortilla chip lengths) is very popular, and so one has to be careful to not end up with two or more students with the same experiment at the end of the pairing procedure.

We have been impressed with how supportive students generally are towards their partners; this exercise can be a good start to guiding students towards more peer-peer discussions throughout the semester. Student sometimes leave out a critical detail of their experiment design when describing it, and the impact that this has on their partner's attempts to reproduce their experiment bring home the importance of being thorough.

1.4 Keywords

Altitude – The altitude of an object in the sky is the number of degrees which it lies above the horizon. At local noon the Sun could have an altitude of 90 degrees (lying directly overhead), and as it sets the altitude falls to a value of zero.

Correlation coefficient – The correlation coefficient R is a measure of the strength of the relationship between two variables x and y. It ranges from -1 to 1, where +1 indicates the strongest possible positive correlation (as x increases, so does y), zero indicates no predictive relationship between quantities, and -1 indicates the strongest possible negative correlation (as x increases, y decreases). Correlation coefficients are well-suited for determining zero-point offsets in periodic relationships (such as syncing sine waves to remove phase offsets).

Data set – A data set is a collection of measurements made within an experiment.

Error bar – An error bar is a symbol attached to a point on a plot, which shows the associated error (how much the point have might shifted in position due the way in which it was measured). It often resembles a small bar (or line) placed on one side or another of the point value.

Histogram – A histogram is a plot which shows the number of measurements of a particular quantity which fall within bins defined to extend over the range of measured values. The bin size should be selected so that the bins with the largest number of measurements within them hold a statistically meaningful number of measurements, and should also not be smaller than the precision (the resolution) of the measurements.

JPG format – Images are often stored on computer disks in JPG-format files, a format which allows the files to be stored and transferred from computer to computer without loss of information. A JPG-format file should have a file name which ends with the extension ".jpg," so that the image analysis and display packages can recognize its contents.

Mean value – The mean value μ of a set of N repeated measurements m_i is defined to be the unweighted average, or

$$\mu = \frac{1}{N}\,(m_1 + m_2 + m_3 + \ldots + m_N) = \frac{1}{N}\sum_{i=1}^{N} m_i.$$

Measurement error – Measurement error refers to the precision with which a set of measurements were made (to how many decimal places the measured values were recorded).

Model – A model fit is a mathematical expression which attempts to reproduce the relationship between two or more variables.

Mu – The Greek letter "m" (μ), often associated with the average value of a set of measurements.

Natural variation – Natural variation refers to the intrinsic width of a distribution of a measured property.

Precision – The precision of a measurement is defined as the smallest change in its value which can be observed with a given experimental technique. A ruler with markings every millimeter (mm), for example, could carry a precision of ± 0.5 mm.

RMS (root mean square) deviation – The rms deviation is the square-root of the average square of the offsets in y between a set of N data points and a fit function. For a linear fit, where $y = mx + b$,

$$\mathrm{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[y_i - (mx_i + b)\right]^2}.$$

Scatter plot – See xy plot.

Sigma – The Greek letter "s" (σ), often associated with a measurement of a standard deviation.

Slope – The slope m of a line is the change in y divided by the change in x, or for two points along the line with coordinates (x_1, y_1) and (x_2, y_2),

$$m = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1}.$$

Standard deviation – The standard deviation σ, also called the spread, of a set of N repeated measurements m_i with an mean (average) value μ is defined as

$$\sigma = \sqrt{\frac{1}{N - 1} \sum_{i=1}^{N} (m_i - \mu)^2}.$$

Systematic error – A systematic error is one which biases all of a set of measurements in the same fashion (as opposed to making some smaller and some larger).

xy plot – A plot which shows the relationship between two variables by plotting one along an x-axis and the other along a y-axis is commonly called an xy, or scatter, plot.

y-intercept – The y-intercept b of a line is the y coordinate of the point on the line for which $x = 0$, or for two points along the line with slope m and coordinates (x_1, y_1) and (x_2, y_2),

$$b = y_1 - mx_1 = y_1 - \left(\frac{y_2 - y_1}{x_2 - x_1}\right) x_1.$$

1.5 Relevant Lecture Chapters

This laboratory exercises draws upon the material in Chapter 2: Scientific Notation and Chapter 9: The Scientific Method. There are peripheral connections to various astronomical topics discussed throughout the course. Questions in the self-review database for Chapter 9 review the statistical material and data fitting techniques for this exercise.

1.6 References and Notes

1. Data for summer temperatures at various locations around the globe were extracted from records at wunderground.com.

2. Figure 1.1 through Figure 1.8 are shown courtesy of Nicole Vogt.

Lab 2

Observing the Sky

2.1 Overview

This project is focused on naked eye observations of the sky – understanding the monthly lunar orbit, visualizing the positions of the Moon, Earth, and Sun throughout this cycle, and relating the changing appearance and position of the Moon in the sky to its phase, illumination and elongation angle. Students also estimate their own latitude from the observed altitudes of the transiting first quarter Moon and Polaris. They build on general skills introduced in the first laboratory exercise by reading and interpreting figures, planning and conducting observations, recording data accurately, and analyzing the results.

This is the only project that must be scheduled in accordance with outside factors, by taking into account the phase of the Moon. It is ideally scheduled to begin a few days after the new Moon occurs, with lunar observations being completed by the full Moon. There is considerable latitude in the start date, however, because students observe the Moon for a period of only eight days, and the project contains an alternate version of the lunar activity designed to be completed during the second rather than the first half of the lunar month. (The primary difference is that certain observations then need to be conducted at dawn rather than at dusk.)

This project contains multiple activities that encourage students to develop the skill of visualization. Visualization is used in two ways throughout the exercise, in the theoretical sense to understand the observed movements of the Moon and stars relative to the Earth and Sun, and in the practical sense to construct and then properly use simple sextants to observe objects against the sky. We employ textual discussion, exposition through figures, paper lunar phase wheels, and detailed demonstrations and animations within a video tutorial to guide students who may be working through the difficult process of making observations remotely without face-to-face guidance and feedback. Not unexpectedly, different students learn best from different subsets of these aids.

Students construct two sextant devices for this project, both built from common household materials. The first sextant (see Figure 2.1) is designed to measure the angle formed between the Moon and Sun on the sky (the lunar elongation angle). Students begin by backing a paper protractor with cardboard to form a stable plane. A sewing pin is pushed vertically through the protractor origin, with its head suspended 0.25″ above the plane. A folded paper tab at the end of the protractor marked 180° suspends a small circular target 0.25’″ above the plane as well. As the student points the end of the protractor marked 0° towards the Sun, the shadow of the pinhead will fall within the circular target. The student then rotates the protractor around the 0°–180° axis until the Moon lies within the plane of the protractor. With both the Sun and the Moon lying in the plane formed by the protractor, the angle between them (the lunar elongation angle) can be read off of the protractor.

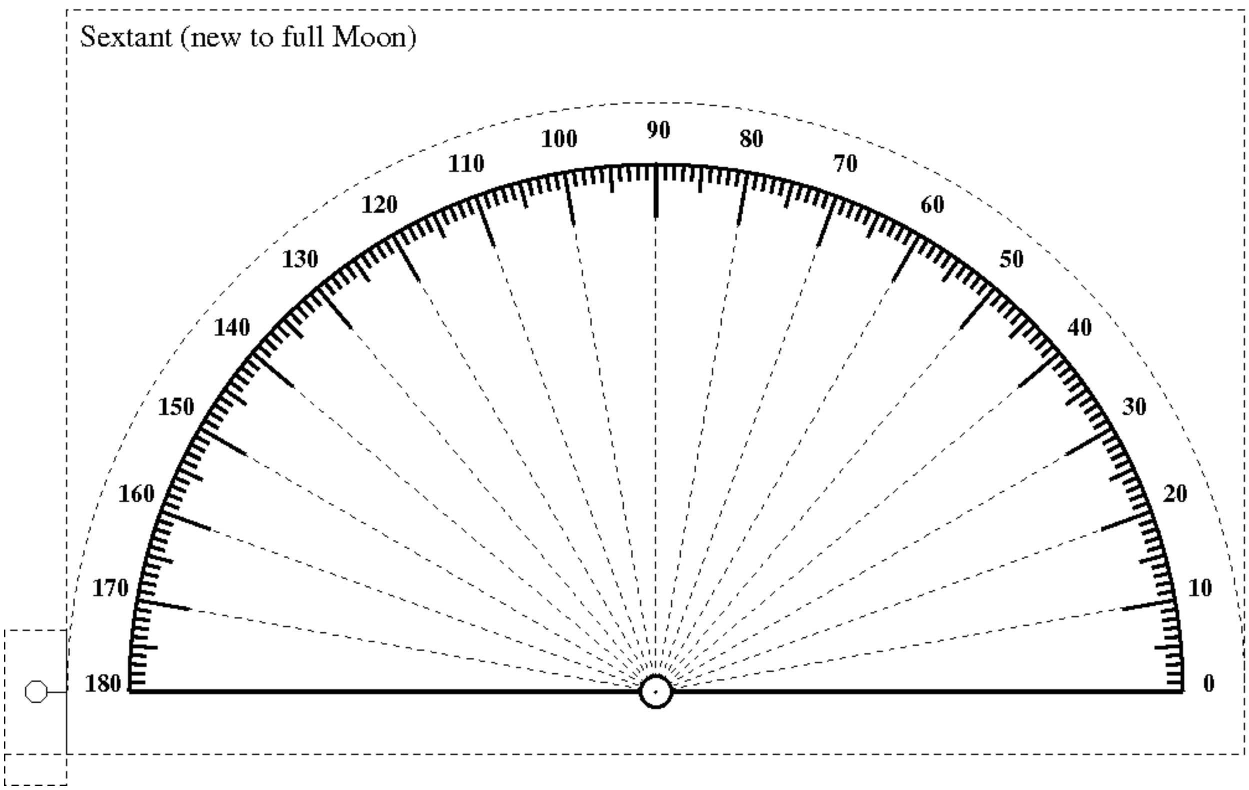


Figure 2.1: The basis of the sextant used to measure the lunar elongation angle (the angle between the Sun and the Moon on the sky). The tab on the left is folded up out of the page to form a backdrop to hold the shadow of a pin stuck through the origin, thus placing the Sun along the line marked 0°.

Students measure the lunar elongation angle over eight days. They record the date and time of day of each set of observations, measuring the elongation angle three times per session and also noting the fractional illumination of the Moon and its approximate phase. They then compute the elapsed time since the new Moon for each set of observations, and combine the MES angle measurements to produce mean values and standard deviations.

By observing the angle grow with time as the Moon "unwinds" its way around the Earth and away from the Sun, they strengthen their understanding of the lunar orbital path. By plotting the elongation angle over time they are able to determine the simple linear trend that it follows with time, and thus to predict the position of the Moon with each passing day. They also estimate the fractional illumination (by comparison with a table of partially illuminated images), and determine that it follows a sine wave trend over time.

Figure 2.1 shows a plot of the lunar elongation angle over time, with a weighted linear fit attached via our standard plotting tool. Error bars were estimated for each day by measuring the elongation angle three times and combining the results. Note that the small size of the error bars relative to the quality of the fit suggests that systematic errors (as opposed to randomly distributed measurement errors) play a role in the usage of the elongation angle sextant. This is usually due to minor construction flaws such as cardboard warps, and to subtle alignment biases in placing the pinhead shadow correctly.

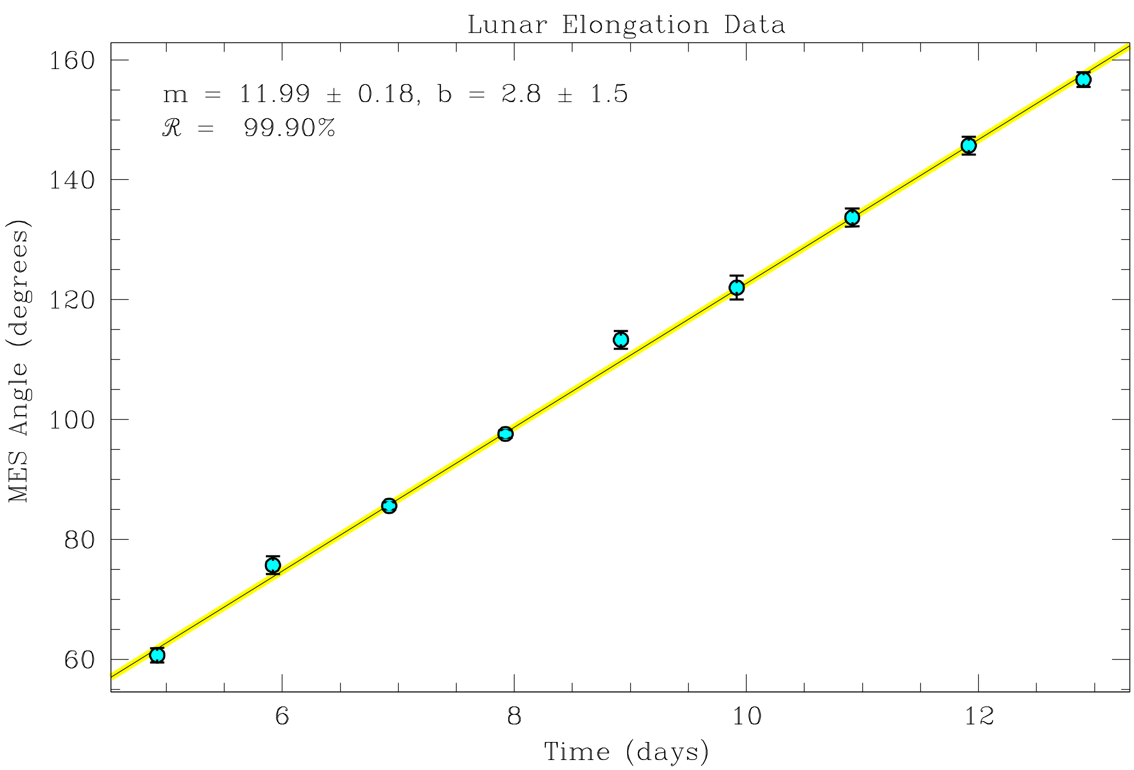


Figure 2.2: The distribution of sample data for the lunar elongation angle, with a clear linear trend and a high correlation coefficient (R). Students make their own observations, create their own plots, and then relate the slope and y-intercept of the linear fit to physical quantities (comparing the slope to the expected number of degrees that the Moon travels around the Earth each day, for example). Note that each such plot is labeled with the time of creation (to the nearest minute) and the student name (trimmed off here to preserve privacy).

The second sextant device is also based around a protractor. In this case, the student simply attaches a drinking straw to the 0°–180° axis and hangs a small weight from a thread looped through the origin. By finding the Moon or a star while looking through the tilted straw, its altitude can be read from the position of the thread lying along the protractor. Students use this sextant to measure the altitude of the transiting first quarter Moon (given its declination) and of the North Star, in order to estimate their own latitude. In this case the physical measurement is quite easy to make, while the larger challenge lies in connecting it conceptually to the observer's latitude. A distance education cohort of student can actually be a benefit in this instance, as students spaced out in latitude can compare their observations of the Moon's altitude made at a single time.

The GEAS website for this exercise contains a table of dates and time drawn from United States Naval Observatory data for new and first quarter Moon phases and for lunar declinations for first quarter Moon transits, as viewed from Las Cruces, New Mexico. We also provide last quarter Moon transit data for students who might need to perform their observations out of phase with their class cohorts. Data for alternate locations are added as needed, to support classes being taught in other locales.

In addition to the general plotting tool, this project employs a specialized plotting tool that allows students to plot their measurements of lunar illumination against time with a sine wave model. Though many of our students lack familiarity with trigonometric functions, they are able to contrast the curving ascension of the sine pattern with a linear fit, and to grasp the concept of variable fitting models and lines producing better or worse fits to data.

2.2 Learning Objectives

After completing this laboratory exercise, the student should be able to do the following:

- Visualize the monthly and yearly movements of the Earth and Moon around the Sun, and relate their locations in drawings to their positions in the sky.

- Understand and explain to others how the motions of the Sun, Earth, and Moon produce the monthly variations in lunar position, phase, and illumination.

- Predict the location and appearance of the Moon on a given date at a given time of the lunar month.

- Connect the latitude of an observer to the altitude of a transiting first quarter phase Moon, given its declination.

- Connect the latitude of an observer to the altitude of the North Star.

- Find the North Star and the Big Dipper in the northern sky.

- Comprehend the meaning of an angle, and relate the linear and angular sizes of an object at a given distance to each other.

- Make appropriate predictions based on information presented in the form of figures.

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For Lab #2 in particular:

This laboratory exercise contains observations to be completed during the third through eleventh days of the lunar month. Instructors should plan accordingly when scheduling it. Note that there is a poor weather back-up plan for observations to be done during the second half of the lunar month.

We *strongly* encourage instructors to perform all of the observations in this exercise for themselves, completely, before asking this of students. The difficulty of scheduling sky observations every evening for a eight-day period should not be underestimated. There also tend to be systematic biases in most of the observations that dominate the measurement errors derived by repeating measurements, leading to plots where the rms deviations are larger than would be expected from plotted error bars based purely on repeated measurements.

By taking your own observational data, you will best understand the difficulties inherent in doing so. You may also discover observational challenges which are peculiar to your region (such as bright lights which dominate the sky in a particular direction, or pernicious weather patterns for wind or rain). It takes practice to become confident using the elongation angle sextant, and you will best aid your students by drawing on your own experiences.

2.4 Keywords

Altitude – The altitude of an object in the sky is the number of degrees which it lies above the horizon. At local noon the Sun could have an altitude of 90 degrees (lying directly overhead), and as it sets the altitude falls to a value of zero.

Angular size, or extent – The angular size of an object is the size of the angle that it spans on the sky, typically expressed in units of degrees.

Arcminute – An arcminute is a unit of angular size, equal to 1/60 of a degree (recall that there are 90 degrees in a right angle). There are 60 arcseconds in an arcminute (see below).

Arcsecond – An arcsecond is a unit of angular size, equal to 1/60 of an arcminute or 1/3600 of a degree (recall that there are 90 degrees in a right angle). Astronomers often measure the angular separation between neighboring objects on the sky in units of arcseconds.

Astronomical unit – The average distance between the Earth and the Sun, equal to 1.5×10^8 kilometers.

Big Dipper – The Big Dipper is made up of the seven brightest stars in the northern hemisphere constellation Ursae Majoris (the Great Bear). It is both large and bright, and so forms a useful landmark in the northern sky. The two stars which form the outer lip of the "dipper" (bowl) shape lie along a line which points toward the North Star.

Cassiopeia – Cassiopeia is a northern hemisphere constellation which looks like a letter "W", making it easy to identify. It is located opposite to the Big Dipper (on the other side of the North Star).

Celestial equator – The celestial equator is the equatorial band of the celestial sphere (see below). It lies in the same plane as the Earth's equator.

Celestial sphere – The celestial sphere is an imaginary construct designed to aid in visualizing the positions and movements of objects through the sky. It comprises a spherical surface with an arbitrarily large radius, which is centered at the center of the Earth. It has a celestial equator which lies in the same plane as the Earth's equator, and celestial north and south poles which extend along the Earth's rotational axis above and below the Earth's North and

South Poles. Objects in the sky can be projected onto the celestial sphere, and their motions understood in the context of the Earth's motions around the Sun.

Culmination – See transit.

Declination – The declination of an astronomical body is its height (in degrees) above the plane defined by the Earth's Equator. It runs from 90° (due north) to −90° (due south).

Degree – A degree is a unit for angular measurements. A right angle contains 90 degrees, and a complete circle encompasses 360 degrees.

Ecliptic plane – The plane in which the Earth orbits about the Sun (inclined by 23° to the plane containing the Earth's equator).

Elongation – The elongation of an astronomical body is the angle between the body and the Sun, when viewed from the Earth. Elongations run from 0° (object aligned with the Sun) to 180° (object on the opposite side of the Earth from the Sun).

Equator – The Equator is the area on the surface of the Earth within the plane which is perpendicular to the rotation axis (running through the North and South Poles).

Gibbous – A moon or planet in the gibbous phase appears more than half, but less than fully, illuminated.

Horizon – The horizon is the boundary observed between the Earth and the sky. It extends in all directions (north, south, east, and west) around an observer.

Latitude – The latitude of a location on Earth is the number of degrees which it lies above the plane of the Equator. It takes on values between 90° (North Pole) to −90° (South Pole).

Linear size – The linear size of an object is its length, in units of length such as centimeters (small) or miles (large).

Little Dipper – The Little Dipper is made up of some of the brightest stars in the northern hemisphere constellation Ursae Minoris (the Little Bear). The North Star, Polaris, located almost due north, is the brightest star in the Little Dipper. It can be found at the end of the handle.

Mean value – The mean value μ of a set of N repeated measurements m_i is defined to be the unweighted average, or

$$\mu = \frac{1}{N}\left(m_1 + m_2 + m_3 + \ldots + m_N\right) = \frac{1}{N}\sum_{i=1}^{N} m_i.$$

Meridian – A meridian is an arc which projects from the North Pole to the South Pole and passes directly overhead for an observer. All observers located along a given meridian share a common longitude (the distance they lie east of the Royal Greenwich Observatory in

England), but have unique longitudes corresponding to how far north or south of the Earth's equator they lie.

Mu – The Greek letter "m" (μ), often associated with the average value of a set of measurements.

North Celestial Pole – The North Celestial Pole (NCP) is the projection of the Earth's North Pole upon the celestial sphere. One can think of it as the extension of the Earth's rotational axis arbitrarily high above the North Pole. The North Star, Polaris, lies very close to the NCP on the sky.

North Star – The North Star, or Polaris (the pole star), is a star which currently happens to lie almost due north of our planet, above the North Pole and along the Earth's rotational axis. Because of its location it is always above the horizon for observers in the northern hemisphere (and never above the horizon for those in the south). The northern night sky appears to revolve around this star, moving counter-clockwise in a full circle once every 24 hours. Because the earth's rotation axis wobbles, over tens of thousands of years it points slightly away from, and then back toward, the North Star. In ten thousand years, the title of North Star will be given to another, neighboring star in the vicinity.

Parallax – A technique for estimating the distances to objects, by measuring their apparent angular shifts on the sky relative to distant objects when they are observed from two separated locations.

Perturbation – A perturbation is a disturbance (in the force, or elsewhere). When the orbit of an astronomical body varies slightly (wobbling, or shifting back and forth), we often describe the variation as a perturbation.

Phase – For a periodic function, such as sine or cosine, the word phase is often used to define the shift of the function away from the default zero point by a fraction of a full period. For the Moon, we generally describe its appearance as it shifts from shadow into full illumination and back over the course of a lunar month in terms of the new, quarter, gibbous, and full phases.

Polaris – see North Star.

Sextant – A mechanical device used to calculate the angle on the sky between two objects, or the altitude of an object (its distance above the horizon).

Sigma – The Greek letter "s" (σ), often associated with a measurement of a standard deviation.

Slope – The slope m of a line is the change in y divided by the change in x, or for two points along the line with coordinates (x_1, y_1) and (x_2, y_2),

$$m = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1}.$$

South Celestial Pole – The South Celestial Pole (SCP) is the projection of the Earth's South Pole upon the celestial sphere. One can think of it as the extension of the Earth's rotational axis arbitrarily high above the South Pole.

Standard deviation – The standard deviation σ, also called the spread, of a set of N repeated measurements m_i with an mean (average) value μ is defined as

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (m_i - \mu)^2}.$$

Systematic error – A systematic error is one which biases all of a set of measurements in the same fashion (as opposed to making some smaller and some larger).

Transit – An astronomical object transits when it passes across the observer's meridian, an arc of constant longitude (the east/west coordinate) along the surface of the Earth connecting the North and South Poles and the observer's location. An object which is transiting lies either to the north, to the south, or or directly overhead of an observer. An object can be transiting for one observer, but appear far to the east or west in the sky for an observer at another location.

Ursae Majoris – A large, bright constellation in the northern hemisphere, named "the Great Bear." The well-known Big Dipper is a part of Ursae Majoris.

Ursae Minoris – A constellation in the northern hemisphere, named "the Little Bear." The well-known Little Dipper is a part of Ursae Minoris, as is Polaris, the North Star.

y-intercept – The y-intercept b of a line is the y coordinate of the point on the line for which $x = 0$, or for two points along the line with slope m and coordinates (x_1, y_1) and (x_2, y_2),

$$b = y_1 - mx_1 = y_1 - \left(\frac{y_2 - y_1}{x_2 - x_1}\right) x_1.$$

Zenith – The zenith is the direction pointing directly overhead for an observer.

Zenith distance – The zenith distance is measured in degrees, and is equal to the angle on the sky between an observer's zenith and an object. The sum of the zenith distance and the altitude is always equal to 90°, for an object.

2.5 Relevant Lecture Chapters

This laboratory exercises draws upon the material in Chapter 4: The Phases of the Moon, Chapter 5: The Seasons on Earth, Chapter 7: The Celestial Sphere, and Chapter 8: Planetary Orbits.

2.6 References and Notes

1. The observational plan (and Figure 2.4) for this exercise benefited greatly from images and information on the movements of major bodies of the solar system provided online by the United States Naval Observatory (USNO), at

http://www.usno.navy.mil/USNO/astronomical-applications/data-services

This is a great resource for planning sky observations from multiple locations or on different dates.

2. Figure 2.1 through Figure 2.3, Figure 2.5 through Figure 2.13, and the three attached sextant designs are shown courtesy of Nicole Vogt.

Lab 3

Cratering and the Lunar Surface

3.1 Overview

This exercise begins a two-exercise module exploring evolutionary processes on terrestrial surfaces. It contains a hands-on cratering activity, an analysis component in which students fit multiple models to their data and determine which physical model best reproduces the observed trend between projectile velocity and crater size, and a cratering simulation which enables them to predict the effects of various solar system projectiles impacting here on Earth (duck!).

Students begin by studying the lunar cratering record through surface images obtained through the National Aeronautics and Space Administration (NASA) Lunar Observer and other missions. They then create a series of craters by dropping ball bearings onto sand from varying heights. Seven craters are measured for each drop height, allowing us to reinforce the lessons from the first two laboratory exercises about averaging multiple trials in order to improve statistics. Drop heights range from one to thirteen feet, but safety is emphasized very strongly. Students are told to work at the highest heights only if they have access to a staircase with a solid banister, and otherwise to limit their activities to the lower range. This message is driven home in the project chapter, and also proactively modeled by student actors in the supporting video tutorial.

After converting drop heights to impact velocities, students plot velocity against crater diameter in a specialized plotting tool. Note that the interfaces for our general and our specialized plotting tools are as similar as possible, so that once students have been exposed to one of these tools they can recognize the common elements in the others. This tool performs a fit to the data for three models: projectile diameter proportional to projectile velocity, diameter proportional to velocity squared, and velocity proportional to diameter squared.

All three models are discussed and motivated in the chapter text, leaving the students to choose a best-fitting model by examining their data and the model curves. We expect them to evaluate the fits via two different methods. They are provided with RMS deviations for each model, and based on the ideas introduced in exercise one and reinforced in exercise two they are expected to associate the lowest RMS value with the best-fitting model. More fundamentally, however, we want students to be able to look at the plot and decide which line runs the closest to the centers of the points by eye. This skill is very under-developed in our students, many of who appear to have never read a plot in this fashion before. Though this is not a difficult task, it is not an intuitive action for them. We thus encourage them to assess the fits directly for themselves, and then to use the RMS deviations to confirm their model choices.

3.2 Learning Objectives

After completing this laboratory exercise, the student should be able to do the following:

- Appreciate that cratering has been an important process in shaping the appearance of the Moon's surface, and in shaping planetary surfaces in general.

- Distinguish between the heavily cratered, older lunar highlands and the younger, smoother and darker lunar maria.

- Understand both relative and absolute dating techniques, and describe the types of data needed to apply either method to lunar features.

- Realize that the Moon's surface, unlike that of the Earth, has changed little in the last three billion years, and that the once-high cratering rate has decreased markedly.

- Describe first-hand the experience of creating impact craters, and using the resulting data to define a relationship between impact velocity and crater diameter.

- Recognize that studying cratering processes and lunar craters can increase our understanding of the Earth's impact history, and the likelihood of future impacts.

- Identify key factors that determine the environmental consequences of impacts here on Earth.

- Realize that a catastrophic impact due to a six-mile meteoroid 65 million years ago produced a large crater and quite probably led to the extinction of the dinosaurs.

- Connect the act of plotting two variables against each other to the process of studying their intrinsic relationship.

- Understand the relationship between a mathematical model and its representation as a curve or set of points on a plot of relevant variables.

3.3 Teaching Toffees

Teaching toffees are practical tips based on the hard-won experience of fellow instructors.

For all GEAS lab exercises:

Please have students access the list of components for the lab exercise (lab chapter, video tutorial, web applications, report template) directly from the GEAS website so that they use the current version of all tools.

By having them save and share the lab report template, they will have their work backed up automatically and instructors will be able to observe their progress 24/7. This allows instructors to check for appropriate progress towards intermediate goals over a two-week period, and for students and instructors to interact asynchronously through threaded comments placed in the report margins at exactly the point where a question occurs. Note that the Lab #1 video tutorial describes how to work with Google resources, and there is a two-page handout on the lab website as well.

Students sometimes try to complete the lab exercise by skipping over the lab chapter entirely and working from just the report template. This is not an effective learning strategy, nor does it save time. The report template contains only abbreviated forms of the questions with spaces for answers, but none of the context or framework for the questions.

We strongly encourage you to strongly encourage all of your students to watch the video tutorial before beginning to work on the exercise. If a picture is worth a thousand words then a video might be worth a million words. Each tutorial is designed to introduce the scientific concepts that motivate the companion exercise. Because students may be working remotely on their own, it also focuses on the most potentially challenging aspects of each project and walks them through key steps by showing them what they look like in practice.

For Lab #3 in particular:

The three labs #1 (Fundamentals of Measurement and Error Analysis), #3 (Cratering and the Lunar Surface), and #4 (Cratering and the Martian Surface) can form a cohesive six-week sequence, particularly for classes which emphasize the solar system or geology.

The video for this exercise shows a group of three students working together to conduct the cratering experiment. They describe the use for each piece of equipment, review how to carefully measure a crater diameter along a ruler, and discuss the need to make a series of craters at each height to improve measurement accuracy.

Safety is prioritized, with the students placing their ball bearing within a small plastic canister (such as a pill bottle) before tossing it back and forth and also being careful to carry the projectile to increasing heights by ascending a stable, well-lit staircase with a solid handrail in a public area. All students must be informed that they may skip conducting the experiment from any heights (in particular for the final two positions at 10 and 13.3 feet) where they feel unsafe, and that they should not use a step ladder or anything else other than a stable staircase for this purpose.

The video also reviews how to enter data into the online plotting tool, and explains how to read the resultant plot with the data points presented on top of three possible model lines.

It then takes students through the process of using the Earth Impact Effects program to model the effect of crater impacts on our home planet. Note that this program is an external resource; we link to a workhouse version which operates through an HTML form, and a snazzier version which utilizes Flash. Both versions produce identical results for identical inputs.

This lab requires a roughly one foot diameter container filled with sand and a top layer of salt (or similar substances), and a ball bearing or marble. If students will work remotely, it is most helpful to let them know about these requirements at the beginning of the course so that they can plan ahead to secure appropriate materials. For students working remotely within driving distance of campus, it is beneficial if instructors are able to offer loaner kits of these items. The sand and salt can often be scooped out and reused over and over, as long as the salt is kept fairly clean and uniform in consistency. It is fine if a bit of salt gets mixed into the sandy lower layer over time.

When conducting this experiment in person with large groups of students, keep in mind that people can work through the first five heights (up to five feet) while simply standing next to their bucket (though having drop heights marked along a wall is helpful if possible). If instructors can set up stations along a staircase at the final three heights (6.7, 10, and 13.3 feet), students can then shift their buckets through those stations in turn fairly efficiently. One can gain an additional factor of two by having half of the group work with the Earth Impact Effects program before conducting the experiment and half do so afterward, if space and sand buckets are limited.

As a rule students do remarkably well conducting this experiment, and their data generally point fairly clearly to the expected model. If a student produces unexpected measurements (with huge scatter or matching one of the other models), the cause is most likely to be the use of a hard-packed material rather than something which is dry, loose, and granular as a surface. If a data set shows no trend with projectile height and the crater diameter is similar to the projectile diameter, the projectile has probably shot straight through the surface layer without interacting at all. If this happens with a steel ball bearing, then switching to a glass marble projectile can often solve the issue. Instructors may find requesting a photograph of a crater, or even a short video of an impact, to be helpful in diagnosing these issues.

The most common conceptual error made by students is to argue that their chosen model is correct because crater diameter increases with projectile velocity/height. It is helpful to emphasize that this trend occurs for all three models, and so does not serve to discriminate between them.

3.4 Keywords

Absolute dating – Absolute dating refers to the process of assigning absolute ages to physical samples (such as rocks) or to geologic events. These ages are usually based on radioactive decay rates.

Central peak – A central mountain peak is produced when molten excavated material from an impact blast flows back towards the center of the excavation and creates an uplift. This typically occurs at the center of large craters, those which are 40 kilometers or more in diameter.

Crater – A crater is a generally circular surface depression, caused by an impact or an explosion, a volcano, or a geyser.

Crystalline rock – Crystalline, or igneous, rock forms as molten rock cools and crystallizes. It is generally harder and denser than sedimentary rock. Granite is an example of crystalline rock.

Density – The density of a three-dimensional object is equal to its mass divided by its volume (or the mass per unit volume), and is typically measured in units of grams per cubic centimeter, or kilograms per cubic meter. The density of water is one g cm^{-3}, while rock is roughly three times more dense, and steel has a density of eight g cm^{-3}. to the surface density of features found on a planetary surface, for example, with units of counts (the number of features) per unit area.

Ejecta – Ejecta refers to a blanket of material surrounding a crater that was excavated during an impact event. The ejecta will become thinner at increasing distances from a crater.

Impact crater – An impact crater is one produced by the collision of an object with a planetary body's surface.

Kinetic energy – Kinetic energy is commonly referred to as energy of motion, and is equal to one-half of an object's mass times the square of its velocity.

Law of Cross-Cutting Relations – The law of cross-cutting relations states that any geological feature that cuts across another geological feature must be younger (must have formed later) than the feature it disturbed.

Maria – The lunar maria are the dark, smooth regions believed to represent ancient lava flows. They are generally younger than the heavily cratered highlands. They were immortalized in Bernstein and Sondheim's 1956 West Side Story.

Meteoroid – A meteoroid is a particle of rocky or metallic debris found in space. If a meteoroid enters the Earth's atmosphere it becomes a meteor, and upon landing any surviving remnant is called a meteorite.

Plate tectonics – Plate tectonics defines a theory of planetary surface dynamics in which a planet's outer skin (the lithosphere) is broken into plates. These plates are driven by internal heat, and shift and interact in various ways (including collisions).

Projectile – A projectile is an object that is launched or dropped into space, or into an atmosphere. It is sometimes called an impactor, once it has struck a surface.

Radioactive – An radioactive isotope of a particular element is unstable, and will decay into other elements and isotopes over time. We define the "half-life" of a radioactive sample as the amount of time in which half of its atoms will decay into another state. By comparing the relative amounts of various isotopes of key radioactive elements, we can often determine absolute ages for samples of various materials.

Rays – Rays are bright linear streaks extending radially outward from certain craters, most notably young ones like Tycho and Copernicus on the Moon. They indicate the presence of thin deposits of lighter material.

Relative dating – Relative dating refers to the process of placing an event along a time line relative to other events (before them or after them), without defining a specific time for any event.

Sedimentary rock – Sedimentary rock, such as limestone or sandstone, is rock that was originally laid down as horizontal sediment (deposited by water, air, or ice). Contrast it with igneous rock, which is formed by the cooling of molten rock.

Terraces – Terraces are stair-like levels in the sloped walls of craters.

Terrestrial – The term "terrestrial" means Earth-like or pertaining to the Earth's surface. Planets with rocky surfaces are sometimes called Terrestrial planets, in contrast to the Jovian gas giants.

Velocity – The velocity of an object is its speed in a particular direction. It has units of distance traveled per unit time, such as miles per hour, or centimeters per second.

3.5 Relevant Lecture Chapters

This laboratory exercises draws upon the material in Chapter 12: The Terrestrial Planets. There are related materials in Chapter 6: The Origin of the Moon and Chapter 11: The Formation of the Planets.

3.6 References and Notes

1. The left-hand image in Figure 3.1 is a mosaic of lunar images collected by the Clementine spacecraft in 1994 [NASA/USGS/ASU]. All three images shown in Figure 3.1 are shown courtesy of NASA.

2. Figure 3.2 is a portion of a larger lunar orbiter image [NASA].

3. Figure 3.3 is an adaptation of a figure taken from D.E. Gault's 1970 article in Radio Science, volume 5, #2, page 277, with permission being given by Dr. Shane Bryne of the Lunar and Planetary Lab of the University of Arizona.

4. Figure 3.4 is composed of two lunar orbiter images of the Apollo mission landing sites (photo IV-125-H3 of Apollo 12, and photo IV-089-H3 of Apollo 16) [NASA].

5. The primary and secondary images in Figure 35 are #C223 and #N5818 from the Consolidated Lunar Atlas, of the Lunar & Planetary Institute [NASA].

6. The basis for the account of the Giordano Bruno crater study is

www.psrd.hawaii.edu/Feb10/GiordanoBrunoCrater.html

which is partially based on the following Plescia, Robinson, & Paige 2010 conference proceeding

www.lpi.usra.edu/meetings/lpsc2010/pdf/2038.pdf.

7. Figure 3.6 is a portion of a larger Landsat satellite image [NASA].

8. The Earth Impact Effects program is used courtesy of Robert Marcus, H. Jay Melosh, and Gareth Collins of Imperial College, London. Detailed information regarding the program can be found in Collins, Melosh & Marcus 2005 publication in Meteorics & Planetary Science, volume 40, #6, pages 817-840.

9. Certain physical measurements for the asteroid 99942 Apophis were taken from its Wikipedia entry.

Lab 4

Cratering and the Martian Surface

4.1 Overview

Exercise four continues our study of terrestrial surface evolution, shifting from the Moon to Mars and exploiting an extensive reservoir of recent high-resolution Martian surface imaging. While exercise three centers on a hands-on cratering experiment, exercise four presents another side of scientific experimentation by having students analyze the terrain within ten surface images drawn from NASA spacecraft archives. These images cover regions dominated by volcanic activity, water-carved features, and water floods caused by volcanic activity studied by the Thermal Emission Imaging System (THEMIS) and the Mars Orbiter Laser Altimeter (MOLA). The cratering record (the surface density of craters of various sizes) is used as a proxy for surface age.

Surface images are presented through a dedicated web-application with pre-loaded images. As shown in Figure 4.1, the tool contains a large-scale view of the surrounding region and a detailed close-up image of a central region extending over a width of three to seventeen kilometers. Students identify and count craters of 250 to 500 meters in size on the larger regions, and focus on smaller craters (down to radii of 16 meters on images with scales of three meters per pixel) on the smallest, highest-resolution, images.

There are several lessons to be learned from the cratering counts data analysis, in addition to the specific topics related to surface evolution. The first is to acquire the skill of reading logarithmic axes, and to understand how logarithms allow us to study behavior over many orders of magnitude. We devote a stand-alone guide to this topic and also focus on it during the associated video tutorial, to help students to understand how to perform the task. The second lesson relates to measuring the number of craters on a given surface down to more than one size limit in order to make multiple estimates of the same surface age. The third lesson relates to the natural distribution of craters across a surface, and the idea that by

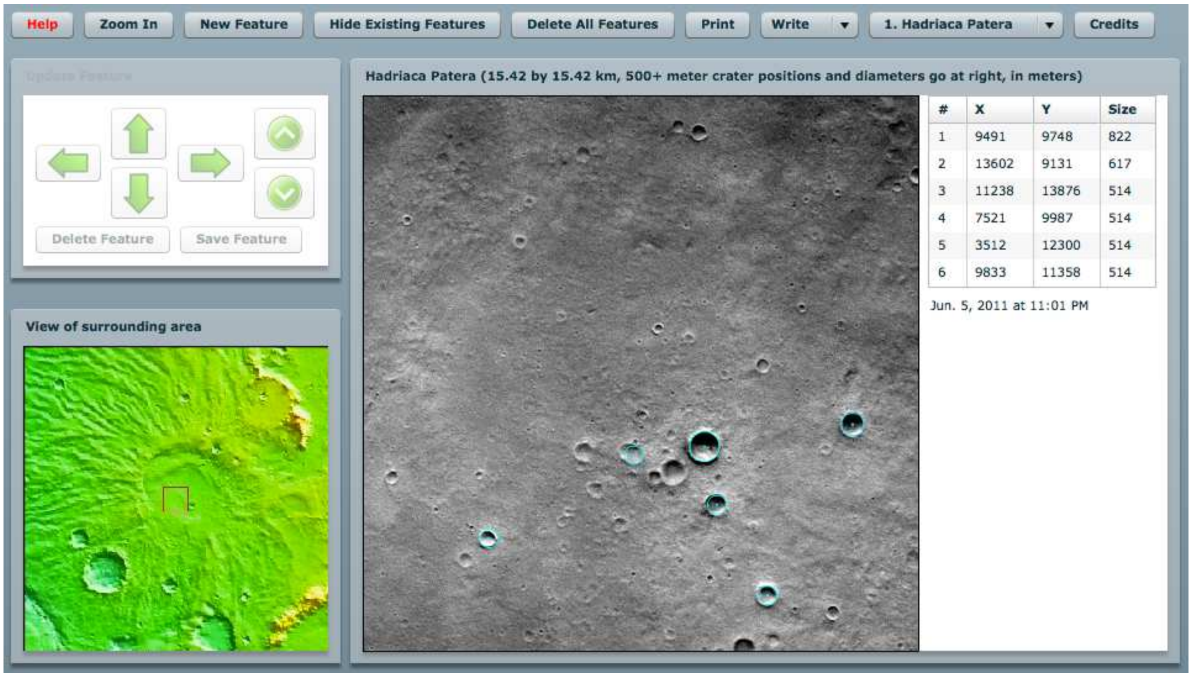

Figure 4.1: A screen capture of our Martian cratering web-application, presenting large-scale color images of regions characterized by various types of surface evolution and close-up, higher-resolution black and white images of central regions for analysis. Students identify all craters that are larger than a certain size within each close-up image. The crater counts are then used to determine an age for the region. Circles are overlaid on top of each crater and adjusted in position and size to match each feature, and a zoom option allows students to focus on individual features.

increasing the size of the sampled region we reduce the relative size of the associated errors on the crater counts, due to Poisson statistics.

4.2 Learning Objectives

After completing this laboratory exercise, the student should be able to do the following:

- Appreciate the breadth of Martian geological and climate history.
- Describe the appearance of the Martian surface, understand why certain features occur in certain regions, and discuss the available physical evidence regarding probable evolutionary histories.
- Estimate local surface densities of craters, given detailed images and physical scale measurements, in order to determine the ages of varied surfaces.
- Compare and contrast Martian and terrestrial volcanoes, understand the history of

volcanism on Mars, and discuss whether Martian volcanoes are still active, given the available evidence for recent eruptions.

- Compare and contrast Martian and terrestrial water histories, evaluate the history of surface water flow volcanism on Mars, and discuss evidence for recent surface water flows on Mars.

- Distinguish between network valleys and outflow channels, by morphology.

- Read values from a logarithmic plot, and understand how it differs from a linear plot.

- Create histograms of several samples of data, and decide whether or not differences between the samples are statistically significant.

4.3 Teaching Toffees

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Students sometimes try to complete the lab exercise by skipping over the lab chapter entirely and working from just the report template. This is not an effective learning strategy, nor does it save time. The report template contains only abbreviated forms of the questions with spaces for answers, but none of the context or framework for the questions.

We strongly encourage you to strongly encourage all of your students to watch the video tutorial before beginning to work on the exercise. If a picture is worth a thousand words then a video might be worth a million words. Each tutorial is designed to introduce the scientific concepts that motivate the companion exercise. Because students may be working remotely on their own, it also focuses on the most potentially challenging aspects of each project and walks them through key steps by showing them what they look like in practice.

For Lab #4 in particular:

The three labs #1 (Fundamentals of Measurement and Error Analysis), #3 (Cratering and the Lunar Surface), and #4 (Cratering and the Martian Surface) can form a cohesive six-week sequence, particularly for classes which emphasize the solar system or geology.

The video for this exercise includes a detailed introduction to our crater-fitting web application, highlighting each of the controls used when fitting a circular aperture to a crater to illustrate their usage. It shows how to derive a crater surface density from the number of craters above a given size found within a field, and then how to determine a corresponding surface age from Figure 4.5. This includes an explicit description of how to read values along the logarithmic axes. This is followed by a filmed meeting between a teaching assistant and a student, in which the student models common concerns about how to work with logarithms and goes through the process of reading values along an axis.

The most challenging mathematical aspect of this exercise is the idea of logarithms, and their utility in illustrating behavior over many orders of magnitude. Students who are unfamiliar with logarithmic plots should benefit from the video tutorial, particularly if they first read through the two-page handout on Linear and Logarithmic Plots and then review it while following along with the tutoring session in the video.

A common mistake is to treat the space between successive small tick marks on an axis linearly rather than logarithmically, when placing an intermediate value on the axis between two tick marks. However, because these spaces represent at most a factor of two change in value, the resulting error in determining a surface age will not invalidate the result. It is definitely helpful to explicitly tell students to not simply default to the closest tick mark to their value, but to make a point of interpolating between tick marks.

A student can in fact complete the exercise with an incomplete comprehension of logarithms and still understand how ages are being derived from crater counts and determine usable age estimates for each field.

The most common computational error made by students is to divide by the wrong surface area (typically reusing a surface area found for a previous field) when computing a surface density of craters, or to forget to divide by any surface area at all.

Occasionally a student will miss the fact that for the Hadriaca Patera field the number of craters larger than 250 meters is given to them in the exercise text – they do not need to count additional craters on the image down to the lower size limit.

4.4 Keywords

Amazonian Period – The last of three major periods in Martian history, lasting from 1.8 billion years to the present. This era is named for Amazonis Planitia, a low plain in the northern hemisphere. Amazonian surfaces exhibit a varied morphology, but contain relatively few impact craters. The bulk of the historical record of cratering on these surfaces has been erased by lava flows, glacial activity, and even occasional liquid water flows. Much of the northern hemisphere is thought to have been resurfaced during the Amazonian Period.

Billion – Ten raised to the ninth power, or $1,000,000,000$.

Caldera – A caldera is a circular crater, the relic of a volcanic explosion or the collapse of a volcanic cone. Caldera is also the Spanish word for cauldron, in reference to the basin-shape of the depression.

Central vent volcano – A volcano with a central vent is constructed as debris and lava are ejected from an upthrust, cylindrical vent, forming a symmetrical structure around it.

Crater – A crater is a generally circular surface depression, caused by an impact or an explosion, a volcano, or a geyser.

Density – The density of a three-dimensional object is equal to its mass divided by its volume (or the mass per unit volume), and is typically measured in units of grams per cubic centimeter, or kilograms per cubic meter. The density of water is one g cm^{-3}, while rock is roughly three times more dense, and steel has a density of eight g cm^{-3}. One could also refer to the surface density of features found on a planetary surface, for example, with units of counts (the number of features) per unit area.

Hesperian Period – The second of three major periods in Martian history, lasting from 3.5 till 1.8 billion years ago. This era is named for Hesperia Planum, an elevated plain in the southern hemisphere. The largest volcano on Mars, Olympus Mons, was active during this time. Surfaces dating back to the Hesperian lack the pattern of large, densely packed craters characteristic of the older Noachian era, as many were erased by intense volcanic activity. Large bodies of water, and catastrophic releases of water, were also believed to be common, and carved channels in regions like the Chryse Palitia basin. The southern hemisphere contains many regions thought to date back to the Hesperian Period.

Impact crater – An impact crater is one produced by the collision of an object with a planetary body's surface.

Lava – Lava flows are streams of liquid rock, or magma, which reach the surface of a terrestrial body through volcanic eruption.

Logarithm – The word logarithm comes from the Greek words for *proportion* and *number*, and means "a number that indicates a ratio." In the expression $x = 10^e$, the exponent e is the base 10 logarithm of the number x. When we plot numbers on a logarithmic scale, we can compare data over wide ranges on a single plot. As ones moves along a logarithmic axis by set amounts, one multiplies by a certain factor (rather than adding a certain amount, as is done along a linear axis).

Mercator projection – A Mercator projection is a cylindrical map of a spherical surface, such as the surface of a planet. By convention, west and east run from left to right, with north at the top and south at the bottom. Because lines of constant latitude are spread out across the entire plot, the regions near to the poles are greatly extended in width relative to those at the equator. (This is why Greenland, Iceland, and Antarctica, for example, appear so huge on Mercator projections of the Earth's surface.)

Meteor – The term meteor is used to refer to a particle of debris (space dust) which has entered the atmosphere of a planet or satellite. It also refers to the visible path left by such an object.

Meteoroid – A meteoroid is a particle of rocky or metallic debris found in space. If a meteoroid enters the Earth's atmosphere it becomes a meteor, and upon landing any surviving remnant is called a meteorite.

Million – Ten raised to the sixth power, or $1,000,000$.

Network valley – A network valley is one of a set of branching valleys found on Mars, with a resemblance to terrestrial river drainage basins. They are usually less than five kilometers wide, though they may extend for thousands of kilometers in length.

Noachian Period – The first of three major periods in Martian history, dating from formation epoch 4.5 billion years ago to 3.5 billion years ago. This era is named for Noachis Terra, a large southern hemisphere highland. Surfaces dating back to the Noachian are covered with many craters, and exhibit the largest impact craters, but widespread evidence for water erosion suggests that the planetary surface was warm and wet during this time. They are found predominantly in the southern hemisphere.

Outflow channel – An outflow channel is a particular type of surface feature found on Mars. Outflow channels are wide and long, and contain streamlined remnants of ancient features which have been sculpted by the passage of fluids (such as lava or water flows). They can extend over hundreds of kilometers in length, and can be up to a few hundred kilometers wide as well. Kasei Vallis is a prominent example of such.

Plate tectonics – Plate tectonics defines a theory of planetary surface dynamics in which a planet's outer skin (the lithosphere) is broken into plates. These plates are driven by internal heat, and shift and interact in various ways (including collisions).

Proto-planetoid – This word is a combination of "proto", meaning first or earliest, and "planetoid," meaning minor planet. The proto-planetoids in the early solar system were the largest of the building blocks which combined (through collisions) to form the major planets which we know, and love, today.

Rille – The word rille (also rill) is used to denote long trenches, or brooks or streams, and was often used in describing lunar features seen through the first telescopes.

River delta – A river delta is land formed from sediment (silt) that builds up at the mouth of a river, where it flows into an ocean or other large body of water.

Scablands – Scablands are erosive features, composed of flat, elevated land characterized by poor soil and little or no vegetation, marked by dry channels which formed through the action of glaciers. The Channeled Scablands of the state of Washington were created by the Missoula Floods during the Pleistocene era, and are the most well-known of such features.

Shield volcano – A shield volcano is one that has built up from fluid lava flows. The name comes from the distinctive large, extended size and low height (low profile), giving rise to a shape that resembles the shield of a warrior.

Terrestrial – The term "terrestrial" means Earth-like or pertaining to the Earth's surface. Planets with rocky surfaces are sometimes called Terrestrial planets, in contrast to the Jovian gas giants.

Topography – A topographical representation of a region involves a detailed physical description, including the relative positions and elevations of features.

Trench – A trench is a long ditch, or a long steep-sided valley.

Tributary – A tributary is a stream that flows into a larger body of water.

Watershed – A watershed is an elevated ridge of land which divides two regions which drain into separate rivers, or a single region which drains into a river or other body of water.

4.5 Relevant Lecture Chapters

This laboratory exercises draws upon the material in Chapter 12: The Terrestrial Planets and Chapter 11: The Formation of the Planets.

4.6 References and Notes

1. The images used in the Martian craters web-application are images from NASA spacecraft. All Thermal Emission Imaging System (THEMIS) images are used courtesy of NASA, JPL, and Arizona State University.

(a) A detailed image (a subset of V01433003) of Hadriaca Patera was taken by THEMIS, and an overview image of the surroundings was taken by the Mars Orbiter Laser Altimeter (MOLA). An appropriate journal reference for MOLA is "The Global Topography of Mars and Implications for Surface Evolution," by Smith et al. in *Science*, vol. 284, pp. 1495-1503 (1999).

(b) A detailed image (a subset of E1001691) of Pavonis Mons was taken by the Mars Orbiter Camera, and an overview image of the surroundings was taken by MOLA.

(c) A detailed image (a subset of M1003730) of Arsia Mons was taken by the Mars Orbiter Camera, and an overview image of the surroundings was taken by MOLA.

(d) A detailed image (from orbit 40364) of channelized flows on the southwestern flank of Olympus Mons was taken by THEMIS, and an overview image of the surroundings was taken by MOLA.

(e) A detailed image (a subset of V33498005) of Nirgal Vallis was taken by THEMIS, and an overview image of the surroundings was taken by MOLA.

(f) A detailed image (a subset of V12508008) of Tiu Vallis was taken by THEMIS, and an overview image of the surroundings was taken by MOLA.

(g) A detailed image (a subset of V07993006) of Warrego Vallis was taken by THEMIS, and an overview image of the surroundings was taken by MOLA.

(h) A detailed image (a subset of V01786010) of Ares Vallis was taken by THEMIS, and an overview image of the surroundings was taken by MOLA.

(i) A detailed image (a subset of V02544003) of Dao Vallis was taken by THEMIS, and an overview image of the surroundings was taken by MOLA.

(j) A detailed image (a subset of MOC-m0703839) of Cerbeus Fossae was taken by the Mars Orbiter Camera, and an overview image of the surroundings was taken by the Viking craft.

2. Figure 4.1 is a mosaic of four crater images. The 2006 image of Crater Lake, a caldera lake in Oregon, is shown under a GNU Free Documentation License, courtesy of Pakistani photographer Zainub Razvi. The image of Ceraunius Tholus was taken with the Mars Orbiter Camera (a subset of MOC2-305) on the NASA Mars Global Surveyor spacecraft. The image of Hyginus Crater (frame 3073 in the Lunar Orbiter Photo Gallery at the Lunar and Planetary Institute) was taken with the NASA Lunar Orbiter 3. The 2010 image of Mauna Kea, a Hawaiian volcano with an abundance of telescopes, is shown under a GNU Free Documentation License, courtesy of Wikipedia contributor Nula666.

3. Figure 4.2 contains three NASA images of the Martian surface; it is used courtesy of the U.S. Geological Service. It can be found in an online lesson plan on impact craters, at http://arizona.usgs.gov/Flagstaff/Outreach/CenterEPO/craters/2relage/ra_OH2.pdf.

4. Figure 4.3 is a Mercator projection of the entire Martian surface, assembled from albedo images taken with THEMIS on the NASA Mars Global Surveyor spacecraft. The journal reference is "The Mars Global Surveyor Thermal Emission Spectrometer Experiment: Investigation description and surface science results," by Christensen et al. in *The Journal of Geophysical Research*, vol. 106, 23, pp. 823-871 (2001).

5. Figure 4.4 is a relief map (derived from altimetry) of the Tharsis Montes region on Mars, taken with MOLA on the NASA Mars Global Surveyor spacecraft.

6. Figure 4.5 was created by Nicole Vogt and is based on information provided in the journal article "Martian Cratering VI: Crater Count Isochrons and Evidence for Recent Volcanism from Mars Global Surveyor," by William K. Hartmann in *Meteoritics and Planetary Science*, vol. 34, pp. 167-177 (1999).

7. Figure 4.6 is an image of Martian lava flows taken with the Mars Orbiter Camera (a subset of MOC2-m0701051) on the NASA Mars Global Surveyor spacecraft. It is centered in the northeast Cerberus plain, north of Tartarus Colles.

8. Figure 4.7 is an image of Ares Vallis taken with THEMIS (a subset of V01786010) on the NASA Mars Global Surveyor spacecraft and produced by NASA/JPL/Arizona State University.

9. Figure 4.8 contains four NASA images of the Jovian moons Callisto, Europa, Ganymede, and Io, all taken with the Galileo Orbiter spacecraft. The image of Callisto is a subset of MRPS93539, which was produced by the Jet Propulsion Laboratory; P48507 MRPS79079 of Europa was produced by Arizona State University; P50040 MRPS89768 of Ganymede was produced by Brown University; MRPS96034 of Io was produced by the University of Arizona.

10. Figure 4.9 is of the Ceraunius Caldera floor, in the Ceraunius Tholus region on Mars, taken with the Mars Orbiter Camera (a subset of MOC2-489) on the NASA Mars Global Surveyor spacecraft and produced by Malin Space Science Systems.

Lab 5

Parallax Measurements and Determining Distances

5.1 Overview

Exercise five centers on a hands-on activity where students perform their own parallax measurements, measuring angular shifts in nearby object positions based on changes in observer vantage point and then connecting their experiment to larger-scale parallax measurements conducted on semi-yearly timescales to measure analogous shifts for nearby Milky Way stars.

As in exercise two, students build their own measuring device and then use it to conduct an astronomical experiment. In this case the device (shown in Figure 5.1) is similar to a surveyors transit. Students begin with a rigid piece of cardboard 30 inches wide and six inches across. They mark two observing positions with upright posts formed by paper clips, separated by a distance of two feet. This separation length is analogous to the two astronomical units that separate the Earths positions at six-month intervals. The right-hand post is also the origin of a small paper protractor that is taped down to the cardboard so that the two posts both lie along the 0°–180° axis.

Students then align a nearby foreground object (within thirty feet of the transit device) so that it lines up with a distant object (at least 200 feet away) when viewed from the left-hand post. When they move two feet to the right and work from the right-hand post, the two objects will no longer line up. They measure the angular gap between the two objects (a gap which was zero at the left-hand post) and then use these data to determine the distance to the nearby object.

We use a slightly more complicated transit device when working face-to-face with students. This version has a protractor fixed at both vantage positions. This enables students to

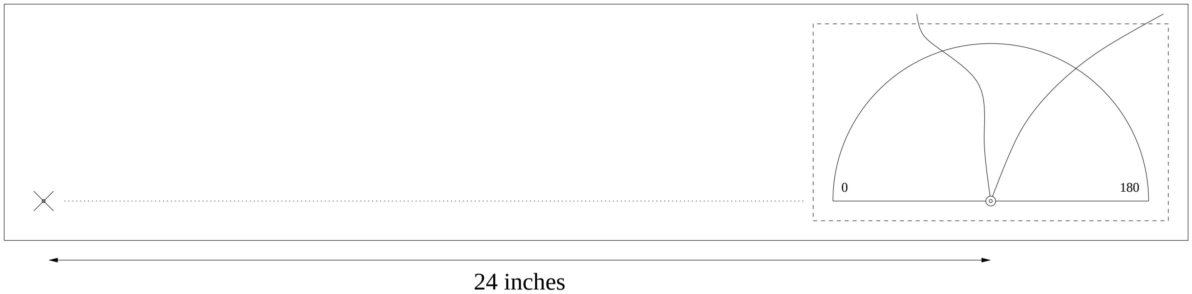

Figure 5.1: The parallax transiting device, used to determine the distances to nearby objects by measuring their angular positions from two vantage points. The device has a base formed from a piece of cardboard 30 inches long. A paper protractor is taped to the right side, and an "X" is marked exactly 24 inches to the left of its origin. This two-foot distance represents the two astronomical units between the Earth's position around the Sun during January and July. Straightened paper clips are attached perpendicular to the surface at the protractor origin and the "X" mark, to mark sight-lines. A piece of thread is doubled and secured at the protractor origin, to create two threads that can be rotated around the protractor to mark various angles between 0° and 180°.

confirm directly that the nearby and distant objects lie at the same protractor angle when viewed from the left-hand post, and to see for themselves that the angular position the distant object is the same when viewed from either vantage point. We remove the second protractor from the device when students are working alone, to minimize confusion about having a measuring tool on which no measurements need to be made to complete the experiment. (The second protractor is a good aid to comprehension, but can complicate the experimental process for students who are not confident in visualizing the entire experiment ahead of time.) It also requires that the two protractor axes be aligned precisely with each other along the length of the cardboard.

As in previous exercises, measurements are made repeatedly to estimate measurement errors, and to attach error bars to derived distances to objects. Students compare their parallax-derived distances to directly-measured distances. If their measurements differ by more than five standard deviations they critique they critique their experimental design, set-up, and process to hypothesize about possible significant causes for the differences. As in previous exercises, success is not defined by whether or not they can determine the exact same distance to an object via the two techniques. We are more concerned with developing their skills to quantitatively compare measurements, to determine whether or not measurements agree, and to judge for themselves the strengths and the limitations of their experiments.

The results of the experiment are quite good in most cases. The differences between distance derivations are a few percent for distances out to ten feet, and stay below 20% at the largest distances (30 feet) where the measured angular shifts are only a few degrees. Roughly 3/4 of our students report differences of less than two standard deviations, and the remaining 1/4 are able to suggest reasonable causes for their larger disagreements.

We have found that there are typically numerous safe, well-lit locations available to students to conduct their parallax experiments. Multi-story buildings with large windows provide access to views of lamp posts, radio towers, and mountains, and nearby object samples can draw on existing distributions of sign posts and trees or be formed from water bottles sitting on stools, for example. Libraries of all sorts are popular experimental sites, and librarians are usually supportive of our students' educational efforts. During daylight hours on days with good weather, the entire experiment can be conducted outdoors. Our video tutorial follows a pair of students working through the transit device construction and the complete process of the doing the experiment for clarity, as well as emphasizing safe and unsafe locations to use.

The experiment proper goes more smoothly and faster with a partner, one who needs no training in astronomy to be of assistance in shifting objects and holding down ends of measuring tapes. We have found that older children can function well in this role, and students who are parents are often pleased to be able to involve their children in their studies this way (as can also be done in exercises one, two, and three).

A potential sticking point in early versions of this exercise involved the use of trigonometry. We worked with multiple pilot groups of students who demonstrated no familiarity with or comprehension of sines or tangents. We discovered that these same students were rather more comfortable discussing ratios of heights to widths for triangles. They could understand the effect on an angle of changing the height or width of the triangle that defined it, so we recast our geometric discussions and figures into this language. To get around the problem of students being unable to calculate tangents of angles reliably on their calculators (and them not knowing whether they were working in degrees or radians), we include a look-up table that lists height-to-width ratios (aka tangents) for angles between 0° and 20°.

The final component of the exercise has students apply the same parallax technique to nearby stars, converting between observed angular shifts in units of arc-seconds to distances of order parsecs. Students work with text-based questions and also measure stellar shifts from stellar diagrams.

5.2 Learning Objectives

After completing this laboratory exercise, the student should be able to do the following:

- Use a ruler to measure linear distances, and a protractor to measure angular separations.
- Describe the effect of varying the observational baseline or the distance to an object on its apparent change in angular position against a panorama of distant objects.
- Understand the concept of a parallax measurement, and explain how the parallax technique can be used to determine the distances to solar system and galactic objects.

- Visualize the connection between an astronomical unit, an arcsecond, and a parsec, and use the first two to define the third.

- Connect the differences between repeated measurements of a single quantity to a measure of error or accuracy.

- Plot two variables against each other, and decide whether a straight line is a good fit to the data over a certain range.

- Determine the slope and zero point of a linear relationship between two variables, and then translate from one variable to the other (apply the relationship $y = mx + b$ to find y for a given value of x).

5.3 Teaching Toffees

Teaching toffees are practical tips based on the hard-won experience of fellow instructors.

For all GEAS lab exercises:

Please have students access the list of components for the lab exercise (lab chapter, video tutorial, web applications, report template) directly from the GEAS website so that they use the current version of all tools.

By having them save and share the lab report template, they will have their work backed up automatically and instructors will be able to observe their progress 24/7. This allows instructors to check for appropriate progress towards intermediate goals over a two-week period, and for students and instructors to interact asynchronously through threaded comments placed in the report margins at exactly the point where a question occurs. Note that the Lab #1 video tutorial describes how to work with Google resources, and there is a two-page handout on the lab website as well.

Students sometimes try to complete the lab exercise by skipping over the lab chapter entirely and working from just the report template. This is not an effective learning strategy, nor does it save time. The report template contains only abbreviated forms of the questions with spaces for answers, but none of the context or framework for the questions.

We strongly encourage you to strongly encourage all of your students to watch the video tutorial before beginning to work on the exercise. If a picture is worth a thousand words then a video might be worth a million words. Each tutorial is designed to introduce the scientific concepts that motivate the companion exercise. Because students may be working remotely on their own, it also focuses on the most potentially challenging aspects of each project and walks them through key steps by showing them what they look like in practice.

5.4 Keywords

Arcminute – An arcminute is a unit of angular size, equal to 1/60 of a degree (recall that there are 90 degrees in a right angle). There are 60 arcseconds in an arcminute (see below).

Arcsecond – An arcsecond is a unit of angular size, equal to 1/60 of an arcminute or 1/3600 of a degree. Astronomers often measure the angular separation between neighboring objects on the sky in units of arcseconds.

Astronomical unit – The average distance between the Earth and the Sun, equal to 1.5×10^8 kilometers.

Degree – A unit used to measure angles. There are 90 degrees in a right angle, and 360 degrees in a full circle.

Light year – A unit of distance (not time), equal to the distance which light travels in a year. One light year is equal to 0.307 parsecs.

Parallax – A technique for estimating the distances to objects, by measuring their apparent angular shifts on the sky relative to distant objects when they are observed from two separated locations.

Parsec – A unit of distance defined as the distance at which an object exhibits a parallax shift of one arcsecond. As the Earth rotates around the Sun and shifts by a length of one astronomical unit, a star which lies one parsec away from Earth will appear to shift by one arcsecond across the sky. One parsec is equal to 3.26 light years or 206,265 astronomical units.

Radian – A unit used to measure angles. There are $\pi/2$ degrees in a right angle, and 2π radians in a full circle.

Small angle approximation – For small angles (less than 10 degrees, or $\pi/18$ radians), the tangent of the angle is roughly equal to the angle itself, measured in radians.

5.5 Relevant Lecture Chapters

This laboratory exercises draws upon the material in Chapter 10: Geocentric and Heliocentric Models. There are loosely related concepts for visualization of objects and orientations in Chapter 7: The Celestial Sphere, and Chapter 8: Planetary Orbits.

5.6 References and Notes

1. This laboratory exercise draws from an in-class parallax exercise taken from the 2007 New Mexico State University Astronomy Department ASTR110G laboratory manual.

2. Figure 5.1 through Figure 5.9 and the attached protractor design are shown courtesy of Nicole Vogt.

Lab 6

The Hertzsprung-Russell Diagram and Stellar Evolution

6.1 Overview

Exercise six focuses on stellar properties and evolution for individual stars and for stellar clusters. It begins with observables such as stellar brightness and color, and uses the Hertzsprung-Russell (H-R) Diagram as a vehicle to track how stellar properties change with age. We begin with an introduction to stellar properties of Main Sequence and giant stars that uses a Nebraska Astronomy Applet Project (NAAP) web-application to illustrate connections between stellar luminosity, temperature, and radius.

The Pleiades cluster represents a young stellar cluster, one with minimal evolution away from the Main Sequence. We work from an optical H-R diagram for the cluster to reinforce ideas about the Main Sequence and to practice manipulating stellar magnitudes. The logarithmic magnitude scale poses a significant challenge for many students, so this exercise contains numerous examples (as does the video tutorial) illustrating how to properly compare apparent and absolute magnitudes.

Our M67 activity (see Figure 6.1) gives students a chance to construct their own H-R Diagram by fitting apertures to individual stars of various colors and brightnesses on a multi-band color Sloan Digital Sky Survey (SDSS) image of the cluster. Robert Lupton was kind enough to provide us with the image, one which would make Antoni Gaudi proud due to its distinctive color palette and strong blue-red contrasts. The cluster image is presented through a specialized web-application, allowing students to focus on how to properly fit apertures that contain the entire stellar light profile but a minimum of neighboring objects and background light. In addition to the cluster image, students evaluate a radial light profile within and around each aperture as it is fit, and the sampled stars are placed on an H-R diagram at positions derived from the student-determined luminosities and colors. After fitting a sample of twelve stars for themselves, they then select a model corresponding to a particular cluster age by fitting the cluster turn-off point on the H-R Diagram to data for the entire cluster.

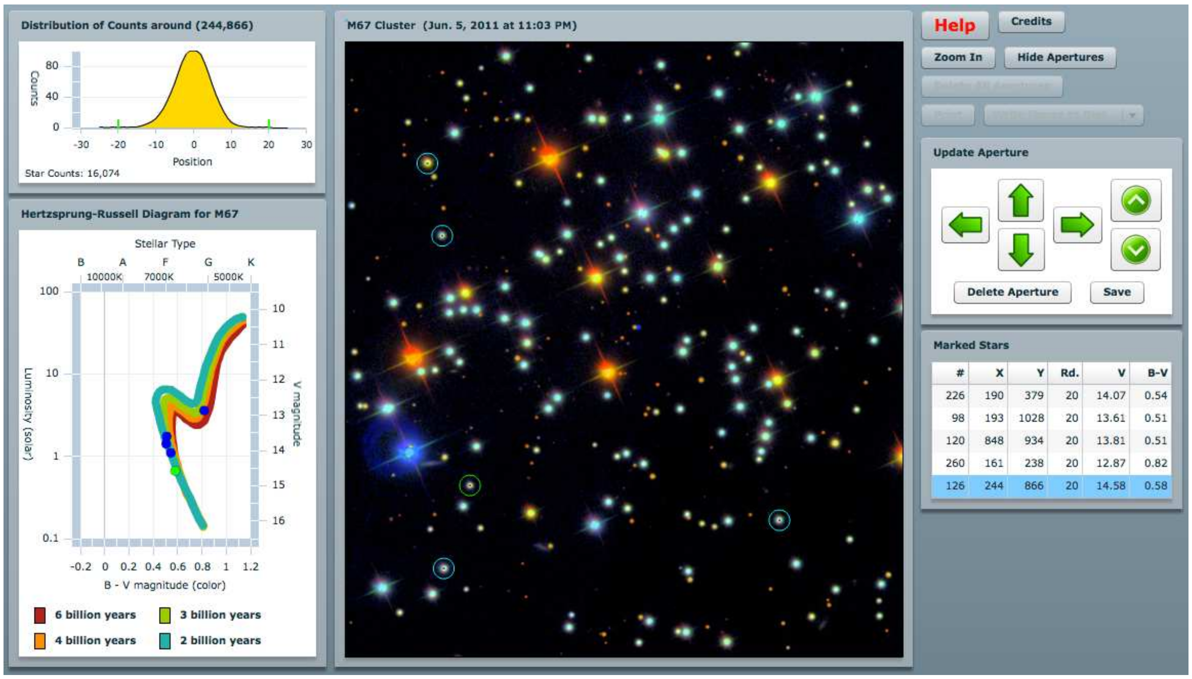

Figure 6.1: A screen capture of our M67 H-R diagram and stellar aperture fitting web-application. The radial profile in the upper left-hand corner shows the distribution of light within the aperture currently being fit on the M67 cluster image. (The star is marked with a green aperture on the image.) Students can vary the aperture size and position with the right-hand side control panel, using aperture controls that match those used in exercise four to fit craters on the Martian surface. The H-R diagram in the lower left-hand corner shows the distribution of stellar luminosities and colors for stars covering a range of properties, selected and fit by students. The four colored tracks illustrate the patterns formed by stars evolving off of the Main Sequence within cluster of various ages. After students fit a sample of twelve stars, the rest of the cluster is added to the H-R Diagram to give students a large sample when selecting an age track for M67.

6.2 Learning Objectives

After completing this laboratory exercise, the student should be able to do the following:

- Understand the difference between apparent properties, which vary with distance, and intrinsic properties. In particular, distinguish between (a) apparent and absolute magnitude, and (b) apparent magnitude and intrinsic luminosity.

- Describe the magnitude scale and explain how magnitudes are determined. In particular, (a) relate magnitude to brightness, (b) comprehend why fainter objects have larger magnitudes, (c) recognize that the magnitude scale is not linear, and (d) understand that brightness can be measured by counts registered in pixels of images, which can be converted mathematically to magnitudes.

- Realize that a star's color can be measured by subtracting magnitudes defined by fluxes from two different filters .

- Visualize the effects of varying the position and size of an aperture placed on an image, and relate them to good and bad technique in measuring stellar fluxes.

- Become comfortable with the H-R Diagram, and identify different forms it can take. In particular, (a) connect the x-axis to temperature, color, and spectral type, and connect the y-axis to luminosity and absolute magnitude, or to apparent magnitude for members of clusters, (b) visualize lines of constant radius, and (c) identify the Main Sequence and the position of the Sun, and the regions where giants and dwarfs of varied colors are found.

- Realize that astronomers can construct H-R diagrams using certain observed quantities (apparent magnitude, color, spectral class, and parallax measurements or other distance estimators) to then study the physical properties of a star such as intrinsic luminosity, temperature, mass, and radius.

- Comprehend that how quickly a star evolves depends fundamentally on its initial mass.

- Explain how the H-R diagram is used by astronomers to study the evolution of stars.

- Use the Stefan-Boltzmann Law to shift between luminosity, temperature, and radius (deriving any one from the other two), connect this relationship to the H-R diagram, and understand the scaling in solar units of stellar properties along the H-R diagram.

- List the fundamental properties a star is born with that determine its other properties, and connect these with the behavior of homogeneous populations in star clusters.

- Appreciate that the appearance of a stellar cluster H-R diagram changes with the age of the cluster in a predictable way, and that this can be used to estimate cluster ages.

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6.4 Keywords

Aperture – A circle, or ellipse, with an open center. Astronomers often place an aperture around a single star or galaxy, and then add up all the light contained within this region in order to determine how bright the object is.

Arcsecond – An arcsecond is a unit of angular size, equal to 1/60 of an arcminute or 1/3600 of a degree (recall that there are 90 degrees in a right angle). Astronomers often measure the angular separation between neighboring objects on the sky in units of arcseconds.

Astronomical unit – The average distance between the Earth and the Sun, equal to 1.5×10^8 kilometers.

Blue supergiants – Rare hot, blue stars with very high mass and luminosity that are ten to fifty times the Sun's size. In the H-R diagram, they occupy a region above the Main Sequence and on the left.

Color index – A number used to gauge a star's color, or relative intensity, at two wavelengths. Often based on the difference between how bright a star appears in two different filters, e.g. B–V for the blue and visual filters.

Hertzsprung-Russell Diagram (H-R Diagram) – A plot of intrinsic brightness (luminosity or absolute magnitude) versus color index (or the analogous surface temperature or spectral class) for stars, used to study stellar evolution for stars of various types and for clusters of stars.

Light year – A unit of distance (not time), equal to the distance which light travels in a year. One light year is equal to 0.307 parsecs.

Luminosity – A measure of intrinsic brightness defined by how much energy a star (or other object) radiates into space per second.

Main Sequence – A narrow region running across the H-R diagram, where hydrogen-burning stars are found. As stars grow old and run out of fuel, they evolve away from the Main Sequence.

Magnitude, absolute – The brightness of an object on the logarithmic magnitude scale, as observed from a distance of ten parsecs. This provides a measure of intrinsic brightness.

Magnitude, apparent – The brightness of an object based on the logarithmic magnitude scale, as observed from Earth. Two equivalent stars (with the same absolute magnitude) will have different apparent magnitudes if one lies closer to Earth than the other does.

Magnitude scale – A logarithmic scale for gauging the brightness of astronomical objects. It is based on historical measurements done by eye in which first magnitude stars were the brightest and sixth the faintest, so brighter objects have smaller magnitude values.

Parsec – A unit of distance defined as the distance at which an object exhibits a parallax shift of one arcsecond. As the Earth rotates around the Sun and shifts by a length of one astronomical unit, a star which lies one parsec away from Earth will appear to shift by one arcsecond across the sky. One parsec is equal to 3.26 light years or 206,265 astronomical units.

Red dwarfs – Cool, red, low luminosity stars with less mass and smaller sizes than the Sun. In the H-R diagram, they are Main Sequence objects, located to the lower right of the Sun's position. Because red dwarfs are such low-mass stars, they spend much more time on the Main Sequence than solar-mass or more massive counterparts.

Red giants – Cool, red, high-luminosity stars that are hundreds of times the Sun's size. In the H-R diagram, they occupy a region well off the Main Sequence to the upper right. The progenitors of red giants are Main Sequence stars, which burn through their hydrogen reserves and then move into the giant phase.

Spectral class – A classification based on the appearance of a stellar spectrum, analogous to the temperature sequence, with blue O class stars being hottest, yellow G stars like the Sun being intermediate, and red M stars being cooler.

Star – A hot, glowing, spherical mass of gas, dominated by hydrogen. Stars are typically found in stable configurations in which the inward-directed force of gravity is balanced by the outward radiation pressure due to nuclear fusion reactions in the cores.

Star cluster – A group of hundreds or thousands of stars bound together by gravity, which formed at a single epoch from a giant cloud of interstellar gas and dust.

Stellar evolution – The process by which a star changes in size, luminosity, temperature, and appearance, as it ages and consumes its fuel. The speed of these changes is driven primarily by stellar mass. The most massive stars may shine for only a few million years, while the least massive could last hundreds of billions of years.

Stefan-Boltzmann Law – A mathematical relationship describing the behavior of spherical, idealized radiators (a.k.a. stars), connecting luminosity L, temperature T, and radius R: $L = (4\pi\sigma)T^4R^2$, where σ is the Stefan-Boltzmann constant.

Turn-off point – The point on the H-R diagram for a particular star cluster where its stars are evolving off of the Main Sequence and becoming red giants. The location, usually specified by the corresponding color index, depends on the cluster's age.

White dwarfs – Hot, low-luminosity stars that are much smaller than the Sun (they are Earth sized!) These old, dying stars are gradually cooling, and growing fainter with time. They are the end-states for intermediate- and low-mass Main Sequence stars which have passed through the giant phase.

6.5 Relevant Lecture Chapters

This laboratory exercises draws heavily upon the material in Chapter 20: The Hertzsprung-Russell Diagram. There are related materials in Chapter 17: Stellar Temperatures, Chapter 18: Nuclear Reactions, and Chapter 21: White Dwarfs.

6.6 References and Notes

1. The H-R exploratory web application is used courtesy of Kevin Lee of the University of Nebraska, Lincoln, and the Nebraska Astronomy Applet Project (NAAP). Questions 2 and 3 in the final (post-lab) questions section were adapted from NAAP materials.

2. The H-R Diagram for the Pleiades presented in Figure 6.4 was created from data for 47 stars taken from the following references. The 14 brightest stars come from Johnson, H. L. Iriarte, B. Mitchell, R. I. & Wisniewski, W. Z., "UBVRIJKL photometry of the bright stars," 1966, Communications of the Lunar and Planetary Laboratory, 4, 99, and the rest come from Mendoza, E. E., "Multicolor Photometry of Stellar Aggregates," 1967, Boletin de los Observatorios Tonantzintla y Tacubaya, 4, 149.

3. The M67 H-R Diagram web application utilizes photometric magnitude data taken from

Laugalys, V., Kazlauskas, A., Boyle, R. P., Vrba, F. J., Philip, A. G. D., & Straižys, V., "CCD Photometry of the M 67 Cluster in the Vilnius System. II. New Photometry of High Accuracy," 2004, Baltic Astronomy, 13, 1.

4. The M67 H-R Diagram web application sky image is a ugr mosaic created from Sloan Digital Sky Survey (SDSS) data, and is shown courtesy of Robert Lupton and the SDSS. Note that in order to preserve a wide range of visual colors across the image, the cores of the brightest stellar profiles are occasionally flat-topped or contain a small dimple. An appropriate journal reference for the latest SDSS data release is "The Eighth Data Release of the Sloan Digital Sky Survey: First Data from SDSS-III," by Aihara et al. in *The Astrophysical Journal Supplement*. vol. 193(2), pp. 29-46 (2011).

5. The H-R diagram for M44 in Figure 6.5 is based on photometric data taken from Johnson, H. L., "Praesepe: Magnitudes and Colors," 1952, Astrophysical Journal, 116, 640.

6. The reference to the Sun being born in a star cluster is based on Zwart, S. F. P., "The Long Lost Siblings of the Sun," November 2009, Scientific American.

7. Figure 6.1 and Figure 6.3 are shown courtesy of Nicole Vogt.

Lab 7

Hubble's Law and the Cosmic Distance Scale

7.1 Overview

Exercise seven is our first extragalactic exercise, highlighting the immense scale of the Universe. It addresses the challenge of determining distances on large scales, working from standard candle techniques to cosmological redshifts. Students study samples of Cepheid variable stars out to 30 Mpc and then move outwards to Type Ia supernovae. They also examine galaxy spectra, using Hubble's Law and observed shifts in the wavelengths of key features to determine distances.

The primary activity involves analyzing a set of 36 brightest cluster galaxies (BCGs) observed by the Sloan Digital Sky Survey (SDSS). In order to clearly connect the outputs of standard candle techniques and redshift-determined distances, we have student utilize both types of techniques on the sample. We begin with the assumption that BCGs have relatively uniform properties, under which their angular size and the square of their observed brightness will both be inversely proportional to distance (for redshifts $z < 0.1$).

Students use the web-application shown in Figure 7.1 to fit apertures to a sample of SDSS BCGs. As with the stellar aperture-fitting tool in the sixth laboratory exercise, this involves balancing the need to extend each aperture outward far enough to contain a maximum amount of light from the galaxy with minimizing the contamination from neighboring galaxies and foreground stars. We want students to realize that there is no "perfect" solution to these types of problems, and that two astrophysicists analyzing the same galaxy image by hand would inevitably place and size their apertures slightly differently, leading to slightly different measurements of such properties as galaxy total brightness and size. This should be regarded as one source contributing to the errors associated with such measurements. We

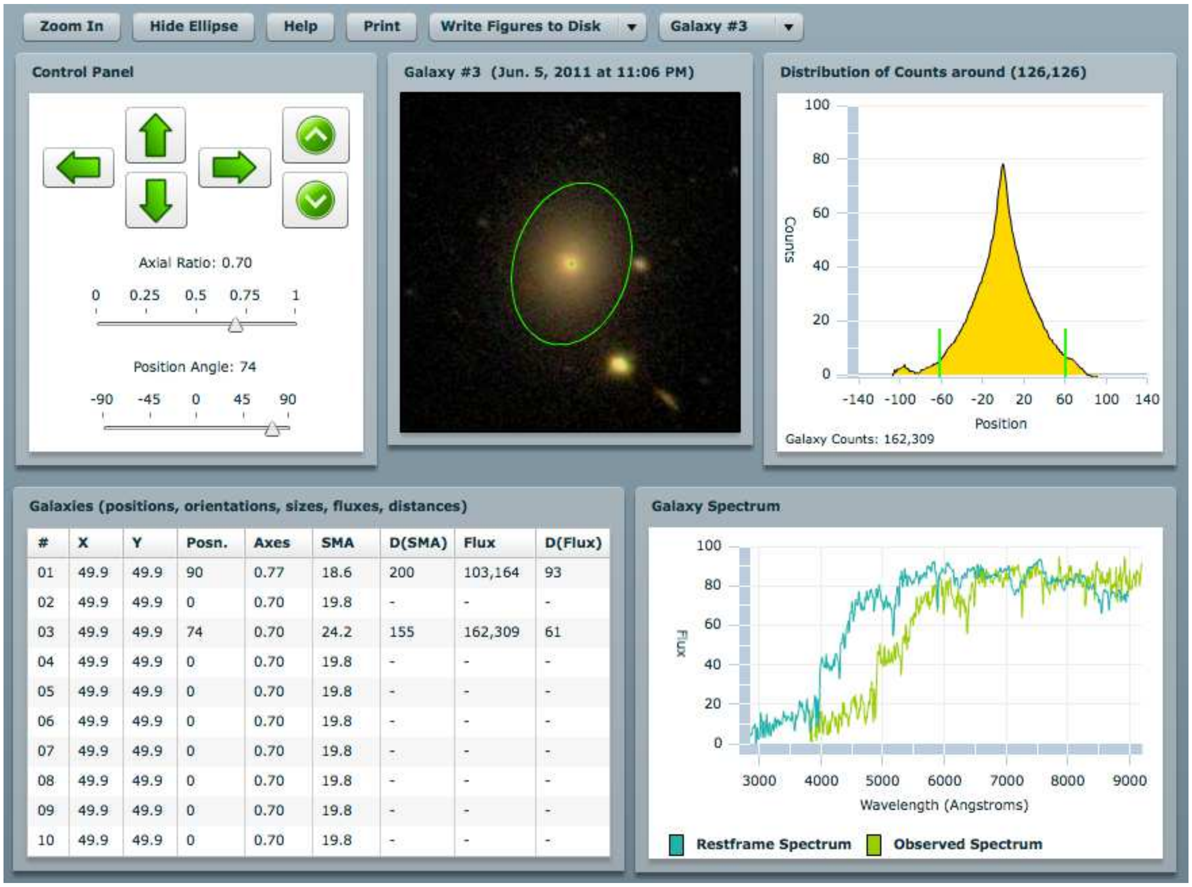


Figure 7.1: A screen capture of our galaxy imaging analysis tool. The top row contains three windows related to fitting an aperture to capture the galaxy light: (1) a control panel for varying the aperture center, radius, axial ratio, and position angle, (2) the galaxy image, and (3) a radial plot of the galaxy light, showing the light profile within and beyond the aperture. The aperture is marked as a green ellipse on the image, and as two green bars on the radial light profile. The bottom row contains (1) a table of fit parameters for each of ten galaxies, including distances derived from the semi-major axis (SMA) and the brightness (flux), and (2) the observed galaxy spectrum and a rest-frame comparison spectrum. Students fit both images (in which the galaxies have smaller and smaller angular sizes with increasing distance) and spectra (in which the galaxy light is shifted to longer and longer wavelengths) during the exercise. We include a diagram of the spectrum when analyzing the image, and a copy of the image when analyzing the spectrum, to help students to connect the changes that occur within each type of data as a function of galaxy distance.

also want them to wrestle with the compromises required in working with real astronomical data, realizing that one has to make informed choices by weighing multiple factors, rather than seeking to "match" a magical answer written down somewhere else by someone else.

Note that the exercise discussion restricts itself to the simple scaling relations that apply between angular size and brightness with distance for nearby galaxies, but the web-applications calculate complete cosmological solutions (for a λCDM universe with $\Omega_0 = 0.30$, $\Omega_\lambda = 0.70$, and $H_0 = 72$ km per second per Mpc).

Figure 7.2: A screen capture of our galaxy spectrum analysis tool. Students determine galaxy redshifts by shifting the galaxy spectrum left and right in wavelength so as to match up absorption and emission features, as well as the general shape of the continuum, to a rest-frame spectrum of an equivalent galaxy. The correlation coefficient is reported numerically and also shown graphically on a symbolic thermometer – the better the match between the two spectra, the higher the level of the green "liquid" in the thermometer. The galaxy image in the lower right-hand corner has a constant angular size, so that galaxies that are further away from us appear smaller.

A second web-application contains spectra for the same set of BCGs, as shown in Figure 7.2. The distances derived from the spectra are less ambiguous than those found from the imaging properties of the galaxies, being defined by the maximum of the correlation coefficient between the observed galaxy spectra and a rest-frame equivalent. Students also line up individual features within the two spectra by eye, such as the sodium feature at 5990Å and the Ca H and K lines.

Having made three estimates of galaxy distance for ten galaxies, students now use a specialized plotting tool to plot these estimates against distances determined for the clusters that contain these galaxies. The cluster values are of course derived from combining the redshifts of the cluster members. We emphasize the idea that combining measurements for up to 100 galaxies provides a large sample with better statistics through averaging – a point we have been making since exercise one. We want students to understand how simple scaling arguments motivate all standard candle estimates. They should also realize that the differences in the intrinsic properties of these galaxies are far greater than those within samples of, for example, Type Ia supernovae, making this a weak technique for these types of objects. We have them derive distances three different ways, emphasizing the connections between the imaging and spectral data, to better connect the concept of redshift to distance. The theoretical connection between a shift in wavelength and a change in galaxy distance is more complicated and so more difficult to grasp than the simple idea that objects which are further away appear smaller and fainter.

To emphasize the dependency of size- or brightness-derived distances on the spread in galaxy properties throughout a sample, we next have students examine histograms of the intrinsic properties of the sample of BCGs. They also verify that on average BCGs that are intrinsically larger are also intrinsically brighter.

In the final section of exercise seven we introduce the concept of a telescope as a time machine, emphasizing that the images of the most distant galaxies show them not as they are today, but as they appeared in the early epochs of the Universe. We then guide them through the exercise of using the value of H_0 to estimate the age of the Universe.

7.2 Learning Objectives

After completing this laboratory exercise, the student should be able to do the following:

- Appreciate that the Universe is expanding.
- Understand how we combine various methods of distance estimation to determine distances to astronomical objects in the solar system, within the Milky Way galaxy, and to other galaxies in the nearby and distant Universe.
- Connect Hubble's Law, the form of Hubble diagrams, and the value of the Hubble constant H_0 to measured velocities and distances to galaxies.
- Connect the value for the Hubble constant to the rate of expansion of the Universe and to the age of the Universe.
- Apply the idea of a standard candle to determine distances to objects, based on apparent brightness or apparent size.
- Fit an elliptical aperture to a galaxy image to determine its basic structural parameters.
- Shift a galaxy spectrum in wavelength to determine its redshift, by studying the underlying shape of the continuum and the observed absorption and emission features.

7.3 Teaching Toffees

Teaching toffees are practical tips based on the hard-won experience of fellow instructors.

For all GEAS lab exercises:

Please have students access the list of components for the lab exercise (lab chapter, video tutorial, web applications, report template) directly from the GEAS website so that they use the current version of all tools.

By having them save and share the lab report template, they will have their work backed up automatically and instructors will be able to observe their progress 24/7. This allows instructors to check for appropriate progress towards intermediate goals over a two-week period, and for students and instructors to interact asynchronously through threaded comments placed in the report margins at exactly the point where a question occurs. Note that the Lab #1 video tutorial describes how to work with Google resources, and there is a two-page handout on the lab website as well.

Students sometimes try to complete the lab exercise by skipping over the lab chapter entirely and working from just the report template. This is not an effective learning strategy, nor does it save time. The report template contains only abbreviated forms of the questions with spaces for answers, but none of the context or framework for the questions.

We strongly encourage you to strongly encourage all of your students to watch the video tutorial before beginning to work on the exercise. If a picture is worth a thousand words then a video might be worth a million words. Each tutorial is designed to introduce the scientific concepts that motivate the companion exercise. Because students may be working remotely on their own, it also focuses on the most potentially challenging aspects of each project and walks them through key steps by showing them what they look like in practice.

7.4 Keywords

Aperture – A circle, or ellipse, with an open center. Astronomers often place an aperture around a single star or galaxy, and then add up all the light contained within this region in order to determine how bright the object is.

Arcminute – An arcminute is a unit of angular size, equal to 1/60 of a degree (recall that there are 90 degrees in a right angle). There are 60 arcseconds in an arcminute (see below).

Arcsecond – An arcsecond is a unit of angular size, equal to 1/60 of an arcminute or 1/3600 of a degree (recall that there are 90 degrees in a right angle). Astronomers often measure the angular separation between neighboring objects on the sky in units of arcseconds.

BCG – The brightest cluster galaxy (BCG) is the brightest galaxy within a cluster of galaxies. It typically resides in the core of the cluster. BCGs are known for having moderately uniform properties (such as linear size and luminosity).

Cosmology – Cosmology is the study of the structure and the evolution of the entire Universe.

Degree – A unit used to measure angles. There are 90 degrees in a right angle, and 360 degrees in a full circle.

Distance Scale – The distance scale, or the cosmic distance ladder, is the combination of various techniques used to determine distances to cosmological objects such as stars and galaxies.

$\Delta\lambda$ – The shift in wavelength for an absorption or emission feature in a spectrum between its observed (λ_{obs}) and its rest-frame (λ_{rest}) wavelengths.

Flux - The flux from a celestial object is the amount of emitted light that is observed, by eye or through a telescope, at a certain distance.

Galaxy – A galaxy is a gravitationally bound set of stars, gas, and dust, spanning up to hundreds of kiloparsecs in size and containing thousands to billions of stars. Our galaxy is called the Milky Way.

Galaxy Cluster – A galaxy cluster contains hundreds or thousands of galaxies, all bound together by their combined gravitational attraction.

Hubble constant – The Hubble constant, H_0, is the slope of the relationship between recessional velocity v and distance d observed for nearby galaxies (those within 400 megaparsecs of the Milky Way galaxy). The current accepted value for H_0 is 72 km sec^{-1} per megaparsec.

Hubble diagram – A Hubble diagram is a plot of recessional velocity v versus distance d for nearby galaxies.

Hubble's Law – Hubble's Law is the relationship $v = H_0\, d$, observed between recessional velocity v and distance d for nearby galaxies.

Inverse square law for light – The observed intensity of light emitted by an object varies inversely with the square of the distance from an observer ($f \propto 1/d^2$). A star or galaxy placed twice as far away from us would thus appear one-fourth as bright.

λ_{obs} - The wavelength of an absorption or emission feature in a spectrum at which it is observed to occur within a celestial object moving at some velocity with respect to the observer.

λ_{rest} - The wavelength of an absorption or emission feature in a spectrum at which it is observed to occur within a celestial object at rest with respect to the observer.

Light curve – A light curve is a plot of the observed brightness of a star (plotted on the vertical y-axis) as a function of time (plotted on the horizontal x-axis).

Light year – A unit of distance (not time), equal to the distance which light travels in a year. One light year is equal to 0.307 parsecs.

Linear size – The linear size of an object is its length, in units of length such as centimeters (small) or miles (large).

Major axis – The major axis of an ellipse is its longest side, the longest line segment which can be placed within it (passing from one side through the center to the other side). It is perpendicular to the minor axis.

Minor axis – The minor axis of an ellipse is its shortest side, the shortest line segment which can be placed within it (passing from one side through the center to the other side). It is perpendicular to the major axis.

Parsec – A unit of distance defined as the distance at which an object exhibits a parallax shift of one arcsecond. As the Earth rotates around the Sun and shifts by a length of one astronomical unit, a star which lies one parsec away from Earth will appear to shift by one arcsecond across the sky. One parsec is equal to 3.26 light years or 206,265 astronomical units.

Redshift – The redshift z of a galaxy is defined as $\Delta\lambda/\lambda_{rest}$, the ratio of the shift in wavelength $\Delta\lambda$ observed for a spectra feature of rest-frame wavelength λ_{rest}.

RMS (root mean square) deviation – The rms deviation is the square-root of the average square of the offsets in y between a set of N data points and a fit function. For a linear fit, where $y = mx + b$,

$$\text{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[y_i - (mx_i + b)\right]^2}.$$

Semi-major axis – The semi-major axis of an ellipse is half the length of the major axis.

Semi-minor axis – The semi-minor axis of an ellipse is half the length of the minor axis.

Standard candle – A class of objects assumed to be of uniform brightness. Any variation in observed brightness for a set of standard candles can be attributed to the distance to each object.

Variable star – A star which varies periodically in luminosity over time.

Velocity of recession – The velocity of an object which appears to be moving away from us. For galaxies, recessional velocities can be measured from spectral redshifts.

7.5 Relevant Lecture Chapters

This laboratory exercises draws upon the material in Chapter 24: The Milky Way, Chapter 25: The Expansion of the Universe, and Chapter 26: A Universe of Galaxies, as well as Chapter 19: Binary Stars.

7.6 References and Notes

1. Edwin Hubble's original data forming a Hubble diagram were taken from the journal article "A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae," by Hubble in *Proceedings of the National Academy of Sciences of the United States of America*, vol. 15. issue 3, pp. 168–173 (1929).

2. The optical spectrum of a galaxy shown in Figure 7.2 is a product of the Sloan Digital Sky Survey, identified as SPSPEC-53713-2292-634, and extracted from http://das.sdss.org/www/cgi-bin/fiber?PLATE=2292&MJD=53713&RERUN=26&FIBER=634.

3. The optical spectra of brightest cluster galaxies (BCGs) shown in Figure 7.3 are Sloan Digital Sky Survey spectra taken from the sixth data release (DR6). The rest-frame spectrum was created by combining the spectra of 26 $z < 0.1$ galaxies taken from the journal article "How Special are Brightest Group and Cluster Galaxies?" by von der Linden, Best, Kauffmann & White in *Monthly Notices of the Royal Astronomical Society*, vol. 379, issue 3, pp. 867–893 (2007) and 10 $z > 0.1$ galaxies taken from the Sloan Digital Sky Survey DR6 Galaxy Clusters Catalog at http://heasarc.gsfc.nasa.gov/W3Browse/galaxy-catalog/sdsswhlgc.html.

These spectra, and images of the same galaxies, are used in the two web applications for this laboratory exercise which allow students to fit elliptical apertures to galaxy images and to fit redshifts to galaxy spectra.

4. The M100 Cepheid variable star images in Figures 7.4 come from the Space Telescope Science Institute HubbleSite news center, at http://hubblesite.org/newscenter/archive/releases/1994/49/image/b/, courtesy of Wendy L. Freedman and NASA.

5. The M100 Cepheid variable star light curves in Figures 7.5 and 7.7 are taken from the journal article "Distance to Virgo Cluster Galaxy M100 from HST observations of Cepheids" by Wendy L. Freedman et al. in *Nature*, vol. 371, pp. 757–762 (1994).

6. The data for the Hubble diagram for Cepheid variable stars in Figure 7.6 are taken from the journal article "Final Results from the Hubble Space Telescope Key Project to Measure the Hubble Constant" by Wendy L. Freedman et al. in *The Astrophysical Journal*, vol. 553, pp. 47–72 (2001), and (for M100) "Distance to Virgo Cluster Galaxy M100 from HST observations of Cepheids" by Wendy L. Freedman et al. in *Nature*, vol. 371, pp. 757–762 (1994).

7. The data for the Hubble diagram for Type Ia supernovae in Figure 7.8 are taken from the journal article "Type Ia Supernova Discoveries at $z > 1$ from the Hubble Space Telescope: Evidence for Past Deceleration and Constraints on Dark Energy Evolution" by Adam Riess et al. in *The Astrophysical Journal*, vol. 607, pp. 665–687 (2004).

8. Figures 7.9 through 7.11 are based on observational data taken from the seventh data release (DR7) of the Sloan Digital Sky Survey.

Lab 8

Properties of Galaxies

8.1 Overview

Exercise eight focuses on galaxy properties and their constituent stellar populations. We introduce the morphological sequence and augment luminosities, sizes, colors, and redshifts with modern morphological indices based on concentration and asymmetry. Students analyze both images and spectra of a sample of nearby galaxies drawn from the Sloan Digital Sky Survey (SDSS), determining intrinsic properties and estimating morphological types based on various factors.

The first activity (see Figure 8.1) is designed to help students to realize how much information is present in a galaxy image. Students sort a mosaic of 25 galaxies of varied types into groups, based on their own first reactions to the images (before having been exposed to definitions of galaxy types or basic structures). They then have a companion sort the same mosaic, and compare and contrast the results afterward. No two people sort the mosaic in the same way. This exercise thus provides a way for students to observe how different viewers focus on different aspects of the images (such as colors, shapes, and levels of sub-structure). The companion for this exercise can be another student, providing an opportunity for peer-to-peer discussion in a cooperative environment, or an adult or older child.

Two more web-applications are provided, similar to the image and spectral analysis tools used in exercise seven. These versions are augmented with morphological type options. As shown in Figure 8.2, students again analyze galaxy images and fit apertures to light profiles to determine structural parameters. Additional measurements are made, of concentration (the fraction of light within the central 30%) and asymmetry (the fraction of light after differencing the normalized image with a copy rotated by 180°) indices. They estimate morphological types as well, having read through a discussion of the observable properties of elliptical galaxies, lenticular galaxies, the spiral sequence, and peculiar and interacting

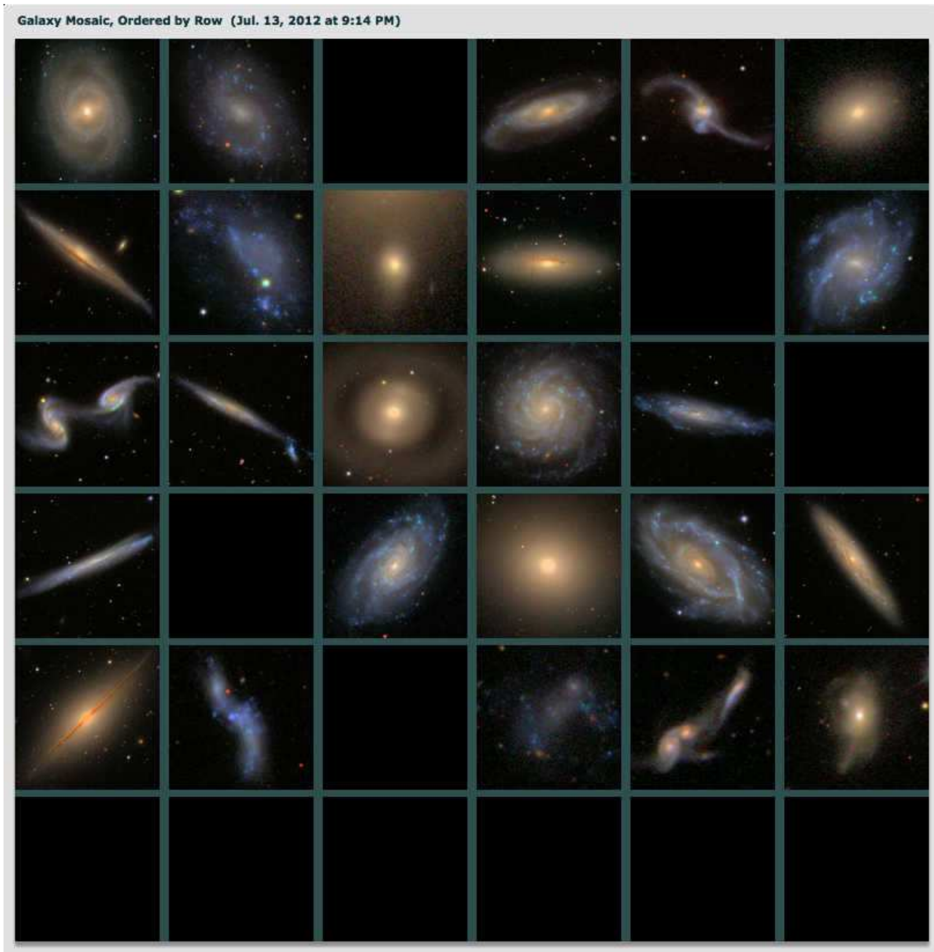
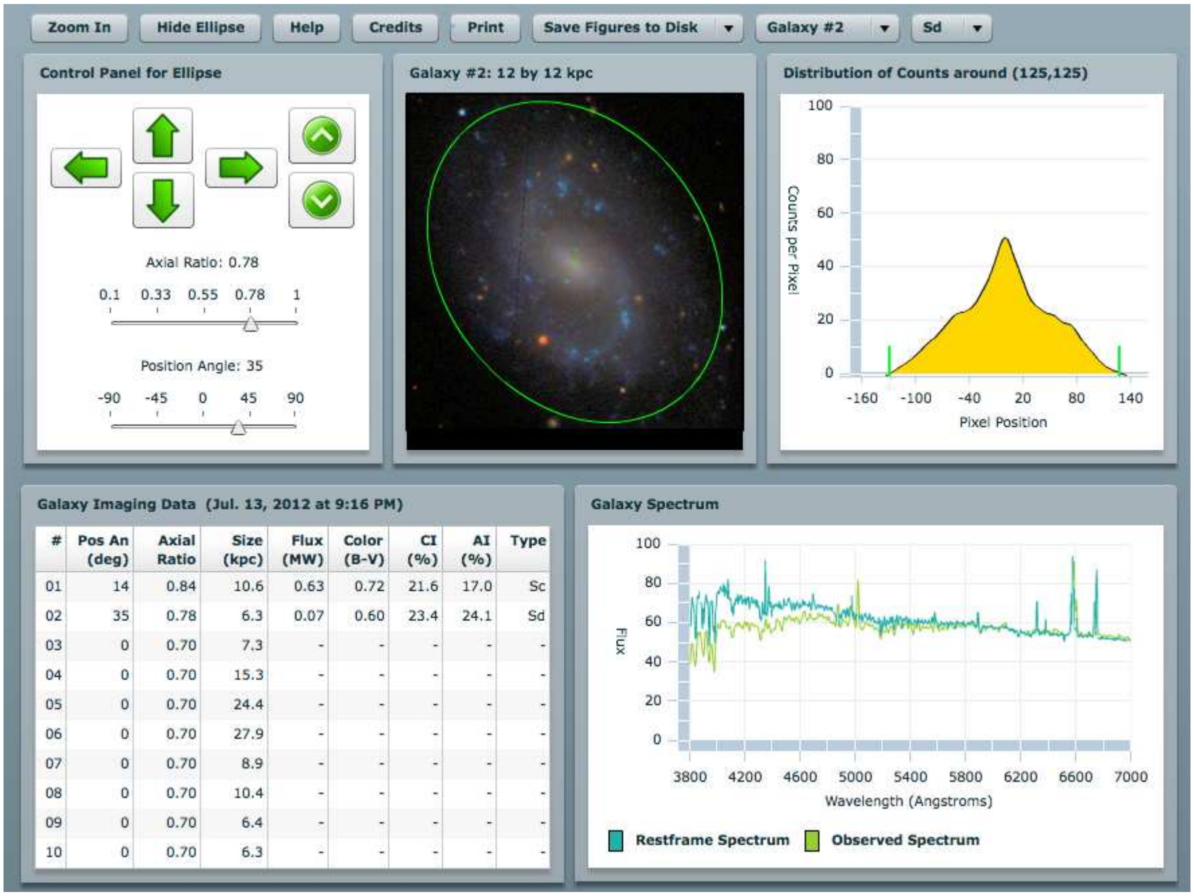


Figure 8.1: A screen capture of our galaxy sorting tool. Students sort the 25 galaxies into 4 to 6 rows, based on what they think are the most important aspects. Everyone sorts the galaxies differently, leading to discussions about various factors being used to place galaxies in different groups.

systems. Basic properties are interpreted in terms of bulge and disk stellar populations and galaxy interaction histories. We also emphasize the difference between observable properties such as bulge-to-disk fraction which vary with the intrinsic properties of the galaxy and those such as disk inclination angle which are purely products of viewing angle, prominent in images but unrelated to galaxy evolutionary history.

Students determine galaxy redshifts from optical spectra (see Figure 8.3). They are also furnished with comparison spectra overlays of various morphological types within the spectral analysis tool, in order to make an independent estimate of type based on the continuum shape and the strength of various absorption and emission features.

As in exercise seven, we want students to experience the process of analyzing images and spectra for themselves. Our web-applications are designed without the need to install software, compile packages, or learn complicated commands in order to examine data and conduct



#	Pos An (deg)	Axial Ratio	Size (kpc)	Flux (MW)	Color (B-V)	CI (%)	AI (%)	Type
01	14	0.84	10.6	0.63	0.72	21.6	17.0	Sc
02	35	0.78	6.3	0.07	0.60	23.4	24.1	Sd
03	0	0.70	7.3	-	-	-	-	-
04	0	0.70	15.3	-	-	-	-	-
05	0	0.70	24.4	-	-	-	-	-
06	0	0.70	27.9	-	-	-	-	-
07	0	0.70	8.9	-	-	-	-	-
08	0	0.70	10.4	-	-	-	-	-
09	0	0.70	6.4	-	-	-	-	-
10	0	0.70	6.3	-	-	-	-	-

Figure 8.2: A screen capture of our galaxy imaging analysis tool. The top row contains three windows related to fitting an aperture to capture the galaxy light: (1) a control panel for varying the aperture center, radius, axial ratio, and position angle, (2) the galaxy image, and (3) a radial plot of the galaxy light, showing the light profile within and beyond the aperture. The aperture is marked as a green ellipse on the image, and as two green bars on the radial light profile. The bottom row contains (1) a table of fit parameters for each of ten galaxies, including concentration, asymmetry, and morphological type, and (2) the observed galaxy spectrum and a rest-frame comparison spectrum of the selected morphological type. Students fit both images and spectra during the exercise. We include a diagram of the spectrum when analyzing the image, and a copy of the image when analyzing the spectrum, to help students to connect the observables within each type of data.

basic analyses. This allows students with no background in data processing to focus on astronomical issues.

At the end of the exercise, students return to the original mosaic of 25 galaxies and re-evaluate the way in which they originally grouped the galaxies into subsets. They are now able to describe variations in color in terms of stellar populations, and to discriminate between disturbed morphologies indicating galaxy interactions and differences in disk appearance due merely to, for example, viewing angle. The result is a more nuanced view of what is

Figure 8.3: A screen capture of our galaxy spectrum analysis tool. Students determine galaxy redshifts by shifting the galaxy spectrum left and right in wavelength so as to match up absorption and emission features, as well as the general shape of the continuum, to a rest-frame spectrum of a galaxy of the selected morphological type. The correlation coefficient is reported numerically and also shown graphically on a symbolic thermometer – the better the match between the two spectra, the higher the level of the green "liquid" in the thermometer.

significant when we study galaxies.

8.2 Learning Objectives

After completing this laboratory exercise, the student should be able to do the following:

- Classify galaxies by morphological type, according to optical images and spectra.
- Understand the relationship between the spectra of individual stars within a galaxy and the resultant galaxy spectrum.
- Describe the basic properties of elliptical, lenticular, spiral, peculiar, and interacting galaxies observed in optical images.
- Describe the basic properties of elliptical, lenticular, spiral, peculiar, and interacting galaxies observed in optical spectra.
- Connect the observed optical properties of elliptical, lenticular, spiral, peculiar, and interacting galaxies to their stellar populations and their gas content.

- Fit an elliptical aperture to a galaxy image to determine its basic structural parameters.

- Describe and identify the continuum, and absorption and emission features, in an optical spectrum of a galaxy.

- Shift a galaxy spectrum in wavelength to determine its redshift, by studying the underlying shape of the continuum and the observed absorption and emission features.

8.3 Teaching Toffees

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For all GEAS lab exercises:

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By having them save and share the lab report template, they will have their work backed up automatically and instructors will be able to observe their progress 24/7. This allows instructors to check for appropriate progress towards intermediate goals over a two-week period, and for students and instructors to interact asynchronously through threaded comments placed in the report margins at exactly the point where a question occurs. Note that the Lab #1 video tutorial describes how to work with Google resources, and there is a two-page handout on the lab website as well.

Students sometimes try to complete the lab exercise by skipping over the lab chapter entirely and working from just the report template. This is not an effective learning strategy, nor does it save time. The report template contains only abbreviated forms of the questions with spaces for answers, but none of the context or framework for the questions.

We strongly encourage you to strongly encourage all of your students to watch the video tutorial before beginning to work on the exercise. If a picture is worth a thousand words then a video might be worth a million words. Each tutorial is designed to introduce the scientific concepts that motivate the companion exercise. Because students may be working remotely on their own, it also focuses on the most potentially challenging aspects of each project and walks them through key steps by showing them what they look like in practice.

8.4 Keywords

Aperture – A circle, or ellipse, with an open center. Astronomers often place an aperture around a single star or galaxy, and then add up all the light contained within this region in order to determine how bright the object is.

Asymmetry Index (AI) - The percentage variation in the difference between the flux emitted at one position within a galaxy and at a corresponding position located 180° around the galaxy center-point. This index tends to be quite low for elliptical galaxies because they have smooth, symmetric light profiles, higher for spiral galaxies due to the spiral arm structure in the disks, and higher still for interacting galaxies, which can appear quite distorted.

Color index – A number used to gauge a star's color, or relative intensity, at two wavelengths. Often based on the difference between how bright a star appears in two different filters, e.g. B–V for the blue and visual filters.

Concentration Index (CI) – The ratio of the amount of flux emitted by the inner 30% of a galaxy and by the total galaxy. Because elliptical galaxies are centrally concentrated they have higher CI values than spiral galaxies, which generally have more slowly decaying, exponential light profiles across their disks.

Correlation coefficient – The correlation coefficient R is a measure of the strength of the relationship between two variables x and y. It ranges from -1 to 1, where +1 indicates the strongest possible positive correlation (as x increases, so does y), zero indicates no predictive relationship between quantities, and -1 indicates the strongest possible negative correlation (as x increases, y decreases). Correlation coefficients are well-suited for determining zero-point offsets in periodic relationships (such as syncing sine waves to remove phase offsets).

$\Delta\lambda$ – The shift in wavelength for an absorption or emission feature in a spectrum between its observed (λ_{obs}) and its rest-frame (λ_{rest}) wavelengths.

Flux - The flux from a celestial object is the amount of emitted light that is observed, by eye or through a telescope, at a certain distance.

Galaxy – A galaxy is a gravitationally bound set of stars, gas, and dust, spanning up to hundreds of kiloparsecs in size and containing thousands to billions of stars. Our galaxy is called the Milky Way.

Galaxy Cluster – A galaxy cluster contains hundreds or thousands of galaxies, all bound together by their combined gravitational attraction.

λ_{obs} - The wavelength of an absorption or emission feature in a spectrum at which it is observed to occur within a celestial object moving at some velocity with respect to the observer.

λ_{rest} - The wavelength of an absorption or emission feature in a spectrum at which it is observed to occur within a celestial object at rest with respect to the observer.

Luminosity – A measure of intrinsic brightness defined by how much energy a star (or other object) radiates into space per second.

Major axis – The major axis of an ellipse is its longest side, the longest line segment which can be placed within it (passing from one side through the center to the other side). It is perpendicular to the minor axis.

Milky Way – The Milky Way is the name of our own galaxy, a barred intermediate-type spiral.

Minor axis – The minor axis of an ellipse is its shortest side, the shortest line segment which can be placed within it (passing from one side through the center to the other side). It is perpendicular to the major axis.

Morphology – Shape, or form.

Redshift – The redshift z of a galaxy is defined as $\Delta\lambda/\lambda_{rest}$, the ratio of the shift in wavelength $\Delta\lambda$ observed for a spectra feature of rest-frame wavelength λ_{rest}.

Semi-major axis – The semi-major axis of an ellipse is half the length of the major axis.

Semi-minor axis – The semi-minor axis of an ellipse is half the length of the minor axis.

Spectral class – A classification based on the appearance of a stellar spectrum, analogous to the temperature sequence, with blue O class stars being hottest, yellow G stars like the Sun being intermediate, and red M stars being cooler.

Velocity of recession – The velocity of an object which appears to be moving away from us. For galaxies, recessional velocities can be measured from spectral redshifts.

8.5 Relevant Lecture Chapters

This laboratory exercises draws upon the material in Chapter 24: The Milky Way, Chapter 25: The Expansion of the Universe, and Chapter 26: A Universe of Galaxies, as well as Chapter 16: Absorption and Emission, Chapter 17: Stellar Temperatures, and Chapter 19: Binary Stars.

8.6 References and Notes

1. The image of the Milky Way as seen from the Black Rock Desert in Nevada shown in Figure 8.1 was taken by Steve Jurvetson on July 22, 2007 using a Canon EOS 5D. It is made available under the Creative Commons Attribution 2.0 Generic license, and can be found at http://www.flickr.com/photos/44124348109@N01/898622334.

2. The image of a galaxy similar to the Milky Way shown in Figure 8.1 is a product of the Sloan Digital Sky Survey (SDSS), identified as J083909.27+450747.7 and extracted with the DR7 Finding Chart Tool from http://cas.sdss.org/dr7/en/tools/chart/chart.asp.

3. The drawings in Figure 8.2 and Figure 8.5 are shown courtesy of Nicole Vogt.

4. The images of galaxies NGC3168, NGC4814, and ARP240 shown in the top row of Figure 8.3 (to illustrate the asymmetry index) are products of the SDSS, extracted with the DR7 Finding Chart Tool.

5. The images of elliptical galaxies NGC3168, NGC163, NGC4187, NGC4839, NGC2675, and NGC2937 (shown from left to right, top to bottom in Figure 8.4) are products of the SDSS, extracted with the DR7 Finding Chart Tool.

6. The images of spiral galaxies NGC5375, NGC5448, NGC2654 (Sa), NGC3351, NGC4814, NGC5777 (Sb), NGC5375, NGC5448, NGC2654 (Sc), and NGC3351, NGC4814, NGC5777 (Sd) (shown from left to right, top to bottom in Figure 8.6) are products of the SDSS, extracted with the DR7 Finding Chart Tool.

7. The images of S0 galaxies NGC2911, NGC4124, NGC3593, NGC5750, NGC4293, and NGC4880 (shown from left to right, top to bottom in Figure 8.7) are products of the SDSS, extracted with the DR7 Finding Chart Tool.

8. The images of peculiar or interacting galaxies NGC660, NGC3628, NGC3187, ARP240, UGC8584, and UGC10770 (shown from left to right, top to bottom in Figure 8.8) are products of the SDSS, extracted with the DR7 Finding Chart Tool.

9. The images of M81 shown in Figure 8.9 are a product of the SDSS, extracted with the DR7 Finding Chart Tool (optical image) and a VLA 21 cm map (courtesy Min Su Yun, radio image).

10. The optical spectrum of a galaxy shown in Figure 8.10 is a product of the SDSS, identified as SPSPEC-53713-2292-634, and extracted from http://das.sdss.org/www/ cgi-bin/fiber?PLATE=2292&MJD=53713&RERUN=26&FIBER=634.

8. The optical spectra of elliptical galaxies shown in Figure 8.11 are SDSS spectra taken from the sixth data release (DR6). The rest-frame spectrum was created by combining the spectra of 26 $z < 0.1$ galaxies taken from the journal article "How Special are Brightest Group and Cluster Galaxies?" by von der Linden, Best, Kauffmann & White in *Monthly Notices of the Royal Astronomical Society*, vol. 379, issue 3, pp. 867–893 (2007) and 10 $z > 0.1$ galaxies taken from the SDSS DR6 Galaxy Clusters Catalog at http://heasarc.gsfc.nasa.gov/W3Browse/galaxy-catalog/sdsswhlgc.html.

9. The optical spectra of nearby elliptical and lenticular galaxies shown in Figure 8.12 are SDSS spectra taken from the seventh data release (DR7). The SDSS fibers are $3''$ in diameter, so these spectra represent only the inner few percent of the galaxies.

10. The optical spectra of nearby spiral galaxies shown in Figure 8.13 are SDSS spectra taken from the seventh data release (DR7). The SDSS fibers are $3''$ in diameter, so these

spectra represent only the inner few percent of the galaxies.

11. The ten optical images of galaxies used in the image web-application for this exercise are products of the SDSS, extracted with the DR7 Finding Chart Tool. These galaxies are all members of the New General Catalog of Nebulae and Clusters of Stars (NGC; Dreyer, 1888), and so are identified by NGC numbers. Basic optical properties of the sample were taken from the Third Reference Catalog of Bright Galaxies (RC3; de Vaucouleurs et al., 1994).

12. The ten optical spectra used in the spectral web-application for this exercise are SDSS spectra taken from the seventh data release (DR7). The SDSS fibers are $3''$ in diameter, so these spectra represent only the inner few percent of the galaxies.