Laboratory Manual

PHSC 12700 Stars

The University of Chicago

Autumn 2018

Labs

LAB 1

Observing Falling Filters

The ability to observe without evaluating is the highest form of intelligence.
Jiddu Krishnamurti

While Mr. Krishnamuri may be making a stretch with his superlative, it remains true that observing without evaluating is essential for the creation of knowledge. In our lives, we have bias (conceptions, self-constructed mental models) that we use as our lens to view the world. These models are based on how each of us were socialized and on our subsequent experience. To learn and create new knowledge, we must develop skill in observation. In this lab, we will direct you to make detailed, careful quantitative observations, describe the patterns you find with mathematics, and finally make some wild guesses ("hypotheses") about a more universal principle that explains this pattern that one could use to make predictions. Due to time and brain constraints, we will not, in this lab, test those hypotheses.

Learning Goals

- Become familiar with measurement, uncertainty, and writing lab reports.
- Learn how to conduct an observational experiment, including collecting data and analyzing the data to find and describe a pattern quantitatively.
- Use measurement uncertainty to describe physical quantities meaningfully.
- Format a lab report in a helpful way.

The Scientific Cycle[1]

One way of describing science is the process of incrementally improving a shared model of how our universe works. In different fields of science, different methods and cycles are used, so there is no "One True Scientific Method." One can still create a model for the process of science, and we describe here one such cycle, summarized in Figure 1.1.

In this cycle, there are three types of experiments, each one representing a different stage of the scientific effort. One stage, often started when encountering a novel phenomenon, is the **observational experiment**. This is an experiment that consists of deciding what to observe and how to observe it, collecting data, finding a pattern, and brainstorming possible explanations for what is observed (also called "hypotheses").

[1] adapted from [1]

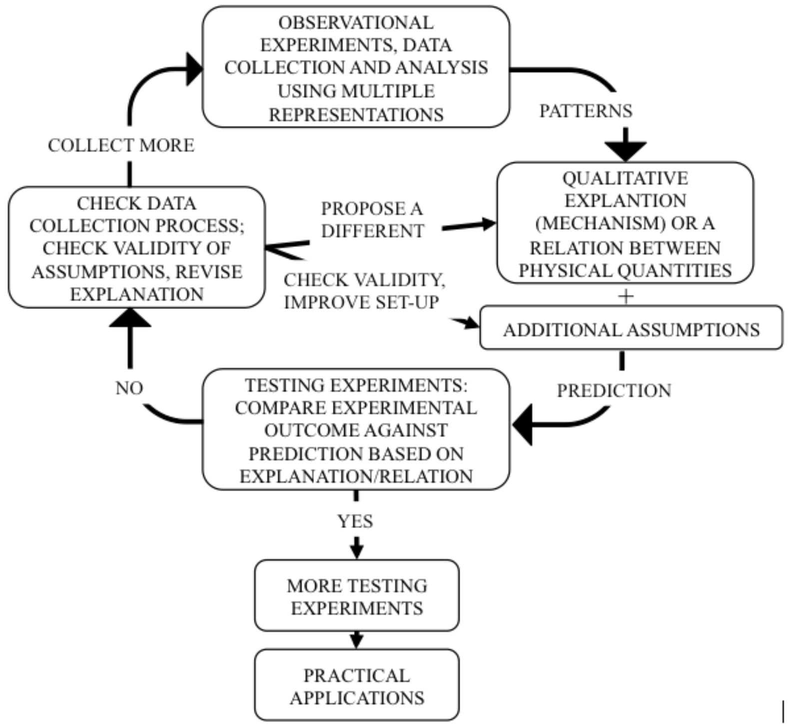

Figure 1.1: A model of the process some scientists go through to create knowledge.[2]

Once one has some trial explanations, one can test one or more of those with a **testing experiment**. Here, one designs a new experimental procedure and uses each hypothesis to predict what will happen. Then the prediction is compared to the procedure's outcome. If they are different, then the hypothesis is judged to be not a helpful explanation for that phenomenon. If they are the same, then it is still helpful. Throughout this stage, one may make various assumptions that would need to be validated, as they can effect the prediction or outcome.

Once a hypothesis has been tested enough for people to find it useful, then it can be applied to solve practical problems, or to determine properties of particular situations, in an "application experiment."

Observation experiment: Observing falling filters

In today's lab, you will investigate the relationship between the size of coffee filters and how long it takes them to fall. In the first section, you will determine the size of the coffee filters. In the second, you will determine how long each take to fall, controlling for other variables, and then find a mathematical pattern that describes the relationship. Note that this lab does not include any hypothesis testing.

> **Self-assessment:** To help you improve your scientific abilities, we provide you with self-assessment rubrics. A rubric is a scoring system. Self-assessment is determining how well you performed a particular task. So, these self-assessment rubrics are designed to help you evaluate your performance while you are designing and performing your experiment.
>
> The complete set of rubrics is available in Appendix B. In each lab, your report will be assessed using Rubric F, found in Table B.5, as well as 5 additional rubric rows listed in that lab. Each week, read through these and use them to evaluate your work as you design and perform the experiment. Your instructor will use the same rubrics to determine part of your grade for the

lab. In particular, each row will be worth 3 possible points (from “Missing” being 0 points to “Adequate” being 3 points).

Rubrics to focus on during this experiment: B5, B7, B8, F1, F2, G1, G2. See Appendix B for details.

Available equipment: several differently-sized coffee filters, meter stick, balance or scale, stopwatch, scratch paper

You may want to **decide on roles** for each group member. Example roles include Facilitator (ensures time and group focus are efficiently used), Scribe (ensures work is recorded), Technician (oversees apparatus assembly, usage), Skeptic (ensures group is questioning itself). Note that each role is responsible for ensuring that the thing happens, rather than necessarily doing it themselves.

How big are the filters?

Goal: Find the cross-sectional area of each coffee filter and make a determination of that area, including uncertainty in that area, for use in the next section.

1. Review Rubric G (Table B.6) and discuss any unclear expectations with your group and the instructor.

2. Brainstorm different methods you could use to determine the cross-sectional area. Feel free to play with the equipment as desired. Here are some things to consider:

   - Will you measure the area directly, or will you measure something else and use that to calculate the area?
   - With any method, you will probably make one or more assumptions about the shape of the filter. How valid are those assumptions?
   - For each method you consider, there may be different sources of uncertainty — the resolution of the measuring devices themselves, how you use them to measure, etc. If there is a source of random uncertainty, then you will need to take several measurements and use Appendix A.1 to determine the uncertainty. The decision of how many measurements to take is a trade-off between increasing precision (decreasing the uncertainty of the mean) and decreasing the time the measurement process takes.
   - If you make a measurement and use that measurement in an equation to find the area, you will need to propagate uncertainty as described in Appendix A.2.

3. Decide on your method and discuss it with an instructor before you begin. They will help increase the chances that your method will lead to successful results, or at least that the unhelpful path that you choose will take a short enough amount of time for you to change it when you discover it does not work. We want you to have productive failure that you have time to learn from.

4. Write down an outline of your intended procedure. You might end up changing this as you go, but it is helpful to start with a plan and then change it, rather than having no plan at all.

5. For your procedure, list the sources of uncertainty involved with each measurement. For each source, identify whether it is a random or instrumental uncertainty.

6. Execute your procedure, including setup, data collection, calculation of area, uncertainty estimation and propagation.

At the end of this step, you should have a table of coffee filter cross-sectional areas, with uncertainties.

7. Once you are done collecting this data, review your written procedure and correct it to match what you actually did, and ensure you have sketched any measurement setups, so you can include it in the lab report. In particular, ensure that you have enough written so you can demonstrate Rubric Rows F1, G1 and G2 in your report (see Tables B.5 and B.6).

How fast do the filters fall?

Goal: Determine how long it takes each coffee filter to fall.

1. Review Rubric B (Table B.2) and discuss any unclear expectations with your group and the instructor.
2. Identify any variables (things that could change between measurements — either between measurements of the same filter, or among different filters) that could affect the fall time other than the coffee filter's cross-sectional area. If there is controversy in the group, feel free to test what variables might affect that fall time.
3. Since you are testing how the fall time is related to the filter's area, you should hold the other variables constant, so that they affect all the filters in the same way. For each variable identified in the previous step, decide how to keep that constant.
4. Brainstorm different methods you could use to determine the time it takes for the filter to fall. Feel free to play with the equipment as desired. Here are some things to consider:
   - Will you measure the fall time directly, or will you measure something else and use that to calculate the time?
   - For each method you consider, there may be different sources of uncertainty — the resolution of the measuring devices themselves, how you use them to measure, etc. If there is a source of random uncertainty, then you will need to take several measurements and use Appendix A.1 to determine the uncertainty.
   - If you make a measurement and use that measurement in an equation to find the time, you will need to propagate uncertainty as described in Appendix A.2.
5. Decide on your method and discuss it with an instructor before you begin. They will help increase the chances that your method will lead to successful results, or at least that the unhelpful path that you choose will take a short enough amount of time for you to change it when you discover it does not work. We want you to have productive failure that you have time to learn from.
6. Write down an outline of your intended procedure. You might end up changing this as you go, but it is helpful to start with a plan and then change it, rather than having no plan at all.
7. For your procedure, list the sources of uncertainty involved with each measurement. For each source, identify whether it is a random or instrumental uncertainty.
8. Execute your procedure, including setup, data collection, calculation of area, uncertainty estimation and propagation.

> At the end of this step, you should have a table of coffee filter cross-sectional areas, with uncertainties, with another column for fall time, with uncertainty in the fall time.

9. Once you are done collecting this data, review your written procedure and correct it to match what you actually did, and ensure you have sketched any measurement setups, so you can include it in the lab report. In particular, ensure that you have enough written so you can demonstrate Rubric Rows B5, F1, G1 and G2 in your report (see Tables B.2, B.5, and B.6).

Now that you have these measurements, it is time to find a pattern.

Finding a pattern

The penultimate step in an observational experiment is to find a pattern. Note that we are not explaining why this pattern is happening yet — we are focusing on describing it first.

Goal: Find a pattern in the data and describe it mathematically. **Available equipment:** Computer with spreadsheet software

1. Use a plotting program, for example LibreOffice Calc or Microsoft Excel, to plot a graph of fall time vs. filter area. The independent variable should be on the horizontal axis. The axes should each be labeled with the quantity name and the unit in parentheses. For example, if you measured fall time in seconds, then the axis label should be something like "fall time (s)".

2. In that graph, include also the uncertainty in each value. This usually involves right-clicking on a data point and selecting "error bars". Then you can highlight the column of cells that include the uncertainties.

3. Visually, discuss what shape the data points make. Speculate what kind of relationship you see. Is it proportional? Linear? Parabolic? Exponential? Logarithmic?

4. Create a line of best fit (or "trend line") in the graph using the software. Choose the equation type to match what your group guessed in the previous step. If the line obviously does not match the data, try again with a different equation type. Quantitatively, the goodness of fit of a line (how close the line is to your data points) can be represented by the correlation coefficient, given as r^2 in the software. If $r^2 \gtrsim 0.8$, then the equation that you found describes the data fairly well. Record that equation and the r^2 (or RMSE if given).

5. Make a final determination for describing in words the pattern found. If it applies, you should use one of the terms given in Step 3 in order to precisely describe the pattern.

6. Review Rubric Rows B7 and B8 in Table B.2 and ensure that you are demonstrating them here or have enough information to do so in your lab report.

Finishing up

Before you leave lab, be sure that you have reviewed the 7 rubric rows that are being used to assess your report and that you are equipped to do as well on them as you would like to. The visuals that you should definitely have in your report are sketches of your measurement setups and a graph of fall time vs. filter area. You may want to have others as well, but those you will definitely need.

Optional Fun Time Extra

To extend the lab just a little bit and break out of the "observational experiment" frame, and to check to see if your mathematical pattern (line of best fit) is consistent with other physics principles, you can extrapolate down to zero cross-sectional area. As an optional part of the lab with no added benefit to your grade (but with perhaps glee for your inner scientist), you can do this.

Using your equation for the relationship between the two variables, predict the freefall time of an object with zero cross-sectional area. You can compare this with the theoretical value for this time t, given for an object that is falling from height h, with the strength of the local gravitational field $g = 9.8\,\mathrm{m/s^2}$, with the following formula:

$$t = \sqrt{\frac{2h}{g}} \tag{1.1}$$

How close did you get?

1.1 Post-lab survey

To assist the instructors with understanding your experience in this lab, please also respond to the following questions on a scale from 1 to 7 (with 7 being the most)

1. To what extent was the instructor's assistance needed?
2. To what extent did you know what to do (goal of the task)?
3. To what extent did you know how to do it?
4. To what extent did you know how well you are doing?
5. to what extent was the assignment challenging?
6. To what extent did you feel knowledgeable and skillful during the lab?
7. To what extent was the lab fun and interesting?

1.2 If in Stars class, also do this:

Remote Observing with the Stone Edge Observatory

For two labs in this course, we will be taking observations remotely with the Stone Edge Observatory in Sonoma, California. We will use a queuing system to submit observations that are automatically scheduled and taken by the telescope. The data are then processed and typically available for analysis several days after they were obtained. To ensure that our data are taken and reduced in time for our in-lab analysis (which is subject to possible delays due to, e.g., the weather at the observing site), we will be submitting observations to the queue several weeks prior to lab in which they will be analyzed.

First, you will need to register for an account that will allow you to access the queue website. Make groups of two to three students so that there are no more than 5 groups in a section. Each group will use one member's email to sign up for an account in the queuing system. A TA will be present to manually add each group. Each group will receive an email that will allow them to create an account. Since you will be sharing an account, be sure to share the account password (and obviously don't re-use one from another personal account).

Once you have an account, you will be able to log onto the queue and submit observations. To do so, go to the website `https://queue.stoneedgeobservatory.com/` and log-in with your group's credentials. Then navigate to `OBSERVATIONS` ▶ `SUBMIT AN OBSERVATION`. This will take you to a form that allows you to input the specifics of your observation. These will be given to you for each lab.

HR Diagram: Taking observations

For this lab, each section will be taking observations of one of two star clusters — NGC 869 and M15. You will then use this data to make color-magnitude diagrams of these clusters, which can then be compared with stellar evolution models to determine when these clusters formed. Table 1.1 lists the parameters for the observations to be taken in this lab - each section will be assigned a cluster, and each group in the section should submit one observation. Each group will then analyze their data in-lab, and will combine datasets. If there are fewer groups than observations, omit the longest-exposure observations.

Table 1.1: HR Diagram Lab Observations

Program	**Target**	**Exp Time (s)**	**Exp Count**	**Bin**	**Filters**
General	M 15	1	1	2	Dark, g', r'
"	"	5	"	"	"
"	"	10	"	"	"
"	"	20	"	"	"
"	"	40	"	"	"
"	NGC 869	0.5	"	"	"
"	"	1	"	"	"
"	"	2	"	"	"
"	"	5	"	"	"
"	"	10	"	"	"

LAB 2

Spectroscopy

2.1 Introduction

In this lab we will study light produced in gas discharge tubes. You will first familiarize yourself with operation of the software by making careful measurements of emission lines from a hydrogen discharge tube. You will then use your knowledge of spectra to identify which elements are present in several other discharge tubes.

2.2 Learning goals

- Use experimentally derived quantities to calculate the Rydberg constant.
- Identify unknown elements based on their spectra.
- Compare continuum vs. line emission.
- Demonstrate an ability to make careful measurements.
- Demonstrate proficiency in basic calculations and plotting using spreadsheets.
- Gain familiarity with a common physics tool (the spectroscope).

2.3 Scientific background

When an electron collides with an atom in the discharge tube, the atom absorbs energy and transitions from its *ground state* to an *excited state*. When the atom later transitions back to its ground state, it emits energy in the form of light. Light from these transitions is emitted only at distinct colors, or wavelengths. The wavelengths of the spectral lines from each element are different, thus each element has it own "fingerprint" by which it can be identified. Spectroscopy can therefore be used to detect and measure elements in a material from a distance. Critically, the same lines that appear in gas discharge tubes the lab are also found in stars, allowing astronomers to study their elemental makeup. Without spectral information, there would be no other way for us to know what stars are made of because we cannot travel and take a sample, even for the closest star — our Sun.

As with much of astrophysics, we'll begin by studying the properties of hydrogen. Although hydrogen is the most abundant element in the universe, its lines in the sun are quite weak because the strength of the lines depends critically on the physical conditions in the star. Hydrogen was first identified on earth by Anders Jonas Ångström in 1853, but it was not detected in the sun until a decade later. Although Ångström was able to measure the four characteristic lines of hydrogen — known today as Hα, Hβ, Hγ, and Hδ — to a high degree of accuracy, it was not until 1885 that Johann Balmer (a sixty year old Swiss school teacher and mathematician with no physics background) found the correct mathematical relationship between the wavelengths of hydrogen. Balmer's relation suggested that the physical processes which produce hydrogen lines are connected to integer numbers, an explanation that ultimately required the overthrow of 19th century classical physics in favor of the first version of quantum theory by Bohr and others circa 1915.

The four Balmer lines correspond to transitions to the $n = 2$ state in hydrogen and follow the equation

$$\frac{1}{\lambda} = R\left(\frac{1}{n_{\text{final}}^2} - \frac{1}{n_{\text{initial}}^2}\right) = R\left(\frac{1}{4} - \frac{1}{n_{\text{initial}}^2}\right), \tag{2.1}$$

where λ is the wavelength of a particular line and $R = 1.097 \times 10^7\ \text{m}^{-1}$ is the Rydberg constant, with $n_{\text{initial}} > 2$.

2.4 Apparatus description: spectrometer

To measure spectral lines, astronomers use a device called a spectrometer, spectroscope, or spectrograph. Spectrometers used for precision scientific measurements have three basic elements:

1. A collimator consisting of a slit and mirror or lens. The collimator produces a parallel beam of light in one direction, similar to an eyepiece of a telescope
2. A dispersive grating that bends the light at an angle that depends on the wavelength of light, thereby decomposing it into a spectrum
3. A mirror or lens that collects the light and focuses it onto a detector The main part of any spectrograph is a dispersive element, which is usually a grating that consists of a very finely spaced lines etched on a substrate. The spacing between the lines can be 1/10 of the diameter of a human hair and the distance between each line is controlled to less than the diameter of a single atom. The process used to etch the grating is similar to that used in making CDs. Not surprisingly, CDs can be used to decompose a white light from a lamp into rainbow.

The angle θ at which grating reflects the light depends on the wavelength and is given by

$$m\lambda = d \sin\theta\,, \tag{2.2}$$

where m is the order of the maximum, λ is the wavelength (generally measured in nanometers, where a nanometer is 10^{-9} meters), d is the spacing of the lines on the diffraction grating (also in nm). Visible light has a wavelength of about 500 nm.

2.5 Apparatus: the digital spectrometer

A digital spectrometer also uses a diffraction grating, but instead of collecting the dispersed light on a screen to be viewed by people, it collects the light with a charge-coupled device (CCD), an array of light-sensitive pixels much like a digital camera. It then translates the position on the CCD to individual wavelengths and displays a plot of intensity vs. wavelength on a computer. Another difference is that we use an optical fiber to collect the light.

Here are a few guidelines:

- Save the images of spectra and numeric files that you generated with SpectraSuite during your experiments on a USB stick, so that you can use them at home during preparation of your report (you can also email them as attachments from your computer at the end of the lab).

- You should open a word processor document and a spreadsheet document in which you can save your measured spectra at the beginning of your work. To save an image of your graph, click on the fourth icon from the left in the Spectrum IO controls. This will copy an image of the graph to the clipboard. Then in your word processor, paste the image by pressing Ctrl-V.

- To save spectrum in the digital form, click on the third from the left icon in Spectrum IO controls (to the right of print icon). This copies it to clipboard. In Excel file make sure you are in a new sheet and press Ctrl-V. This should create to columns of numbers: wavelength (in nm) and counts for your spectrum.

- An alternative way to save the data is to click on the floppy disk icon in the Spectrum IO controls. The format must be "Tab delimiter, no header". The writing directory must be specified ("Browse" button). The spectrum is saved in a text file (.txt) as two columns, the first column giving the wavelength in nm, the second column the corresponding intensity. This file can be imported into a spreadsheet or plotting program.

2.6 Observation experiment: Spectrum of the sky and of fluorescent lamps

Goal: Observe the spectrum of the sky and of the fluorescent lights in the room, notice the differences, and identify some elements present in the fluorescent light bulb.

Rubric rows to focus on: B5, F1, F2. See Appendix B for details.

Available equipment: Ocean Optics Red Tide digital spectrometer with USB cable and fiber optic cable attached, computer with SpectraSuite software, window with daylight visible (or incandescent bulb if night-time lab), fluorescent light source

Caution: Fragile Equipment! The fiber optic cable is a precision instrument. If it is bent in too tight a curve, it will be damaged. Do not bend these cables beyond a 12 cm radius (4.5 inches) (into part of a circle with a radius smaller than that).

Also, the openings have covers to protect from dust and debris. Be sure to replace the end cover when you are done with the cable.

1. Turn on the computer and start Spectra Suite.

2. Ensure the digital spectrometer is connected to the computer and the fiber optic cable is connected to the spectrometer.

3. Remove the blue end cap from the fiber optic cable by twisting it.

4. Press S ("Scope") to start measuring the spectrum and point the fiber towards the overhead fluorescent light. You should see live spectrum of the light entering the fiber in the graph window, which is characterized by many strong peaks (strong emission lines).

A **fluorescent lamp tube** is filled with a gas containing low pressure mercury vapor, argon, neon, xenon or krypton, with corresponding lines in the spectrum. Emission lines are also produced by a phosphorous material (typically europium and terbium) covering the glass, after excitation by the ultraviolet emission from the lamp gas.

5. Record a spectrum and identify the different lines and their corresponding element, by comparison with other measurements of fluorescent light spectra (see Table 2.2). Save the spectrum and include it in your lab report along with markers of lines that you were able to identify.

6. Once you examine the spectrum you obtained with spectrometer, look at it with the visual spectroscope and identify lines you see visually with the lines you see in the digital spectrum.

7. Repeat the above procedure, but looking out a window at the sky. Record what you see, and make notes of how the spectrum from the sky differs from the spectrum of the fluorescent lights.

2.7 Application experiment: Measuring the Rydberg constant

Goal: Measure the wavelengths of light emitted from electrified hydrogen gas, and use those wavelengths to determine the Rydberg constant.

Rubrics rows to focus on: D4, D7, F1, F2, G2, G4. See Appendix B for details.

Available equipment: direct viewing spectrometer, Ocean Optics Red Tide digital spectrometer with USB cable and fiber optic cable attached, computer with SpectraSuite software, gas discharge tube power supply, hydrogen gas discharge tube

Warning: Shock Hazard! When turned on, the power supply generates 5000 V of electric potential difference across the terminals, with enough current available to injure you. Make sure that the discharge tube has its ON/OFF switch (on the side) in the OFF position when you install or change the discharge tube. If not, switch the lamp into the OFF position. Switch on the lamp to ON position only after tube is installed. The lamp will now be illuminated when the pedal is pressed. While the pedal is pressed, do not touch any part of the tube. Moving the whole unit by the base is safe.

Caution: Fragile Tube! Avoid touching the tube with your skin, as skin oils can degrade the glass over time. Wear a nitrile glove when touching a tube.

Also, the tubes have a limited lifetime of running. Turn on the tube only for as long as you need it to be on for measurement.

1. Ensure that the hydrogen tube is installed in the power supply.

2. Turn on the power supply and examine its spectrum through a direct viewing spectroscope. You should be able to see a bright magenta and a cyan line — these are the first two lines in the Balmer series. The other two lines are probably too faint for you to see; in order to measure them, we will need to use a more sensitive device.

3. Observe using the digital spectrometer by starting the SpectraSuite software, uncapping the optical fiber, and placing it as close as possible to the discharge tube and turn on the lamp. Adjust pointing of the fiber so that the height of the lines in the acquired spectrum is maximized. If the strongest lines are saturated, you can either move the fiber a bit farther away from the discharge tube or adjust integration time within the SpectraSuite software.

4. Follow these steps to measure the spectrum of light that enters the fiber using controls of the SpectraSuite software:

   a) Make sure you are in a new graph and enter Scope mode by pressing S in the controls. Point fiber at the discharge tube.

   b) Take a background “dark” measurement with the light source under study off by clicking the gray light bulb button in spectrum storage controls

   c) Subtract the background spectrum from the signal by clicking gray light bulb with minus sign button in the Processing controls. This removes contribution of background light to the spectrum.

Energy level (n)	**Measured Wavelength (nm)**	**Rydberg constant (nm^{-1})**
3		
4		
5		
6		

Table 2.1: Suggested table for recording data for Step 6 in Section 2.7.

d) turn on the source discharge tube and record its spectrum, saving an image of it as describe above in the guidelines.

e) While source is on, click on the spectrum graph. You should see a peak icon in the bottom right corner of the graph. This is useful peak finder: click on it and adjust controls, setting the Baseline, which is the intensity above which it will search for peaks. Peak finder identifies peaks and you can step through them and see their wavelengths using < and > buttons in the bottom left corner of the graph.

5. You should adjust the setup and acquisition time so that you can easily see four peaks (emission lines in the spectrum). Analyze the spectra and determine the wavelength of the four most prominent lines. Assume that these wavelength measurements are exact for the purposes of uncertainty analysis.

6. Write down the measured wavelengths of each line in the descending order of wavelength ($n_1 = 3$ corresponds to the peak with the longest wavelength that you measure, while $n_1 = 6$ to the shortest of the four you measure) in a table like Table 2.1. Be careful to measure the correct lines! The spectrometer is sensitive to wavelength is the near infrared and near ultraviolet, beyond detection of the human eye. Do you observe any such lines? Can they be included in your analysis?

Analysis

Using your data for each line, calculate the corresponding value of the Rydberg constant in units of 1/nm using Equation 2.1 and enter it into the column for the Rydberg constant in each line's row. The spectral lines you observe correspond to the first four transitions in the Balmer series, the transitions of electrons to the $n_{\text{final}} = 2$ level from higher energy levels.

The differences in values you get for the Rydberg constant are due to random uncertainty. To find your determination for this quantity, use your average for the value, and calculate the standard deviation for the uncertainty.

A more sophisticated way of calculating the Rydberg constant would be to plot a graph of your measurements of $1/\lambda$ vs $1/n_i^2$ and fit a straight line through it. The average value of the Rydberg constant is the slope of this line, which will be given by the slope. Carry out and present such a measurement along with the plot in your report.

2.8 Application experiment: identification of mystery elements

Goal: Identify the gas that is contained in the four tubes with colored tape on them.

Rubric rows to focus on: F1, F2

Available equipment: Ocean Optics Red Tide digital spectrometer with USB cable and fiber optic cable attached, computer with SpectraSuite software, gas discharge tube power supply, various gas discharge tubes with unknown gases

Helium (nm)	Argon (nm)	Neon (nm)	Mercury (nm)
389	697	585	365
447	707	594	404
469	738	614	435
492	751	627	546
502	764	640	579
588	772	651	
668	795	660	
707	801	668	
727	811	693	
	826	703	
	841	717	
	852	744	
	866		
	912		

Table 2.2: Some known emission lines of various elements.

Turn off the lamp using the switch on the side, and replace glass tube with hydrogen gas with one of the color-coded bulbs that will be provided to you. As before, use the spectrometer to acquire spectrum using the SpectraSuite software and measure wavelengths of the prominent lines (peaks in the spectrum).

Once you have measured a few prominent wavelengths, compare them with wavelengths of known lines of elements listed in the table below and identify the mystery element within the color-coded tube. Present your measurements of wavelengths in a list and a plot of the graph with several lines from Table 2.2.

2.9 End of Lab - Queue observations for 61 Cygnus AB

As we did in the first lab session, we will end this lab by queuing observations for a future lab. Specifically, each group will take an observation of the binary star system 61 Cygnus AB. The observational parameters are listed in Table 2.3. Refer to the previous chapter for instructions on submitting observations.

Table 2.3: 61 Cyg AB Observations

Program	Target	Exp Time (s)	Exp Count	Bin	Filters
General	61 Cyg	1	1	2	Dark, g'

LAB 3

The H-R Diagram

3.1 Introduction

In this lab we will analyze our observations of star clusters taken with the Stone Edge Observatory (SEO) to make one of the key figures in all of observational astronomy - the Hertzsprung-Russell (H-R) Diagram. This will give us insight into the stellar populations in the clusters we observe, and allow us to estimate the age of their constituent stars.

3.2 Learning goals

- Gain an understanding of astronomical observation, image analysis and photometry
- Gain practice performing basic calculations on datasets and making informative scientific figures from those data
- Learn where different stellar populations lie on the HR diagram, and understand the physical reasons behind these localizations
- Estimate stellar cluster ages using the predictions of stellar evolutionary models.

Rubric rows to be assessed: D1, D4, F1, F2, G2, G4, G5

3.3 Scientific background

Stars evolve (i.e., change their properties) over millions and often billions of years – too slow for us to see the evolution over a human lifespan. Such impressive longevity is due to the fact that stars are powered by thermonuclear reactions, which are very efficient in generating abundant energy and have quite a bit of fuel to last for a long time. Stars like our Sun last about 10 billion years (so the Sun is in its middle age). The long timescale of evolution also means that we have to develop a different way to study stellar evolution.

Astronomers explore evolution of stars by observing large populations of stars where different stars are in different stages of evolution. Of course, in order to do this we need to be able to tell which star is in what stage. This is done by a combination of observations – which measure luminosity and surface temperatures – and theoretical models – which predict how luminosity and surface temperature change as stars evolve. The key is that luminosity and temperature at a certain age are determined by star's mass, chemical composition, and details of thermonuclear reactions (which elements are burning, over what fraction of star's volume, etc.).

Luminosity and temperature of stars are related because they are both determined by their internal structure, which, in turn, is determined by the basic physical properties (mass, chemical composition, age). Therefore, stars are not scattered randomly in the luminosity and temperature space but follow well-defined sequences, which reflect the ranges of the controlling parameters in a given stellar population.

The surface temperatures of stars can be deduced by fitting a blackbody radiation spectrum to their spectra. Even for stars that do not have spectra measured, their temperatures can be deduced from their colors (Recall: does bluer color correspond to cooler or hotter temperature?). Our eyes and brain perceive color by analyzing spectral composition of the incoming light. In astronomy, a star's color is defined as the difference between its magnitudes measured through two different filters that block out all light except light within a fairly narrow range of wavelengths.

In order to interpret evolutionary states, we look at physical groupings of stars called stellar clusters, which are located at the same distance from us and were born at the same time from the same cloud of dense gas. The spread in their properties will thus not be due to different ages or initial compositions, but mainly due to different masses. As you will see, stars occupy distinct regions of the observable equivalent of the luminosity-temperature space – the magnitude-color space called the Hertzsprung-Russell (HR) diagram. We will make this diagram for the star cluster we observed.

3.4 Astronomical Observation: A Brief Overview

Telescopes

A **telescope** is any tool an astronomer uses to collect light from astronomical objects. Telescopes are effectively light buckets — they enable the visualization and analysis of astronomical objects by collecting enough light that these faint sources can be detected. This is enabled by a large **primary mirror** off of which incident light is reflected and focused into an eyepiece or onto a detector. A schematic for a type of telescope similar to the Stone Edge observatory is given in Fig 3.4. Thus the surface area of the primary mirror indicates the light-gathering abilities of a telescope: the human pupil is at most $\sim$ 8mm in diameter, while the largest amateur telescopes have apertures approaching $\sim$ 20cm, and the largest observatories in the world have primary mirrors of up to 10m. The telescope we used for these observations has a 50cm diameter, giving it the light-gathering power of approximately 3000 maximally-dilated human eyes!

Filters

Light is composed of energy-packets termed **photons** with energies that determine their wavelengths (sorter wavelength $\implies$ higher energy). Thus every light source exhibits a **spectrum** of energies based on its components, which are determined by the physics of the light emission process. Observing the spectrum of radiation emitted from astronomical objects is a fundamental tool in observational astrophysics. However, obtaining the specific intensity of radiation as a function of energy for many dim sources is challenging. An easier way to asses the electromagnetic energies observed is to image them in different **filters**: materials placed at the opening of a telescope that are transparent to a known range of wavelengths and opaque to all others (thus "filtering" the light). Thus, one can image the same object with multiple different filters to get a sense of the wavelength regimes that dominate the light from a source.

A filer is characterized by its **transmission function**: a function that characterizes the amount of light that is transmitted by the filter at each wavelength. Figure 3.4 shows the transmission functions for some standard astronomical filters (similar to the one's you'll be using in this class).

CCD Cameras

While telescopes do the job of gathering and focusing light from astronomical objects, and filters isolate an energetic subset of that light, one needs an attached detector to record images digitally for further

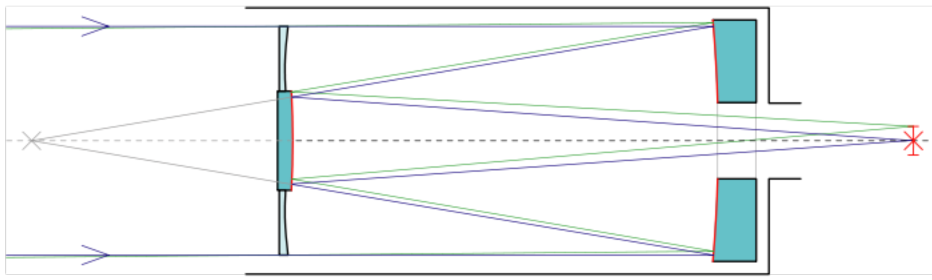

Figure 3.1: Schematic for a reflection telescope of a Schmidt-Cassegrain design, similar to the SEO telescope used to take the data for this lab. Light rays from astronomical objects enter the telescope in parallel because their source is effectively at infinite distance. They are then reflected by a parabolic primary mirror onto a secondary mirror that again reflects the light to a focus. An eyepiece or a camera is placed at the focal plane of the resulting image. Image source: `https://en.wikipedia.org/wiki/Cassegrain_reflector#/media/File:Schmidt-Cassegrain-Telescope.svg`

analysis. Modern astronomical observation primarily uses **Charge Coupled Devices (CCDs)** for this purpose. Every time a photon hits the detector, an electron is knocked off of the incident pixel, effectively charging that pixel. Thus, for each pixel, more photons $\implies$ more electrons $\implies$ more charge, and the charge can be read off into a digital signal that is then processed as an image. In this way, the brightness of the image on the detector is measured at each pixel. This brightness information constitutes the digital images astronomers analyze to understand their observational targets, as we will do in this lab.

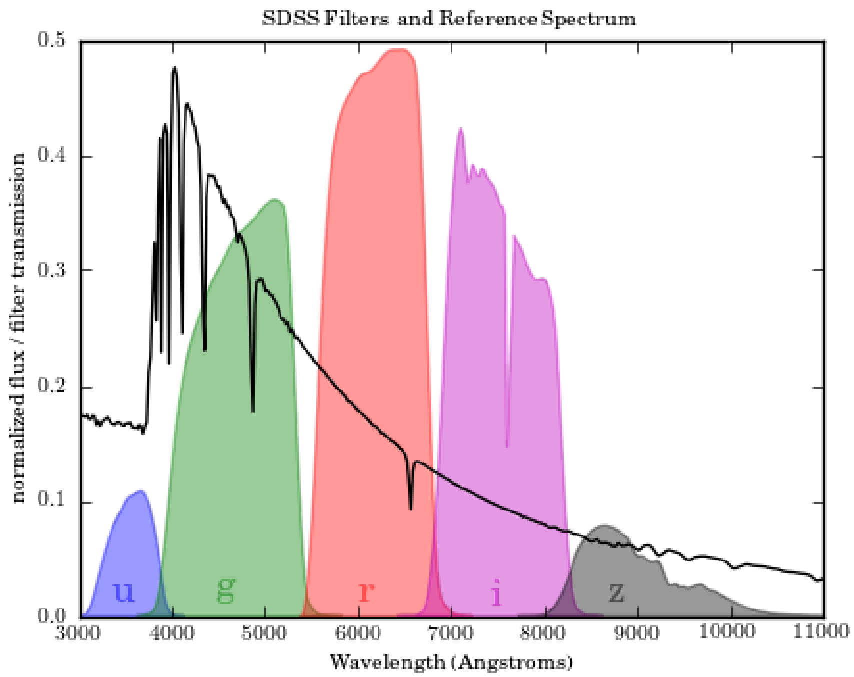

Figure 3.2: Filter Transmission Functions for the Sloan Digetal Sky Survey, overlaid on a stellar spectrum. The magnitude observed by each filter will be proportional to the integrated spectrum multiplied by the filter transmission. It's clear in this image that the underlying spectrum of the star will cause the different filters to have different magnitudes. Image source: `http://www.astroml.org/_images/fig_sdss_filters_1.png`

3.5 Obtaining Observational Data

To view images taken by the SEO and download the associated data, sign into your account on the queue website (`https://queue.stoneedgeobservatory.com/`), navigate to `OBSERVATIONS` ▶ `MY OBSERVATIONS`. The observation you queued should be listed, and `Yes` should appear in the `Completed` column if the data have been taken. To view and download completed observations, click `Actions` ▶ `Go To Images`. This will link you to an external page with both an image viewer and links to directly download the data. One of your observations should be immediately visible. To download your data, click `View Selected AOR Folder`, which contains the data products of your observation, and download the files that end in `BDF.fits` — there should be one for each filter. If for some reason you lack this file for *either* of your filters, ask for both from another group. You need to analyze data from both filters using the same exposure time.

3.6 Analyzing the data in DS9

To analyze our observations we will be using DS9 (`http://ds9.si.edu/site/Home.html`), a popular software package for the visualization and basic analysis of image data within the astronomical community. If you are working on a lab computer, the software is already installed. If you are using your personal computer, it can be downloaded and installed from the provided link.

We will use this tool to measure the flux in both observed filters for as many stars as possible. Each group should use separate, adjacent computers - bring up images in DS9 for each filter, one filter per computer. To better visualize the images in DS9, logarithmically scale the display by selecting `scale ▶ log`. Contrast and bias of the display image can be modified by right clicking and dragging - you should adjust these so that the stars are optimally visible.

To determine how much flux comes form each star, we will use the "regions" functionality of DS9 that gives information about a selected region in the image. First click `edit ▶ region`, and then you will create a region – indicated by a green circle – each time you click on the image. Clicking in the center of the region will allow you to move it about the image, while clicking on the edge allows you to adjust it's size. For each star you measure, you'll want to create a region that contains as much flux as possible without contamination from a nearby star or the background. Once this is accomplished, double click the region (which will cause a window with basic information to appear), and select `Analysis ▶ Statistics`, which will cause a separate panel to appear with information about the data contained in that region. `Sum` is an instrument-and-observation specific measure of the flux — the energy per unit surface area per unit time — incident on the detector from the light of the astronomical object we observe. Record this value and it's listed error. How are these values related (hint: you can directly calculate the error from the sum with a simple mathematical operation)? Why are they related in this way?

Note that even regions in the image that do not contain a discernable source have non-zero flux. This **background** is from scattered light from the earth's atmosphere (particularly when it's cloudy) and from light scattered by the apparatus inside the telescope. Since this background is not the signal we wish to analyze from our source, we should subtract it from the measured flux from each star. From several circular regions over nothing in particular, determine how many counts there are per unit area, just from the backgrounds. The `surf_bri` value gives what we need. Do this several times to determine the variance in the background. Thus quantify this background and its error. For each of your stars, compute the background that was likely in the aperture. This involves multiplying the surface brightness by the area you chose. Note that the error in the surface brightness propagates, so if you have a very big region, that will likely determine the error on your final measurement.

Try to measure fluxes and errors for as many stars as possible in your lab session. There will inevitably be some overlap between groups, which is fine, but try to obtain measurements for stars at a wide range of brightness's. 50 stars is a good target, but the more the better. Thirty minutes before lab ends, stop collecting data, and share your data among your section so that you can finish the rest of the analysis.

3.7 Calculating Magnitudes

In astronomy we deal with magnitudes, which are scaled logarithmically, and increase with decreasing source brightness. Specifically, the equation for the magnitude m_X of an object in a wavelength band X with flux F_X is given by

$$m_X = -2.5 \log_{10} \left(\frac{F_X}{F_{X,\mathrm{ref}}} \right) \tag{3.1}$$

where $F_{X,\mathrm{ref}}$ is a reference flux value for the given band and magnitude system. Note that the `sum` value we recorded is not actually the physical flux – the process of converting observed image brightness's to physical fluxes is a non-trivial calibration procedure we will not undertake here. Instead, we will calculate instrument-specific magnitudes by adopting the counts from the brightest star as the reference flux $F_{X,\mathrm{ref}}$. *Note: you must use the same star in both bands for these magnitudes to be compared. Determine the reference star in your section, and calculate magnitudes in both bands from all of the stars measured by your section using Excel or any other software/coding language of your choice.*

3.8 Making an HR Diagram

Since different bands measure brightness in different wavelengths, the ratio of flux in two bands is a measure of an object's color. Therefore, the difference between astronomical magnitudes of an object in different bands is a measure of its color, since the magnitude scale is logarithmic:

$$m_A - m_B = -2.5 \log \left(\frac{F_A}{F_B} \right). \tag{3.2}$$

An H-R diagram is a plot of stellar magnitude vs. color - aka a "color magnitude diagram". A star's color is an observational indication of it's surface temperature. Since all of the stars in a star cluster are at approximately the same distance, their apparent magnitude gives a good relative indicator of luminosity. Therefore, a color-magnitude diagram of stars at roughly constant distance is effectively a temperature-luminosity diagram, and stars fall in characteristic regions of this parameter space based on their mass, age, and metallicity.

We have data in two wavelength bands, so we can subtract those magnitudes to get a color measure. With the software or coding language of your choice, plot r' on the y-axis and $g' - r'$ on the x-axis. Add error bars to your plot. If doing so for each data point becomes crowded on your figure, you can estimate a typical error from your data and include it in a legend.

3.9 Making an HR Diagram – with proper photometry

In reality, your estimated error from the background is a lower limit, since there are many other possible sources of imprecision and inaccuracy in this measurement. Moreover, our analysis was an extremely crude approximation of the photometry done by professional astronomers. Finally, you may simply have recorded values for too few stars to make a color-magnitude plot to fully populate the different regions of the color-magnitude plot — in practice, astronomers use more automated techniques that allow them to analyze all stars in the image with adequate data. To make H-R diagrams that can be interpreted scientifically, use the data provided for the cluster you observed, each of which has a file on the course website containing data on these clusters obtained from publications in the astronomical literate ([3] for M15, [4] for NGC 869). Note that, if you observed NGC 869, the publicly available data was made with different filters than our observations, and thus the expected positions and shapes of stellar populations on a color-magnitude diagram change, but the same general features should be apparent. Label the different stages of stellar evolution on both the professionally reduced data and, if possible, on the data you obtained in lab.

3.10 Comparing to stellar evolution models

The last portion of this lab involves estimating the age of these stellar populations by comparing their color magnitude diagrams with predictions from a stellar evolution model. Stellar physics is sufficiently well-understood that accurate evolutionary models have been constructed to calculate the observable properties of stars across their lifetimes. Because stars evolve in their position on the HR diagram, we can estimate the age of our observed cluster by comparing these models to our observations.

Several files containing model predictions for the magnitudes of stars at different ages (from `http://stev.oapd.inaf.it/cgi-bin/cmd`), where you can easily access the predictions of stellar evolution models with parameters you specify) are contained in files on the course website. These have been calculated using the observed metallicity of the star cluster to predict the positions of stars at ages 10^7, 10^8, 10^9, and 10^{10} years. These are called isochrones - stellar properties as a function of stellar mass for a fixed age (and metallicity). Note that these magnitudes were calculated using prior knowledge of the star cluster metallicity, and have been corrected for cluster distance and extinction due to intervening galactic dust (taken from [5] for M15 and [6] for NGC 869).

Plot these isochrones on your H-R diagrams and compare them to your data to estimate the cluster age. Be sure to estimate an error on this value and explain your method in your lab report. What changes in stellar properties are represented by the different locations of isochrones of different ages? What physical processes occuring inside the star underlie those changes?

LAB 4

The Binary Orbit of 61 Cyg AB

4.1 Introduction

In this lab we will estimate the orbital parameters of the binary star system Cyg 61 AB using our own (in addition to data from historical) observations. Specifically, we will estimate the period P and semi-major axis a of the orbit, which we will then plug into Kepler's Third Law of orbital motion to calculate the combined mass of the two stars

4.2 Learning goals

- Gain an understanding of the Celestial coordinate system used in astronomical observation
- Understand how Kepler's Laws can be used to determine the physical properties of astrophysical systems
- Gain practice graphically representing scientific data and inferring values (and their uncertainties) from those graphs

Rubric rows to be assessed: D1, D4, D7, F1, F2, G2, G5

4.3 Introduciton to 61 Cygni AB

One of the questions beguiling humanity for millennia was: how far away are the stars? Until 1838, no one could tell! They looked to be almost astoundingly far away, because their parallax, their back-and-forth motion on the sky when the Earth orbits the Sun, was too small to measure. In fact, stars appearing fixed on the sky was an argument for geocentricism!

Friedrich Wilhelm Bessel made the first measurement of parallax, and thus the distance to a star. Giuseppe Piazzi had tipped him off, discovering in 1804 that the binary star 61 Cygni AB had a high proper motion, and thus was likely close to us. By 1838, Bessel had carried out the precise measurements needed to determine that it is only 10.3 light years away (modern figure, 11.4 light years). Quickly other investigators measured parallaxes for other stars, including the closest star we know of now, Proxima Centauri (part of the triple system Alpha Centauri, which is in the southern celestial hemisphere).

Newton's triumph was to realize the gravitational acceleration pulling on falling objects is the same force that holds the Moon in orbit. This insight can be generalized further to pairs of stars that orbit around their mutual center-of-mass. The 61 Cygni binary system has an observable orbit. We have a long baseline of measurements on it partially due to the intense observations to determine its parallax.

We will use these measurements to determine its orbit, and from that, the mass of the system This measurement serves as an example of how we use dynamical properties of stars to learn about their physical properties.

4.4 Introduction to Keplerian Orbits

Kepler's three laws are the following:

1. Planetary Orbits are elliptical with the Sun at one focus
2. The line between a planet and the Sun sweeps out equal areas in equal intervals of time
3. The orbital period squared is proportional to the semi-major axis cubed

These *empirical* (i.e. data-derived) laws were given a physical explanation by Newton. He postulated that a gravitational force proportional to the inverse square of the mutual distance acts between all bodies, and he showed this postulate resulted in Kepler's three laws. Newton's theory gives the constant of proportionality in Kepler's third law:

$$P^2 = \frac{4\pi^2}{G(M_A + M_B)} a^3 \tag{4.1}$$

where P is the orbital period, $G = 6.672 \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$ is Newton's Gravitational Constant, $M_A + M_B$ is the sum of the masses of the two orbiting bodies, and a is the **semi-major axis** of the ellipse swept out by the difference in the positions between bodies A and B. The semi-major axis of an ellipse is half the length of its longest axis. This week we will estimate P and a for 61 Cyg AB from both our contemporary data as well as centuries-old data. Then we will then use the above equation to estimate the sum of the masses of the stars.

4.5 The Celestial Coordinate System

Right Ascension (RA, symbol α ("alpha"), not to be confused with the semi-major axis in the previous section, which uses a cursive 'a') and Declination (Dec, symbol δ ("delta")) are the coordinates on the Celestial Sphere. They serve the same purpose as Latitude and Longitude on the surface of the Earth.

Declination tells us how far away from the celestial equator the star is. Conveniently, for the past millennium there has been a star (Polaris, the North Star) within a few degrees of the North Celestial Pole, so it has $\delta \sim 90°$. The celestial equator has $\delta = 0°$. Stars with negative δ are best viewed from the Southern Hemisphere of the Earth. Stars with δ of our current latitude minus 90°are always hidden from view by the horizon. Right Ascension tells us the longitude-like angle. Its lines bunch up at the poles of the coordinate system, just as lines of longitude do. These coordinates rotate with the sky so that an astronomical object fixed with respect to the sky maintains a constant Right Ascension and Declination, despite the 24-hour rotation of the sky as viewed by an observer on Earth. Consequently, this is the system we will use to analyze the binary star data.

4.6 Assembling the data

Adding a 2018 value to the 61 Cygni AB Observations

Download your data for 61 Cyg in the same way as you did for the HR diagram lab, except this time use the `WCS.fits` file. If you do not have one of those in your observation's directory, use the example observation posted to the class website (since everyone took observations with the same parameters, this won't change your analysis). Open up the image in DS9. Note that occasionally the telescope becomes misaligned and takes an observation in the wrong part of the sky. If this is the case, you

Table 4.1: Historical Data for 61 Cyg AB

Date	Separation r (arcsec)	Position Angle θ (°)	Reference
1753	19.6	35	J. Bradley, obtained via WVDSC
1838	16.204	95.325	Bessel 1938, AN, 16, 65
1914	23.3 ± 1.4	136.4 ± 3.5	Yerkes Plates
1951	26.3 ± 3.0	141 ± 7	Digitized Sky Survey, Blue I
2018			your measurement

won't see a bright binary (i.e. double) star in the center of the image, and you should use the example observation instead.

In the top panel of the DS9 display, you should notice coordinates labeled α and δ which correspond to Right Ascension and Declination in the celestial coordinate system. To record both coordinates *in degrees* for the centers of both stars, make a region centered on your star, and double-click to show region info. Right of `Center` coordinates is a menu. In the last section of that menu, change `Sexagesimal` to `Degrees` to get center coordinates in degrees. Record these for both stars.

The relative orbital position of the stars depends on the difference in these coordinates, $(\Delta\alpha, \Delta\delta)$, which are the positions of star B (the fainter star) minus the positions of star A (the brighter star). Calculate these values with the central coordinates you just obtained, and convert them to **arcseconds**. There are 60 **arcminutes** in a degree, and 60 **arcseconds** in an arcminute. Also calculate the average Declination of the two stars δ_{avg}, in degrees. As always, record errors for each value.

To compare our observation with historical data, we have to convert our differences in the celestial coordinate system to a polar coordinate system defined by separation r and position angle θ between the two stars. Usually, r is measured in arcsec and θ is measured in degrees counter-clockwise from North, so 0°means star B is directly North of star A, and 90°means star B is directly East of star A (East seems backwards, because we're looking up at the sky), and so on. This coordinate transformation can be calculated from the celestial coordinates using the following equations:

$$r = \sqrt{[\cos(\delta_{\text{avg}})\Delta\alpha]^2 + \Delta\delta^2} \tag{4.2}$$

$$\theta = \arctan\frac{\cos(\delta_{\text{avg}})\Delta\alpha}{\Delta\delta} \tag{4.3}$$

Two pitfalls to be aware of:

1. Be certain your calculator-of-choice expects angles in degrees, not radians.
2. If your calculator returns a negative θ, then use your knowledge of geometry to equivalently express it as a positive angle.

These quantities (including their uncertainties) can now be added to the historical data given in Table 4.1. **Note:** The uncertainties given for 1914 and 1951 are pretty large, greater than the pixel scale, because the images of the stars were saturated. The pre-1900 values were given in the literature by other methods, and without an uncertainty quoted.

4.7 Estimating Orbital Parameters

A precise and accurate measurement from our data would require fitting the positions of the stars as a function of time for an orbital model including eccentricity and inclination, which is too complicated for this lab. Instead, we can estimate visually the period and orbital semi-major axis by plotting our data. To do this, we must convert our polar (r, θ) coordinates to rectangular (x, y) coordinates with the following equations:

$$x = r\cos\theta \quad y = r\sin\theta \tag{4.4}$$

To put these in physical units, divide these values by the measured parallax of the system, 0.314 arcsec, to get coordinates in AU. Plot the (x, y) data points using the software or coding language of your choice. Estimate the semi-major axis of the orbit as half the greatest distance between two data points, and the period as twice the difference in time between those same points. Determine an uncertainty estimate, which you should explain and record for both quantities.

4.8 Deriving the mass of the binary

Now that we have the orbital period P and semi-major axis a of the binary star system, calculate the combined mass $M_A + M_B$ using Kepler's Third Law, stated at the beginning of the manual. Estimate and report your error on this measurement.

LAB 5

Intro to Radioactivity

5.1 Introduction

Over the next two weeks, we will explore a few basic properties of radioactive decay: (1) counting statistics, (2) types of radioactive decay, and (3) half-life. In the first week, we'll use samples of radioactive materials — isotopes of cobalt, strontium, cesium, and polonium — to generate energetic particles. We'll then make measurements to explore the properties of these particles and the counting statistics related to their decays. In the second week, we'll produce our own short-lived isotope of silver and watch the new atoms decay by counting the number of particles they emit. From that, we will measure the so-called half-life of the silver isotope we produce.

Learning Goals

- Become familiar with the statistics of counting events.
- Describe the four types of radioactive decay products
- Identify sources of random and systematic error.
- Make careful measurements.
- Use a spreadsheet application to calculate and plot data.
- Relate small scale physics (studying atoms in the lab) to large scale astrophysics (dating the big bang, supernovae, and the solar system)

Scientific Background

Nuclear reactions play an important role in astronomy, geophysical sciences, archaeology, and physical anthropology. They explain energy generation in stars, the relative abundance of chemical elements, and provide a method for determining the age of things — from a piece of wood, to a meteorite, to the universe itself.

Most elements exist in a number of different forms, called isotopes, some of which are unstable and can change from one type of element to another. When this occurs, a high-energy particle is usually emitted from the nucleus of the element as it changes. By measuring the ratios of isotopes with differing decay rates, one can infer the age of an object.

5.2 Testing experiment: Do radioactive isotopes decay randomly?

Goal: Answer the question, "Given what we understand about the standard deviation of measurements of random processes, do radioactive isotopes decay randomly?" Or, in the frame of a testing experiment, test the following hypothesis: "Radioactive sources decay randomly."

Rubrics to focus on during this experiment: C1, C4, C7, C8, F1, F2, G2. See Appendix B for details.

Available equipment: Stopwatch, SpecTech Geiger counter, computer with spreadsheet software, radioactive source (^{137}Cs)

> **Warning: Radioactive Material!** The radiation levels are very low and they present no hazard for the short time that you are in the lab. We estimate that you will receive an additional 2–10 μSv dose of ionizing radiation for the time that you are in lab today, about the same as you receive every day normally. You can compare this to the example doses in Fig. 5.1. Here are tips to keep your exposure low:
>
> - **Do not have any food, drink, food containers, or make-up on the lab bench, and do not consume any food or drink, and do not apply cosmetics, in the lab.** If the sealed button source were to leak, your food, drink, food container, or cosmetics could become contaminated with low levels of radioactive material that could be ingested.
> - **Decrease time with and increase distance from sources.** Handle the sources only when you need to be for the lab, and return them to their container when not using them.

> **Caution: Fragile Equipment!** The Geiger tube (the upright cylinder sitting in the plastic stand and connected to a coaxial cable at the top) hold a gas under vacuum, with a thin, fragile window at the bottom of the tube. Do not touch it, as it breaks extremely easily.

Theory of counting statistics

If you've ever worked in a not-too-busy retail environment, you've probably had the experience of realizing (perhaps) that random and uniform are two quite different things. You no doubt have sat waiting for customers, with nobody around for long stretches of time, and then, as though they'd coordinated in advance, a half dozen people all show up within a few minutes of each other. Each customer is indeed independent (no, they didn't have a Twitter call to organize a flashmob![1]) yet their arrival times clearly appear clustered. They are, in fact. But randomly. Uniform – one customer each minute – is quite dramatically different than a random procedure that yields one customer per minute on average. Retail customers (to a great extent), and elementary particles, act randomly, not uniformly.

Each atom in a radioactive sample has, per unit time, some probability of undergoing radioactive decay. That probability is independent of all the other atoms in the sample. Each atom decays, or not, based on its own probability and no other. The ensemble of particle decay counts that one would measure in the sample (using a Geiger counter as we will do, for example) is described by the something called the Poisson distribution, which gives, in this instance, the probability of a integer number of events occurring in a fixed interval of time, given an average rate. For large count rates, like we have here, the Poisson distribution is indistinguishable from the normal distribution (that is, a simple Gaussian function).

[1] Yes, popular interest in flash mobs peaked in 2011. Bear with us here.

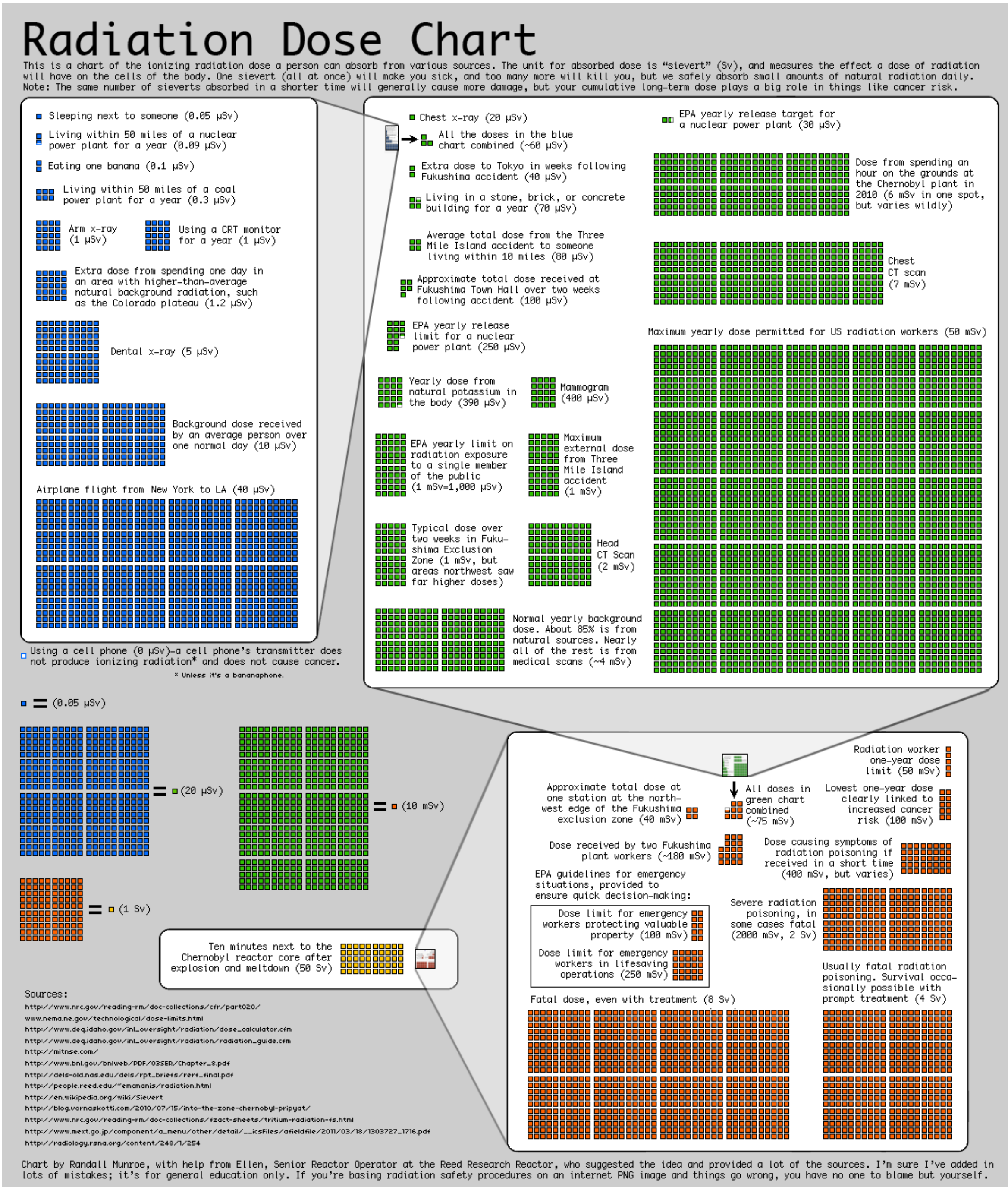

Figure 5.1: A chart of ionizing radiation dose from various sources. Source: https://xkcd.com/radiation/

Specifically, for a process that produces an average $\bar{N}$ counts in a certain time duration (in the case of large N), the expected measurement of that count for that time duration is a random draw from a normal distribution with mean $\bar{N}$ and a standard deviation of $\sqrt{N}$.

Procedure and analysis

1. To find the steps of a testing experiment, review Rubric C, found in Table B.3.

2. A prediction is what the hypothesis says will happen in the event of a particular experimental procedure. Given the hypothesis stated in the goal, and the theory described above, if you collect a series of counts of radioactive decay, what does the hypothesis predict the standard deviation of those counts should be equal to? Record this prediction in your lab notebook.

3. **Collecting data.** In order to find the standard deviation of a number of measurements, you will need to take those measurements. In the following steps, you will do 10 trials of measuring the count rate (counts per unit time) during periods of about 30 seconds, then take the standard deviation of those 10 trials. Since you will not be able to stop the counter after exactly 30 seconds, you will divide the displayed count by the displayed time to get a count rate (in units of "counts per second"), and then multiply this by 30 to get the count-rate per 30 seconds.

> **The Apparatus.**
>
> For this lab and the following one, you will be provided with a number of different radioactive materials packaged in small plastic disks. Note that each disk has the name of the isotope (e.g. ^{60}Co), the type of radiation, and the half-life printed on one side of the sample. Half lives can range from fractions of a second to billions of years, depending on the isotope.
>
> The energetic particles produced in radioactive decay reactions can be detected by a device called a Geiger counter. This consists of a tube filled with inert gas with a wire running through it. A high voltage is applied between the wire and the tube. When a high- energy particle enters the tube, it can ionize the gas. The freed electrons produce a brief pulse of current at the output of the device. The pulses can then be counted.
>
> The counter itself is controlled using buttons on the front panel. `COUNT` begins the count and starts the timer, `STOP` pauses the count and timer, and `RESET` sets the count and timer to zero. Use the dial on the counter to change the display between the count and the elapsed time. When you first turn on the Geiger counter you need to set the voltage to 1000 V — the TA will demonstrate how. **Caution:** Do not turn off the voltage during the experiment; use the `STOP` button to stop the count. **Do not touch the window on the bottom of the tube, as it breaks extremely easily.**

   a) Take one of the ^{137}Cs disks and place it printed side down in the plastic shelf shaped to hold it, and place that shelf in the slot second from the top in the stand under the Geiger counter. Note that if you have the Geiger counter on, that it is measuring a large count rate.

   b) Use the controls `COUNT`, `STOP`, and `RESET` to measure the number of counts in 10 approximately 30-second intervals. Use the dial on the display to access both the counts and the elapsed time. The provided stopwatch may also help you organize your effort — *but use the time from the Geiger counter apparatus directly* for your calculations.

   c) Record the counts and elapsed time in each interval in a spreadsheet and calculate the count rate in counts per half-minute.

4. **Analysis.** Note that the count rate is not identical in each trial, even though you accounted for the different measurement durations. Let's see how far away the standard deviation here is from

the prediction in Step 2. Calculate the standard deviation of these measurements. How close is it? Answer this quantitatively by calculating the *percent difference*,

$$\text{percent difference} = 200\% \times \frac{|A-B|}{A+B}\,, \tag{5.1}$$

where A and B are the two quantities that you are comparing. Without taking the time to find the uncertainty in the standard deviation, this is the best you can do to say how close it is.

5. Use this quantitative comparison to determine if the prediction and the outcome agree or not.

6. Based on that agreement, and taking into account the experimental conditions, make a judgment about the hypothesis. Is the radioactive decay happening randomly?

5.3 Observational experiment: types of radiation

Goal: Observe the effects of shielding on different types of radiation and generate some ideas about the patterns you see.

Rubrics to focus on: F1, F2, G2. See Appendix B for details. *Note that the C rubric rows from the previous experiment do not apply to an observational experiment.*

Available equipment: Stopwatch, SpecTech Geiger counter, computer with spreadsheet software, radioactive sources (^{60}Co, ^{137}Cs, ^{90}Sr), shielding of various thicknesses

Background: types of radiation

There are four basic types of radiation: alpha particles, which are the nuclei of helium atoms consisting of two protons and two neutrons; beta particles, which are energetic electrons; gamma rays, which are very energetic photons, *i.e.* particles of light; and finally neutrons. (The terms "alpha," "beta," and "gamma" were coined before anyone knew much about the actual particles involved.) We'll be working with gamma and beta radiation in what follows. Part 2 of this lab next week includes the use of a neutron radiation source.

Different types of radiation of the same energy interact with matter in different ways. Alpha is stopped by a piece of paper, beta is stopped by a book, while gamma rays are stopped by a shelf of books, or many inches of steel or lead.

Procedure

1. We will begin by attempting to measure how much material it takes to stop the beta particles from ^{90}Sr. Take a sample of ^{90}Sr and put it under the Geiger counter in the second slot down from the top, printed side down, removing the ^{137}Cs source you used previously if you still have it in place.

2. Count the number of particles detected in 60 seconds from this source, and record this number.

3. Qualitative observe the effect of different shields by placing them between the sample and the Geiger counter and recording the count rate (for example, in counts per minute) for each shield. You should try a few different shields with different thicknesses (measured in mg/cm^2).

4. One way to quantity the penetrating ability of radiation is to find it's "stopping length", which is the thickness of shielding that reduces the detected count to half the unshielded amount. Find the stopping length of the radiation emitted by ^{90}Sr and include uncertainties in your reported count rates.

5. Now find the stopping length for ^{60}Co. This time, **place the sample holder in the third slot from the top instead of the second**. If you need to use a thicker shield than the thickest one, you can use two of them and add the thicknesses together.

6. How do the two stopping lengths compare, qualitatively, to each other. What does this tell you about the relative penetrating ability of beta and gamma radiation?

7. As before, note your measured count rates, with uncertainties, in your lab report, as well as recording the stopping length.

8. Now, finally, we will examine the radioactive properties of the ^{137}Cs source. Place it in the sample holder as before, and record the unshielded count rate in a 60 second interval. The sample is noted as having both gamma and beta radiation. Use the shields to attempt to establish this experimentally, by comparison to the results you got for the ^{60}Co and ^{90}Sr samples. *Note that this last step is not a standard part of an observational experiment, but rather an application experiment.*

Questions for discussion, to include in your lab report

1. You probably didn't find a shield that produced an exact 50% reduction in counts. However, we can still estimate what the properties an exact 50% reduction shield would be. Describe a procedure to estimate the properties of such a shield and then perform that calculation.

2. What fraction of the total counts from the ^{137}Cs source are due to gamma rays?

3. Is the stopping length of the ^{137}Cs gamma rays similar to the stopping length of the ^{60}Co gamma rays? Would you expect it to be?

4. Is the stopping length of the beta particles from the ^{137}Cs source more, less, or similar to that for the Sr source? What might you have expected, if you'd known that the beta particles for the ^{137}Cs in most cases have energies of 0.512 MeV and those from the decay of ^{90}Sr have an energy of 0.546 MeV?

5. If you put the ^{90}Sr source in once more (this time in the third slot) and measured the counts, and then placed two of the shields previously determined to cut the source counts by a factor of 2 between the source and Geiger counter, what count rate would you expect, relative to the unshielded rate? Why? Would you expect the same behavior from the ^{137}Cs source?

6. How do the stopping lengths for beta particles compare to the stopping lengths for gamma rays? Can you come up with a physical explanation for the patterns you observe? Does this explanation extend to what you know about alpha particles?

LAB 6

Radioactive Half-Life

Building on our work from last week, we will continue to study the radioactive decay. The physical laws of radioactivity predict that the rate of decay (number of atoms decayed / time interval) is proportional to the number of radioactive nuclei present. This is due, as we saw in counting statistics previously, to the independence of the decay of each atom in the sample. The proportionality constant that describes the decay rate depends on the specific radioactive nucleus. A concise and suggestive way to characterize the nucleus is by its half-life, the time it takes for the number of radioactive nuclei to decrease to half of the initial value. You will obtain data to check the form of the law and to determine the half-life of one or more isotopes of silver.

We will use a device known as a neutron "Howitzer". It consists of a source of alpha particles and a material that absorbs alpha particles and immediately decays by emitting neutrons. (The neutrons shoot out from the barrel of the shielded volume, vaguely like shells from WWI artillery, hence the name.)

6.1 Background

We will let the neutrons bombard a small sample of the stable isotope of silver, $^{107}\mathrm{Ag}$, to produce $^{108}\mathrm{Ag}$, via the reaction

$$^{107}\mathrm{Ag} + \mathrm{n} \rightarrow {}^{108}\mathrm{Ag} + \gamma \,, \tag{6.1}$$

where n represents a neutron and γ a gamma particle — that is, a high energy photon.

The radioactive isotope of silver, $^{108}\mathrm{Ag}$, spontaneously decays to an isotope of cadmium with the same mass number, $^{108}\mathrm{Cd}$, by the reaction

$$^{108}\mathrm{Ag} \rightarrow {}^{108}\mathrm{Cd} + \mathrm{e}^- + \gamma \,, \tag{6.2}$$

where e^- is an electron (that is, a β particle, as we saw and measured last week).

Your TA will bombard silver foils with neutrons using the neutron howitzer. Some of the nuclei in the foil will have captured a neutron and transformed into a different isotope which is unstable and can be detected via their decay products. Each group will be given one of these silver foils.

6.2 Procedure

Rubric rows to be assessed: D1, D4, F1, F2, G2, G3 (ignore actually doing it), G4

Your task is to measure the half-life of $^{108}\mathrm{Ag}$. We will use the Geiger tube to count decays. That is, we will count the β particles — the gamma rays make only a small contribution to the counts in this instance. You should attempt to carry out the counting fairly quickly after the silver foil is removed from the howitzer as the decay time is quite short.

Before the neutron irradiation begins you will want to record the background rate. Press `STOP` and `RESET` on the counter to set the display to zero. Next, press `COUNT` with no sample below the Geiger tube and collect the total number of background counts, N_{bkg} , that accumulate in approximately 5 minutes. Once 5 minutes has elapsed press `STOP` to end the count. Turn the dial to `TIME` and record a precise measurement of the elapsed time, t, in seconds. The background rate R_{bkg} is found with

$$R_{\mathrm{bkg}} = N_{\mathrm{bkg}}/t \tag{6.3}$$

with an uncertainty given by Poisson statistics. Report both the background rate and uncertainty in your lab report.

While the samples are being irradiated, set up your measurement apparatus. Once the samples are ready, quickly place a silver foil sample in the tray below the Geiger tube. Using a stopwatch and the counter, record the number of counts and the time at 30 second intervals for about 10 minutes, continuously. Unlike last week's lab with the same apparatus, you will be recording data continuously, and so will need to use the watch to record times rather than timer built into the Geiger counter. Record your data.

6.3 Calculations

The experimental data will be used to determine a half-life (or half-lives). We know that the decay rate ($R = \Delta N/\Delta t$) of a radioactive nuclide is proportional to the number of nuclei present. The proportionality constant is called the decay constant λ, and the equation that describes what was just discussed is

$$R = \lambda N\,, \tag{6.4}$$

where N is the background-subtracted counts. Using integral calculus and the above equation, we find

$$\frac{N}{N_0} = e^{-\lambda t}\,, \tag{6.5}$$

where N_0 is the number of nuclei at the initial time $t = 0$. The half life $T_{1/2}$ is defined by the time it takes for $N = N_0/2$ and is related to the decay constant by $T_{1/2} = \ln(2)/\lambda$, where ln() is the natural logarithm function, and so $\ln(2) \approx 0.693$.

We can now write the radioactive decay equation as

$$R = \lambda N_0 e^{-t\ln(2)/T_{1/2}}\,. \tag{6.6}$$

Taking the logarithm of both sides and substituting for N gives

$$\ln(R) = -\left(\frac{\ln(2)}{T_{1/2}}\right) t + \mathrm{const}\,. \tag{6.7}$$

Your TA will help you to understand the details of this derivation.

Make a plot showing $\ln(R)$ on the vertical axis and elapsed time, t, along the horizontal axis. Don't forget to subtract the background where appropriate. Calculate the slope and use this value to solve for the half life using the above equations. Report this value along with a table of your decay rate data and the plot described above.

6.4 Questions (these should be included in your lab report)

1. Look up the half-lives of the various nuclides of silver. What is the published half-life of the nuclide you're observing? How does this compare with your calculated result? Calculate the percent difference in your result.

2. For the silver foil, how long would it take before you would expect to detect only one count per second, background corrected?

3. The detector only measures particles that travel up into the detector. The majority of particles traveling in the other directions escape detection. Will this short- coming affect the measured half-life? If so, how? If not, why not?

4. Describe one thing you could change in this experiment that could lead to a more accurate measurement of the half-life of the silver isotope.

5. The particular irradiated silver sample you used contained some unknown percentage of the unstable silver isotope, and was irradiated at some unmeasured time before you began your experiment. Does this matter to your results? Explain.

APPENDIX A

Analysis of Uncertainty

A physical quantity consists of a value, unit, and uncertainty. For example, “$5 \pm 1\,\mathrm{m}$” means that the writer believes the true value of the quantity to most likely lie within 4 and 6 meters[1]. Without knowing the uncertainty of a value, the quantity is next to useless. For example, in our daily lives, we use an implied uncertainty. If I say that we should meet at around 5:00 pm, and I arrive at 5:05 pm, you will probably consider that within the range that you would expect. Perhaps your implied uncertainty is plus or minus 15 minutes. On the other hand, if I said that we would meet at 5:07 pm, then if I arrive at 5:10 pm, you might be confused, since the implied uncertainty of that time value is more like 1 minute.

Scientists use the mathematics of probability and statistics, along with some intuition, to be precise and clear when talking about uncertainty, and it is vital to understand and report the uncertainty of quantitative results that we present.

A.1 Types of measurement uncertainty

For simplicity, we limit ourselves to the consideration of two types of uncertainty in this lab course, instrumental and random uncertainty.

Instrumental uncertainties

Every measuring instrument has an inherent uncertainty that is determined by the precision of the instrument. Usually this value is taken as a half of the smallest increment of the instrument’s scale. For example, 0.5 mm is the precision of a standard metric ruler; 0.5 s is the precision of a watch, etc. For electronic digital displays, the equipment’s manual often gives the instrument’s resolution, which may be larger than that given by the rule above.

Instrumental uncertainties are the easiest ones to estimate, but they are not the only source of the uncertainty in your measured value. You must be a skillful experimentalist to get rid of all other sources of uncertainty so that all that is left is instrumental uncertainty.

[1] The phrase “most likely” can mean different things depending on who is writing. If a physicist gives the value and does not given a further explanation, we can assume that they mean that the measurements are randomly distributed according to a normal distribution around the value given, with a standard deviation of the uncertainty given. So if one were to make the same measurement again, the author believes it has a 68% chance of falling within the range given. Disciplines other than physics may intend the uncertainty to be 2 standard deviations.

Random uncertainties

Very often when you measure the same physical quantity multiple times, you can get different results each time you measure it. That happens because different uncontrollable factors affect your results randomly. This type of uncertainty, random uncertainty, can be estimated only by repeating the same measurement several times. For example if you measure the distance from a cannon to the place where the fired cannonball hits the ground, you could get different distances every time you repeat the same experiment.

For example, say you took three measurements and obtained 55.7, 49.0, 52.5, 42.4, and 60.2 meters. We can quantify the variation in these measurements by finding their standard deviation using a calculator, spreadsheet, or the formula (assuming the data distributed according to a normal distribution)

$$\sigma = \sqrt{\sum_{i=1}^{N} \frac{(x_i - \bar{x})^2}{N-1}}\,, \tag{A.1}$$

where $\{x_1, x_2, \ldots, x_N\}$ are the measured values, $\bar{x}$ is the mean of those values, and N is the number of measurements. For our example, the resulting standard deviation is 6.8 meters. Generally we are interested not in the variation of the measurements themselves, but how uncertain we are of the average of the measurements. The uncertainty of this mean value is given, for a normal distribution, by the so-called "standard deviation of the mean", which can be found by dividing the standard deviation by the square root of the number of measurements,

$$\sigma_{\text{mean}} = \frac{\sigma}{\sqrt{N}}\,. \tag{A.2}$$

So, in this example, the uncertainty of the mean is 3.0 meters. We can thus report the length as $52 \pm 3\,\text{m}$.

Note that if we take more measurements, the standard deviation of those measurements will not generally change, since the variability of our measurements shouldn't change over time. However, the standard deviation of the mean, and thus the uncertainty, will decrease.

A.2 Propagation of uncertainty

When we use an uncertain quantity in a calculation, the result is also uncertain. To determine by how much, we give some simple rules for basic calculations, and then a more general rule for use with any calculation which requires knowledge of calculus. Note that these rules are strictly valid only for values that are normally distributed, though for the purpose of this course, we will use these formulas regardless of the underlying distributions, unless otherwise stated, for simplicity.

If the measurements are completely independent of each other, then for quantities $a \pm \delta a$ and $b \pm \delta b$, we can use the following formulas:

$$\text{For } c = a + b \text{ (or for subtraction), } \delta c = \sqrt{(\delta a)^2 + (\delta b)^2} \tag{A.3}$$

$$\text{For } c = ab \text{ (or for division), } \frac{\delta c}{c} = \sqrt{\left(\frac{\delta a}{a}\right)^2 + \left(\frac{\delta b}{b}\right)^2} \tag{A.4}$$

$$\text{For } c = a^n,\ \frac{\delta c}{c} = n\frac{\delta a}{a} \tag{A.5}$$

For other calculations, there is a more general formula not discussed here.

Expression	Implied uncertainty
12	0.5
12.0	0.05
120	5
120.	0.5

Table A.1: Expression of numbers and their implied uncertainty.

What if there is no reported uncertainty?

Sometimes you'll be calculating with numbers that have no uncertainty given. In some cases, the number is exact. For example, the circumference C of a circle is given by $C = 2\pi r$. Here, the coefficient, 2π, is an exact quantity and you can treat its uncertainty as zero. If you find a value that you think is uncertain, but the uncertainty is not given, a good rule of thumb is to assume that the uncertainty is half the right-most significant digit. So if you are given a measured length of 1400 m, then you might assume that the uncertainty is 50 m. This is an assumption, however, and should be described as such in your lab report. For more examples, see Table A.1.

How many digits to report?

After even a single calculation, a calculator will often give ten or more digits in an answer. For example, if I travel 11.3 ± 0.1 km in 350 ± 10 s, then my average speed will be the distance divided by the duration. Entering this into my calculator, I get the resulting value "`0.0322857142857143`". Perhaps it is obvious that my distance and duration measurements were not precise enough for all of those digits to be useful information. We can use the propagated uncertainty to decide how many decimals to include. Using the formulas above, I find that the uncertainty in the speed is given by my calculator as "`9.65683578099600e-04`", where the '`e`' stands for "times ten to the". I definitely do not know my uncertainty to 14 decimal places. For reporting uncertainties, it general suffices to use just the 1 or 2 left-most significant digits, unless you have a more sophisticated method of quantifying your uncertainties. So here, I would round this to 1 significant digit, resulting in an uncertainty of 0.001 km/s. Now I have a guide for how many digits to report in my value. Any decimal places to the right of the one given in the uncertainty are distinctly unhelpful, so I report my average speed as "0.032 ± 0.001 km/s". You may also see the equivalent, more succinct notation "0.032(1) km/s".

A.3 Comparing two values

If we compare two quantities and want to find out how different they are from each other, we can use a measure we call a t' value (pronounced "tee prime"). This measure is not a standard statistical measure, but it is simple and its meaning is clear for us.

Operationally, for two quantities having the same unit, $a \pm \delta a$ and $b \pm \delta b$, the measure is defined as[2]

$$t' = \frac{|a - b|}{\sqrt{(\delta a)^2 + (\delta b)^2}} \tag{A.6}$$

If $t' \lesssim 1$, then the values are so close to each other that they are indistinguishable. It is either that they represent the same true value, or that the measurement should be improved to reduce the uncertainty.

If $1 \lesssim t' \lesssim 3$, then the result is inconclusive. One should improve the experiment to reduce the uncertainty.

If $t' \gtrsim 3$, then the true values are very probably different from each other.

[2]Statistically, if δa and δb are uncorrelated, random uncertainties, then t' represents how many standard deviations the difference $a - b$ is away from zero.

APPENDIX B

Rubrics

Each lab is graded 50% on attendance and participation during the lab, and providing evidence in the lab report of completing all steps of the lab, including answering every question. The other 50% is based on a selection of scientific abilities. Each scientific ability rubric row assessed is worth a possible 3 points, with "Missing" being 0 points, "Inadequate" 1 point, "Needs Improvement" 2 points, and "Adequate" 3 points.

The scientific abilities rubrics are found on the following pages.

	Scientific Ability	Missing	Inadequate	Needs Improvement	Adequate
A11	**Graph**	No graph is present.	A graph is present but the axes are not labeled. There is no scale on the axes.	The graph is present and axes are correctly labeled, but the axes do not correspond to the independent and dependent variables, or the scale is not accurate.	The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate.

Table B.1: Rubric A: Ability to represent information in multiple ways

	Scientific Ability	Missing	Inadequate	Needs Improvement	Adequate
B1	**Is able to identify the phenomenon to be investigated**	No phenomenon is mentioned	The description of the phenomenon to be investigated is confusing, or it is not the phenomenon of interest.	The description of the phenomenon is vague or incomplete.	The phenomenon to be investigated is clearly stated.
B2	**Is able to design a reliable experiment that investigates the phenomenon**	The experiment does not investigate the phenomenon.	The experiment may not yield any interesting patterns.	Some important aspects of the phenomenon will not be observable.	The experiment might yield interesting patterns relevant to the investigation of the phenomenon.
B3	**Is able to decide what physical quantities are to be measured and identify independent and dependent variables**	The physical quantities are irrelevant.	Only some of physical quantities are relevant.	The physical quantities are relevant. However, independent and dependent variables are not identified.	The physical quantities are relevant and independent and dependent variables are identified.

	Scientific Ability	Missing	Inadequate	Needs Improvement	Adequate
B4	**Is able to describe how to use available equipment to make measurements**	At least one of the chosen measurements cannot be made with the available equipment.	All chosen measurements can be made, but no details are given about how it is done.	All chosen measurements can be made, but the details of how it is done are vague or incomplete.	All chosen measurements can be made and all details of how it is done are clearly provided.
B5	**Is able to describe what is observed without trying to explain, both in words and by means of a picture of the experimental setup.**	No description is mentioned.	A description is incomplete. No labeled sketch is present. Or, observations are adjusted to fit expectations.	A description is complete, but mixed up with explanations or pattern. Or the sketch is present but is difficult to understand.	Clearly describes what happens in the experiments both verbally and with a sketch. Provides other representations when necessary (tables and graphs).
B6	**Is able to identify the shortcomings in an experiment and suggest improvements**	No attempt is made to identify any shortcomings of the experiment.	The shortcomings are described vaguely and no suggestions for improvement are made.	Not all aspects of the design are considered in terms of shortcomings or improvements.	All major shortcomings of the experiment are identified and reasonable suggestions for improvement are made.
B7	**Is able to identify a pattern in the data**	No attempt is made to search for a pattern.	The pattern described is irrelevant or inconsistent with the data.	The pattern has minor errors or omissions. Terms like "proportional" used without clarity, e.g. is the proportionality linear, quadratic, etc.	The pattern represents the relevant trend in the data. When possible, the trend is described in words.
B8	**Is able to represent a pattern mathematically (if applicable)**	No attempt is made to represent a pattern mathematically.	The mathematical expression does not represent the trend.	No analysis of how well the expression agrees with the data is included, or some features of the pattern are missing.	The expression represents the trend completely and an analysis of how well it agrees with the data is included.

	Scientific Ability	Missing	Inadequate	Needs Improvement	Adequate
B9	**Is able to devise an explanation for an observed pattern**	No attempt is made to explain the observed pattern.	An explanation is vague, not testable, or contradicts the pattern.	An explanation contradicts previous knowledge or the reasoning is flawed.	A reasonable explanation is made. It is testable and it explains the observed pattern.

Table B.2: Rubric B: Ability to design and conduct an observational experiment [7].

	Scientific Ability	Missing	Inadequate	Needs Improvement	Adequate
C1	**Is able to identify the hypothesis to be tested**	No mention is made of a hypothesis.	An attempt is made to identify the hypothesis to be tested but it is described in a confusing manner.	The hypothesis to be tested is described but there are minor omissions or vague details.	The hypothesis is clearly, specifically, and thoroughly stated.
C2	**Is able to design a reliable experiment that tests the hypothesis**	The experiment does not test the hypothesis.	The experiment tests the hypothesis, but due to the nature of the design it is likely the data will lead to an incorrect judgment.	The experiment tests the hypothesis, but due to the nature of the design there is a moderate chance the data will lead to an inconclusive judgment.	The experiment tests the hypothesis and has a high likelihood of producing data that will lead to a conclusive judgment.

	Scientific Ability	Missing	Inadequate	Needs Improvement	Adequate
C4	**Is able to make a reasonable prediction based on a hypothesis**	No prediction is made. The experiment is not treated as a testing experiment.	A prediction is made, but it is identical to the hypothesis, OR prediction is made based on a source unrelated to the hypothesis being tested, or is completely inconsistent with hypothesis being tested, OR prediction is unrelated to the context of the designed experiment.	Prediction follows from hypothesis but is flawed because relevant assumptions are not considered, OR prediction is incomplete or somewhat inconsistent with hypothesis, OR prediction is somewhat inconsistent with the experiment.	A prediction is made that follows from hypothesis, is distinct from the hypothesis, accurately describes the expected outcome of the experiment, and incorporates relevant assumptions if needed.
C5	**Is able to identify the assumptions made in making the prediction**	No attempt is made to identify assumptions.	An attempt is made to identify assumptions, but the assumptions are irrelevant or are confused with the hypothesis.	Relevant assumptions are identified but are not significant for making the prediction.	Sufficient assumptions are correctly identified, and are significant for the prediction that is made.
C6	**Is able to determine specifically the way in which assumptions might affect the prediction**	No attempt is made to determine the effects of assumptions.	The effects of assumptions are mentioned but are described vaguely.	The effects of assumptions are determined, but no attempt is made to validate them.	The effects of assumptions are determined and the assumptions are validated.
C7	**Is able to decide whether the prediction and the outcome agree/disagree**	No mention of whether the prediction and outcome agree/disagree.	A decision about the agreement/disagreement is made but is not consistent with the results of the experiment.	A reasonable decision about the agreement/disagreement is made but experimental uncertainty is not taken into account.	A reasonable decision about the agreement/disagreement is made and experimental uncertainty is taken into account.

	Scientific Ability	Missing	Inadequate	Needs Improvement	Adequate
C8	**Is able to make a reasonable judgment about the hypothesis**	No judgment is made about the hypothesis.	A judgment is made but is not consistent with the outcome of the experiment.	A judgment is made, is consistent with the outcome of the experiment, but assumptions are not taken into account.	A judgment is made, is consistent with the outcome of the experiment, and assumptions are taken into account.

Table B.3: Rubric C: Ability to design and conduct a testing experiment [7].

	Scientific Ability	Missing	Inadequate	Needs Improvement	Adequate
D1	**Is able to identify the problem to be solved**	No mention is made of the problem to be solved.	An attempt is made to identify the problem to be solved but it is described in a confusing manner.	The problem to be solved is described but there are minor omissions or vague details.	The problem to be solved is clearly stated.
D2	**Is able to design a reliable experiment that solves the problem.**	The experiment does not solve the problem.	The experiment attempts to solve the problem but due to the nature of the design the data will not lead to a reliable solution.	The experiment attempts to solve the problem but due to the nature of the design there is a moderate chance the data will not lead to a reliable solution.	The experiment solves the problem and has a high likelihood of producing data that will lead to a reliable solution.
D3	**Is able to use available equipment to make measurements**	At least one of the chosen measurements cannot be made with the available equipment.	All of the chosen measurements can be made, but no details are given about how it is done.	All of the chosen measurements can be made, but the details about how they are done are vague or incomplete.	All of the chosen measurements can be made and all details about how they are done are provided and clear.

	Scientific Ability	Missing	Inadequate	Needs Improvement	Adequate
D4	**Is able to make a judgment about the results of the experiment**	No discussion is presented about the results of the experiment.	A judgment is made about the results, but it is not reasonable or coherent.	An acceptable judgment is made about the result, but the reasoning is incomplete, OR uncertainties are not taken into account, OR assumptions are not discussed, OR the result is written as a single number.	An acceptable judgment is made about the result, with clear reasoning. The effects of assumptions and experimental uncertainties are considered. The result is written as an interval.
D5	**Is able to evaluate the results by means of an independent method**	No attempt is made to evaluate the consistency of the result using an independent method.	A second independent method is used to evaluate the results. However there is little or no discussion about the differences in the results due to the two methods.	A second independent method is used to evaluate the results. The results of the two methods are compared correctly using experimental uncertainties. But there is little or no discussion of the possible reasons for the differences when the results are different.	A second independent method is used to evaluate the results and the evaluation is correctly done with the experimental uncertainties. The discrepancy between the results of the two methods, and possible reasons are discussed.
D7	**Is able to choose a productive mathematical procedure for solving the experimental problem**	Mathematical procedure is either missing, or the equations written down are irrelevant to the design.	A mathematical procedure is described, but is incorrect or incomplete, due to which the final answer cannot be calculated. Or units are inconsistent.	Correct and complete mathematical procedure is described but an error is made in the calculations. All units are consistent.	Mathematical procedure is fully consistent with the design. All quantities are calculated correctly with proper units. Final answer is meaningful.

	Scientific Ability	Missing	Inadequate	Needs Improvement	Adequate
D8	**Is able to identify the assumptions made in using the mathematical procedure**	No attempt is made to identify any assumptions.	An attempt is made to identify assumptions, but the assumptions are irrelevent or incorrect for the situation.	Relevant assumptions are identified but are not significant for solving the problem.	All relevant assumptions are correctly identified.

Table B.4: Rubric D: Ability to design and conduct an application experiment [7].

	Scientific Ability	Missing	Inadequate	Needs Improvement	Adequate
F1	**Is able to communicate the details of an experimental procedure clearly and completely**	Diagrams are missing and/or experimental procedure is missing or extremely vague.	Diagrams are present but unclear and/or experimental procedure is present but important details are missing. It takes a lot of effort to comprehend.	Diagrams and/or experimental procedure are present and clearly labeled but with minor omissions or vague details. The procedure takes some effort to comprehend.	Diagrams and/or experimental procedure are clear and complete. It takes no effort to comprehend.
F2	**Is able to communicate the point of the experiment clearly and completely**	No discussion of the point of the experiment is present.	The experiment and findings are discussed but vaguely. There is no reflection on the quality and importance of the findings.	The experiment and findings are communicated but the reflection on their importance and quality is not present.	The experiment and findings are discussed clearly. There is deep reflection on the quality and importance of the findings.

Table B.5: Rubric F: Ability to communicate scientific ideas [7].

	Scientific Ability	Missing	Inadequate	Needs Improvement	Adequate
G1	**Is able to identify sources of experimental uncertainty**	No attempt is made to identify experimental uncertainties.	An attempt is made to identify experimental uncertainties, but most are missing, described vaguely, or incorrect.	Most experimental uncertainties are correctly identified. But there is no distinction between random and instrumental uncertainty.	All experimental uncertainties are correctly identified. There is a distinction between instrumental and random uncertainty.
G2	**Is able to evaluate specifically how identified experimental uncertainties affect the data**	No attempt is made to evaluate experimental uncertainties.	An attempt is made to evaluate uncertainties, but most are missing, described vaguely, or incorrect. Or the final result does not take uncertainty into account.	The final result does take the identified uncertainties into account but is not correctly evaluated. Uncertainty propagation is not used or is used incorrectly.	The experimental uncertainty of the final result is correctly evaluated. Uncertainty propagation is used appropriately.
G3	**Is able to describe how to minimize experimental uncertainty and actually do it**	No attempt is made to describe how to minimize experimental uncertainty and no attempt to minimize is present.	A description of how to minimize experimental uncertainty is present, but there is no attempt to actually minimize it.	An attempt is made to minimize the uncertainty in the final result is made but the method is not very effective.	The uncertainty is minimized in an effective way.
G4	**Is able to record and represent data in a meaningful way**	Data are either absent or incomprehensible.	Some important data are absent or incomprehensible. They are not organized in tables or the tables are not labeled properly.	All important data are present, but recorded in a way that requires some effort to comprehend. The tables are labeled but labels are confusing.	All important data are present, organized, and recorded clearly. The tables are labeled and placed in a logical order.

	Scientific Ability	Missing	Inadequate	Needs Improvement	Adequate
G5	**Is able to analyze data appropriately**	No attempt is made to analyze the data.	An attempt is made to analyze the data, but it is either seriously flawed or inappropriate.	The analysis is appropriate but it contains errors or omissions.	The analysis is appropriate, complete, and correct.

Table B.6: Rubric G: Ability to collect and analyze experimental data [7].

APPENDIX C

Lab Report Format

Following the last session of a particular lab, each person will be responsible for turning in a lab report. In a general sense, the labs should demonstrate Rubric Rows F1 and F2 (see Table B.5), in addition to the other rubric rows listed in the lab write-up.

C.1 General

- The report should be typed for ease of reading. Text should be double-spaced, and the page margins (including headers and footers) should be approximately 2.5 cm, for ease of marking by the grader. Each page should be numbered.
- The first page should include the title of the lab; lab section day, time, and number; and the names of the other members of your lab team.
- If the rubric row refers to a particular part of your lab report, clearly label that part of the report with that rubric row. For example, you should label the section where you demonstrate uncertainty propagation with "G2" if that rubric row is being assessed in that lab.

C.2 Organizing the report

If the lab is clearly framed as an observational, testing, or application experiment, you can follow the corresponding rubric for the elements to include in the report (see, respectively, Rubrics B, C, and D in Appendix B).

In general, the report **must** include the following sections:

1. **Introduction.** A written description of what the lab is designed to investigate and a brief summary of the procedure used. This section should be at least a full paragraph long, and not more than 3 double-space pages.

   You don't need to include too much detail here, but it should be a complete and concise description of the purpose and general method used in the lab. Imagine a classmate who hasn't seen the lab writeup asked you, "what is this lab about? What do you do?" You should be able to hand them your introduction, and they'd be able to understand the purpose and general structure of the lab. But you need not mention every step and calculation here.

2. **Analysis and discussion.** For most labs that have more than one part, this should be broken up into parts and labeled in order. This section must include all of the following, in the same order in which these elements appear in the lab instructions.

- Any data that you've collected: tables, figures, measured values, sketches. Whenever possible, include an estimate of the uncertainty of measured values.
- Any calculations that you perform using your data, and the final results of your calculation. Note that you must show your work in order to demonstrate to the grader that you have actually done it. Even if you're just plugging numbers into an equation, you should write down the equation and all the values that go into it. This includes calculating uncertainty and propagation of uncertainty.
- If you are using software to perform a calculation, you should explicitly record what you've done. For example, "Using Excel we fit a straight line to the velocity vs. time graph. The resulting equation is $v = (0.92\,\mathrm{m/s^2})t + 0.2\,\mathrm{m/s}$.
- Answers to any questions that appear in the lab handout.

3. **Conclusion.** This can be very short, and will generally only require one or two paragraphs. In your conclusion, you should summarize the point of the lab and what you learned, both in the frame of a scientist conducting the experiment ("What did the experiment tell us about the world?") and in the frame of a student ("What skills or mindsets did I learn?").

C.3 Graphs, Tables, and Figures

Any graph, table, or figure (a figure is any graphic, for example a sketch) should include a caption describing what it is about and what features are important, or any helpful orientation to it. The reader should be able to understand the basics of what a graph, table, or figure is saying and why it is important without referring to the text. For more examples, see any such element in this lab manual.

Each of these elements has some particular conventions.

Tables

A table is a way to represent tabular data in a quantitative, precise form. Each column in the table should have a heading that describes the quantity name and the unit abbreviation in parentheses. For example, if you are reporting distance in parsecs, then the column heading should be something like "distance (pc)". This way, when reporting the distance itself in the column, you do not need to list the unit with every number.

Graphs

A graph is a visual way of representing data. It is helpful for communicating a visual summary of the data and any patterns that are found.

The following are necessary elements of a graph of two-dimensional data (for example, distance vs. time, or current vs. voltage) presented in a scatter plot.

- **Proper axes.** The conventional way of reading a graph is to see how the variable on the vertical axis changes when the variable on the horizontal axis changes. If there are independent and dependent variables, then the independent variable should be along the horizontal axis.
- **Axis labels.** The axes should each be labeled with the quantity name and the unit abbreviation in parentheses. For example, if you are plotting distance in parsecs, then the axis label should be something like "distance (pc)".
- **Uncertainty bars.** If any quantities have an uncertainty, then these should be represented with so-called "error bars", along both axes if present. If the uncertainties are smaller than the symbol used for the data points, then this should be explained in the caption.

Bibliography

[1] E. Etkina, G. Planinsic, and A. Van Heuvelen, *College physics: explore and apply*, 2nd (Pearson, New York, 2014), 981 pp.

[2] E. Etkina, “Millikan award lecture: students of physics—listeners, observers, or collaborative participants in physics scientific practices?”, American Journal of Physics **83**, 669 (2015).

[3] D. An, J. A. Johnson, J. L. Clem, B. Yanny, C. M. Rockosi, H. L. Morrison, P. Harding, J. E. Gunn, C. Allende Prieto, T. C. Beers, K. M. Cudworth, I. I. Ivans, Ž. Ivezić, Y. S. Lee, R. H. Lupton, D. Bizyaev, H. Brewington, E. Malanushenko, V. Malanushenko, D. Oravetz, K. Pan, A. Simmons, S. Snedden, S. Watters, and D. G. York, “Galactic Globular and Open Clusters in the Sloan Digital Sky Survey. I. Crowded-Field Photometry and Cluster Fiducial Sequences in ugriz”, The Astrophysical Journal Supplement **179**, 326 (2008).

[4] C. L. Slesnick, L. A. Hillenbrand, and P. Massey, “The Star Formation History and Mass Function of the Double Cluster h and χ Persei”, The Astrophysical Journal **576**, 880 (2002).

[5] P. R. Durrell and W. E. Harris, “A color-magnitude study of the globular cluster M15”, Astronomical Journal **105**, 1420 (1993).

[6] T. Currie, J. Hernandez, J. Irwin, S. J. Kenyon, S. Tokarz, Z. Balog, A. Bragg, P. Berlind, and M. Calkins, “The Stellar Population of h and χ Persei: Cluster Properties, Membership, and the Intrinsic Colors and Temperatures of Stars”, The Astrophysical Journal Supplement **186**, 191 (2010).

[7] E. Etkina, A. Van Heuvelen, S. White-Brahmia, D. T. Brookes, M. Gentile, S. Murthy, D. Rosengrant, and A. Warren, “Scientific abilities and their assessment”, Physical Review Special Topics - Physics Education Research **2** (2006) `10.1103/PhysRevSTPER.2.020103`.