Laboratory Manual

ASTR 24100 Physics of Stars

The University of Chicago

Winter 2023

Labs

LAB 1

Inventing Color

Everything glows (gives off electromagnetic radiation) when it has a temperature — particles are wiggling around randomly (faster if it's hotter) and giving off energy as they wiggle. This **thermal radiation**, also called blackbody radiation, is the same for any object at the same temperature. This means we can take something's temperature by looking at the spectrum of light it gives off. This is great for learning about something's temperature at a distance, like stars.

Incandescent lightbulbs are so warm that they glow in the visible spectrum (like stars). In this lab, you'll investigate the radiation that is given off by a lightbulb at various temperatures, then use filters to mimic the situation astronomers are in when they observe astronomical objects with different color filters. You'll invent a metric to numerically state the temperature of the lightbulb, even without knowing the actual temperature. Finally, you will make a color image by combining colors from different wavelength ranges! This is the same method as is used to make beautiful space photos that we see from NASA and other academic places.

Team roles

1. **Decide on roles** for each group member.

The available roles are:

- 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

These roles can rotate each lab, and you will report at the end of the lab report on how it went for each role. Some members will be holding more than one role. For example, you could have the skeptic double with another role. Consider taking on a role you are less comfortable with, to gain experience and more comfort in that role.

Additionally, if you are finding the lab roles more restrictive than helpful, you can decide to co-hold some or all roles, or think of them more like functions that every team needs to carry out, and then reflect on how the team executed each function.

1.1 Lightbulbs

Light can be made of many different wavelengths at the same time. It combines to form a color that we perceive. To see what colors make up light, we can split them up with a triangular prism, or with a *diffraction grating.*

2. Use the diffraction grating to view the lightbulb while the lightbulb is at full voltage (120 V). Hold up the grating in front of your eye, with the text on the frame upright. Start by looking at the lightbulb through it, then turn your feet to the left or right about 30 degrees, letting your whole body-arm-grating system rotate with your feet. You should see a rainbow. This is all the colors that make up the light coming from the lightbulb, split into different wavelengths.

Orientation to the digital spectrometer

Warning! Fragile Equipment! If the fiber optic cable is bent into a circle of less than 9 cm (6 inch) diameter, then the fiber inside may break.

Also, the blue end cap should be replaced on the end of the fiber optic cable when you are done using it, to protect from dust and debris entering.

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:

- **Background subtraction.** When you are observing the spectrum of something, there may be stray light entering that is not coming from the thing you are studying. To remove this *background* from the plot, select the gray lightbulb icon in the toolbar. This records the current plot as the background. To display the plot while subtracting the background, select the icon with the minus-lightbulb. To go back to viewing the full spectrum including the background, select the blue S icon.
- **Oversaturation**. If, when you zoom out all the way, the plot includes a flat line near the top of the plot, this means that the pixels of the image sensor are recording their maximum value, and they cannot tell you the actual intensity. Reduce the intensity by either reducing the integration time (upper-left corner) or moving the fiber optic cable off-center, so that it receives less light. Note that if you change either of these, then the background frame is no longer correct and must be remeasured.
- **Saving data.**
  - 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
- How does the shape change when the brightness increases? **Record your answer.** 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.

Observing the lightbulb - see the rainbow!

3. Using the spectrometer, observe the spectrum created by a lightbulb at various brightnesses / voltages. What's the overall shape? **Record your answer.**

4. How does the shape change when the brightness increases? How about the total radiated power (area under the curve?) **Record your answer.**

5. How does the peak frequency change? **Record your answer.**

6. How does the visual color of the bulb change as it gets brighter? **Record your answer.**

7. Load the interactive thermal radiation simulation at `https://phet.colorado.edu/sims/html/blackbody-spectrum/latest/blackbody-spectrum_en.html`

8. Play with the controls and see what happens. Discuss among your team.

9. Based on your observations of the lightbulb spectrum and of the sim, report the pattern you see: what happens when the temperature increases? **Record your answer.** You will test the consistency of this pattern later in the lab.

10. At what peak wavelength do you radiate? Use the sim to determine this and estimate your uncertainty. **Record your findings.**

11. Humans can see in the range of 380 to 700 nanometers (aka 10^{-9} m). Does your answer for the peak wavelength from the previous step make sense? For example, if you are in a dark room, would you be able to spot the human from their glow? **Record your answer.**

1.2 Make the rainbow! (But please don't taste the rainbow!)

Cameras have come a long way since the days of developing film, but sensors are not as smart you might think. They register light, but they can't usually tell the color (i.e. wavelength) of the incoming photons. So then how do you get a color image? In astronomy (and in your cell phone!) color images are generated by measuring the amount of light at specific colors and then combining these measurements to create a colorful image. A filter is used to select bands of color to allow through. In consumer cameras and phone cameras, these filters are permanently attached to the front of individual pixels. In astronomical imaging, there is no permanent filter, and different filters are moved into place.

12. View the lightbulb's spectrum with the diffraction grating again, this time alternately holding the red and green filters between the grating and the bulb. Observe and **record** the effect of the filter on the spectrum.

13. Use the red and green filters in front of the fiber optic input to the spectrometer to see how they affect the spectrum that is received. **Save a graph of the spectrum with each filter and include in your report.**

In a regular astronomical image, each pixel gives just one value — the number of counts detected in that pixel, regardless of the wavelength of the photon detected. We can treat the fiber optic as a single-pixel camera if we count up the total number of counts detected. To find that total number, you can find the area under the curve in the plot.

14. With no filter, add up the total number of counts detected by calculating the area under the curve. To do this in an approximate way, count the number of boxes underneath the curve, then multiply this by the height of one box (in counts per nanometer) and by the width of one box (in nanometers). **Record this value.** (to do this more precisely, you can press the copy icon to paste the data into a spreadsheet)

15. Without moving the fiber optic or lightbulb, do the same for the spectrum using the red and green filters separately. Note that the values are different for different filters. This difference (for example, the green value divided by the red value) can tell us a quantitative number for what color this object is. **Record the red, green, and g/r values.**

Now you have the value of our single-pixel camera for the case of clear (no filter), red, and green filters. Time to revisit the pattern found above in Step 9.

16. If that pattern from Step 9 is true, what should happen to the relative values of red and green as the voltage is increased? Should one increase more than the other? What should happen to the quantitative color g/r? **Record your answers.**

17. Perform an experiment to test whether this prediction is supported. **Record your procedure, analysis, and results.**

    Hints:

    a) Choose 5 or so different voltages you'd like to use for the adjustable lamp. Set your lamp to the *highest* of these 5 voltages. Move the cable as close to the lightbulb as possible *without* saturating the spectrometer, i.e. without the spectrum "leveling out" in the spectrometer program. Mark the position of the clamp and **do not move** the cable from now on.

    b) For each voltage, measure the total counts for the red and green filters, then divide them to get your g/r value for each voltage.

    c) Plot these and judge whether your prediction above was suppported.

In next week's lab, you will use this quantitative color index to determine the age of a star cluster.

1.3 Creating a color image

To create the beautiful color astronomy images we like to see, one must manually combine images taken with different filters. There are always choices to be made that will change how the combined image looks.

18. Using the directions below, create a false color image of either the Orion nebula (M42), a stellar nursery, or the Crab nebula (M1), the remnant of a supernova. You can find the relevant images on Canvas in the Lab module.

Now you'll create a color image from three separate images of the same target with r (red), g (green), and i (infrared) filters. Since one of the filters is infrared, and we only have red, green, and blue colors available in DS9, then you will assign the image taken in the infrared to the color blue. This makes this image a *false color image*, since the blue we will see in it does not correspond to the actual wavelength of the light captured.

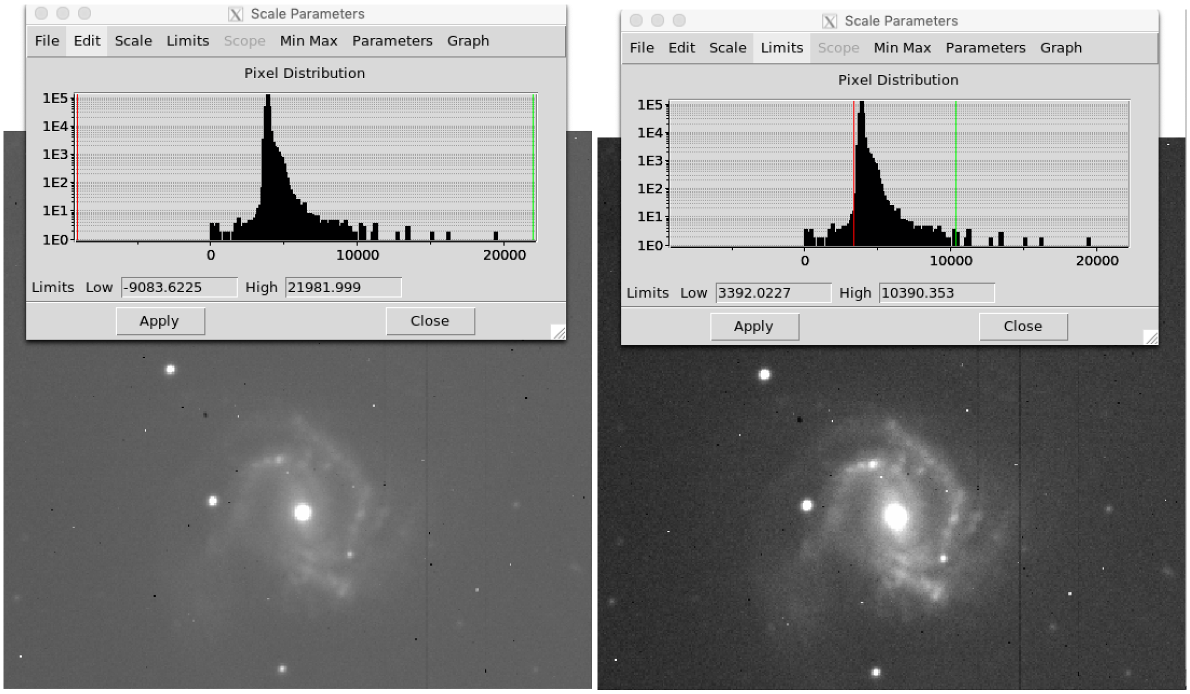

Figure 1.1: Proper choice of data ranges is important. The default for ds9 is often the min/max values in the image, which can be a poor choice if there are outlier pixels, as shown here on the left. The red line shows the lower limit z1, which is mapped to no color (black here), and the green line is the upper limit z2, mapped to full color (white here). Pixel values between these are shown in various brightnesses of the color. On the right, z1 and z2 are more tuned to the distribution of pixel values, which more effectively uses the dynamic range of the display for pixel values where there are significant amounts of data.

Fun fact: This is actually how photos from telescopes like Hubble are taken! Astronomers take photos of celestial bodies in multiple filter ranges, than artificially color them to make beautiful space images!

Loading and manipulating images in ds9 consists of:

- loading an image (file > open)
- setting lower, upper limits (z1,z2) on an image (scale > various algorithms; use scale > scale parameters for full control). See Figures 1.1–1.2 for examples.
- controlling the intensity mapping within those bounds (mouse right click-and-hold and drag)

You can change the zoom and center location in an image by

- moving around in image (mouse middle click if edit>point is set[the default], or edit>pan and mouse left click)
- zooming in and out (mouse wheel, zoom> +,- etc.)

To build a color image

- Identify and download from Canvas your three different filter image FITS files.

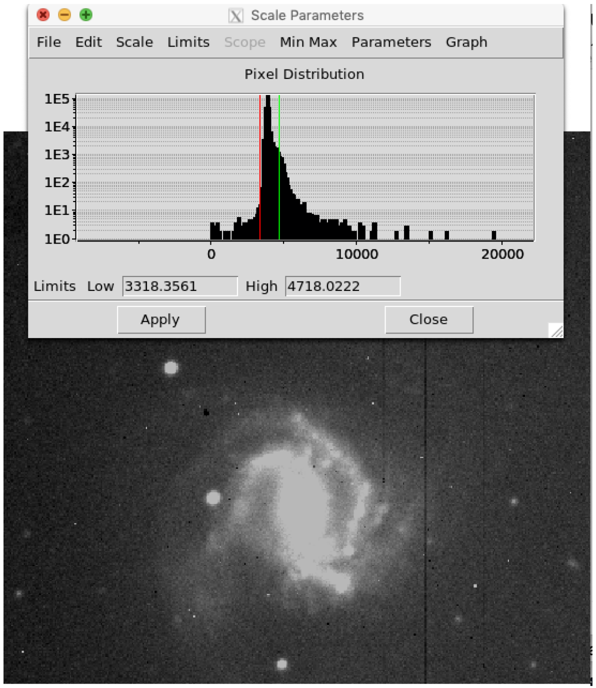

Figure 1.2: Smaller values of z2 will emphasize fainter values in the target. Compare the image to the left to the right-hand image above.

- Open a color (rather than monochrome) frame: Frame > new rgb
- Open the red, green, infrared files using the rgb subwindow to select which channel you are working in, and then scale and control intensities on each one.
- There are many possible ways to scale the images. Some testing suggests that choosing Scale > ASINH (or Linear or Square Root as other choices) and Scale > 99.5% (or maybe 99% or 98%) produces reasonable results. Experiment!
- One thing to note: the rgb subwindow allows you to control how the images are aligned spatially via the "align" menu at the top. There are three relevant choices: "WCS", "Image" or "Physical". The latter two should give the same result in this instance. "WCS" alignment uses information in the image header that has been added by the processing pipeline, that establishes a World Coordinate System (this tells ds9 and other programs how pixel x,y values are mapped into the sky coordinates - typically Right Ascension [east/west] and Declination [north/south]). The default is WCS and should work fine, if the images processed correctly. If that doesn't look good, you could try the others. If that still doesn't look good, note that you tried your best, and give an example of how it didn't work will in either mode. Examples of good and bad image alignment are shown in Figure 1.3.

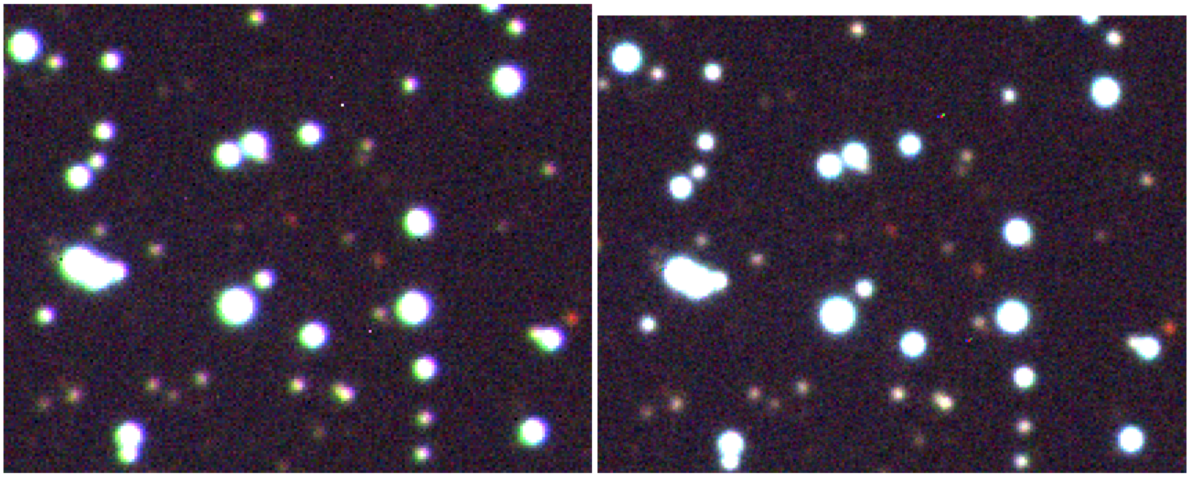

Figure 1.3: Zoom-in on a color image, showing poor (left) and good (right) image alignment across filters. Note how objects are shifted between different color channels in the poorly aligned image.

1.4 Report checklist and grading

Each item below is worth 10 points. See Appendix B for guidance on writing the report and formatting tables and graphs.

1. Qualitative observations with the digital spectrometer (Steps 3–6).
2. The pattern / relationship between temperature and spectrum (Step 9).
3. Your own wavelength and reasoning (Steps 10–11).
4. Effect of filters on spectrum (Steps 12–13).
5. Total intensity calculations and plots of spectra with clear, red, and green filters. (Steps 14–15).
6. Prediction of what should happen to g/r with temperature increase, and procedure, analysis, results of testing that prediction (Steps 16–17).
7. Your beautiful color image (Section 1.3).
8. Discuss the findings and reflect deeply on the quality and importance of the findings. This can be 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?").
9. Write a 100–200 word paragraph reporting back from each of the four roles: facilitator, scribe, technician, skeptic. Where did you see each function happening during this lab, and where did you see gaps? What successes and challenges in group functioning did you have? What do you want to do differently next time?

LAB 2

Characterizing stars with H-R diagrams

2.1 Introduction

In this lab you will use a Hertzsprung-Russell (H-R) Diagram to learn about a star cluster. 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.

2.2 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
- Retrieve data from astronomical databases.
- Learn where different stellar populations lie on the HR diagram, and understand the physical reasons behind these localizations

2.3 Scientific background

For the basics of H-R diagrams, you can also read this textbook chapter: https://openstax.org/books/astronomy/pages/18-4-the-h-r-diagram

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 (H-R) diagram. We will make this diagram for a star cluster.

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 filter is characterized by its **transmission function**: a function that characterizes the amount of light that is transmitted by the filter at each wavelength. Figure 2.3 shows the transmission functions for some standard astronomical filters (similar to the one's you'll be using in this class).

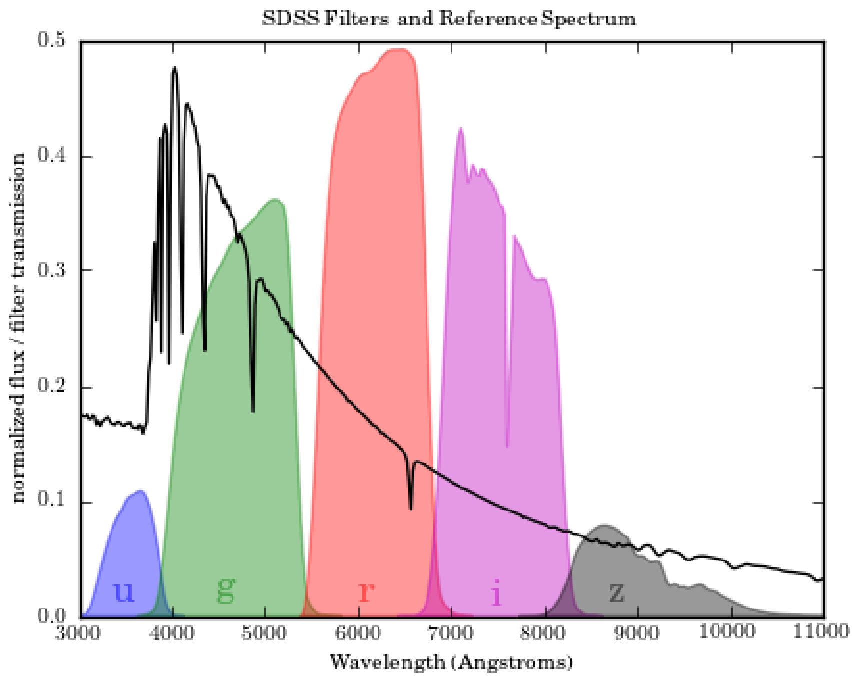

Figure 2.1: Filter Transmission Functions for the Sloan Digetal Sky Survey, overlaid on a stellar spectrum. The magnitude observed by each filter will be proportional to the integrated spectrum multiplied by the filter transmission. It's clear in this image that the underlying spectrum of the star will cause the different filters to have different magnitudes. Image source: `http://www.astroml.org/_images/fig_sdss_filters_1.png`

2.4 Defining color

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:

$$m_A - m_B = -2.5 \log \left(\frac{F_A}{F_B} \right). \tag{2.1}$$

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 will have data in two wavelength bands, so we can subtract those magnitudes to get a color index. With the software or coding language of your choice, you will plot g on the vertical axis and $g - r$ on the horizontal axis.

2.5 Team roles

Decide on roles for each group member. The available roles are:

- 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

These roles can rotate each lab, and you will report at the end of the lab report on how it went for each role. If you have fewer than 4 people in your group, then some members will be holding more than one role. For example, you could have the skeptic double with another role. Consider taking on a role you are less comfortable with, to gain experience and more comfort in that role.

Additionally, if you are finding the lab roles more restrictive than helpful, you can decide to co-hold some or all roles, or think of them more like functions that every team needs to carry out, and then reflecting on how the team executed each function.

2.6 Making an HR Diagram

To learn about a star cluster, you'll make a color-magnitude diagram of the stars in that cluster. You'll be analyzing M15, a globular star cluster in the Pegasus constellation. To make the diagram, you need magnitudes in at least two different filters for many stars in the cluster.

You will first construct a rudimentary H-R diagram by analyzing images taken with our robotic Stone Edge Observatory (the files are in the Modules section on Canvas), then use catalog data to create a research-grade diagram to analyze later.

2.7 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? Also record the "Center" coordinates and radius of the region. Do this in both filters, for each star that you measure.

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 brightnesses. 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.

2.8 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

$$m_X = -2.5 \log_{10} \left(\frac{F_X}{F_{X,\mathrm{ref}}} \right) \tag{2.2}$$

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.*

2.9 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:

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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.

2.10 Making a diagram from catalog data

1. Open the SkyServer Search Form in a browser: http://cas.sdss.org/dr7/en/tools/search/form/Default.aspx.

2. Select ”Show me [stars] in the region [around:]”. Note that you will need to know the celestial coordinates of the part of the sky that you want retrieve data about, as well as the radius of a circle that captures all the objects you want.
3. Find the J2000 equatorial coordinates (RA and Dec) of M15. You can do this by looking up M15 in the software or browser-based virtual planetarium “Stellarium” or another reference and record its RA and Dec. Note that ”J2000” means the coordinates it had at 12:00 TT (terrestrial time, very close to UTC) January 1, 2000, so you will need to set the date accordingly. It may be helpful to turn off the ground and atmosphere to get a better view. Then, determine a radius in arcminutes that includes all of the cluster. You can either use the Field Of View (FOV) listed on the screen, or you can turn on the Equatorial Grid by selecting that option in the bottom toolbar or pressing ’e’ and use the contour lines.
4. The Search Form wants the RA and Dec in decimal degrees. So convert the RA and Dec that you recorded to decimal degrees and enter this (for example, an RA of 15h30m20s converts to 232.5833 degrees). You can use this website to assist: `https://www.swift.psu.edu/secure/toop/convert.htm`.
5. In the Form, tell it to output 1000 objects, and the magnitudes of the objects.
6. Select “Generate” or “Update Query” and it will convert all the options into a database query that you should then “Submit”. This opens a new tab with the output from the query.
7. If the outcome from the query has much fewer than 1000 objects, then increase the radius (and/or check to ensure you have the correct RA and Dec entered).
8. Once you have lots of objects, change the form to output a CSV file.
9. Plot the data from the CSV file using your favorite spreadsheet or programming environment. Specifically plot ’g’ vs. ’g-r’, with ’g’ on the vertical axis, as a scatter plot.
10. Label the different stages of stellar evolution on your plot.

2.11 Report checklist and grading

Each item below is worth 10 points, and there is an additional 10 points for attendance and participation.

1. Description of your procedure to analyze the images. You can reference the lab manual, and include any changes you made to that procedure. Include screenshots of your work.
2. The H-R diagram created from your data, with any features marked that you can identify (e.g. main sequence, turn-off, red giants, white dwarfs).
3. From the catalog data, your plot of g vs. $g - r$ with labels of different stages of stellar evolution.
4. Discuss the findings and reflect deeply on the quality and importance of the findings. This can be 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?”).
5. Write a paragraph (100–200 words) reporting back from each of the four roles: facilitator, scribe, technician, skeptic. Where did you see each function happening during this lab, and where did you see gaps? Which did you do, and how did that go? what successes and challenges in group functioning did you have, and what would you do differently?

LAB 3

Radioactive Half-Life

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 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.)

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.

3.1 The irradiation process

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

$$^{107}\mathrm{Ag} + \mathrm{n} \rightarrow {}^{108}\mathrm{Ag} + \gamma\,, \tag{3.1}$$

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

$$^{108}\mathrm{Ag} \rightarrow {}^{108}\mathrm{Cd} + \mathrm{e}^- + \gamma\,, \tag{3.2}$$

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.

3.2 The neutron source

The source is a mixture of plutonium and beryllium. The plutonium decays via alpha emission and the beryllium absorbs the alpha to become carbon + a free neutron. The neutron has an energy given by a very complicated distribution, but the energy distribution goes up to $\sim 11\,\mathrm{MeV}$. The paraffin shielding (and the lucite in the plug) slows down neutrons, so that anything which escapes is thermalized such that $E \sim kT \sim 1/40\,\mathrm{eV}$. At the point where the foils are placed, the neutrons have been slowed some, but not completely... if they are a full 11 MeV still, they are too energetic to bind with the silver, so the foils are absorbing from the lower end of the spectrum or from neutrons that have scattered enough material to have less energy than they started with.

The activity of the Pu-Be core is an astounding 5 Ci (!!), but that's the alpha flux which doesn't penetrate out of the core. The neutron flux is considerably less. There is about 80 g of plutonium mixed with 41 g of beryllium and a listed, unshielded emission rate of 9×10^6 n/sec.

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 dose of ionizing radiation that is much less than what you receive every day normally. You can compare this to the example doses in Fig. 3.1. 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.**
- **Decrease time with and increase distance from sources.** Handle the silver foils only when you need to be for the lab.

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

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

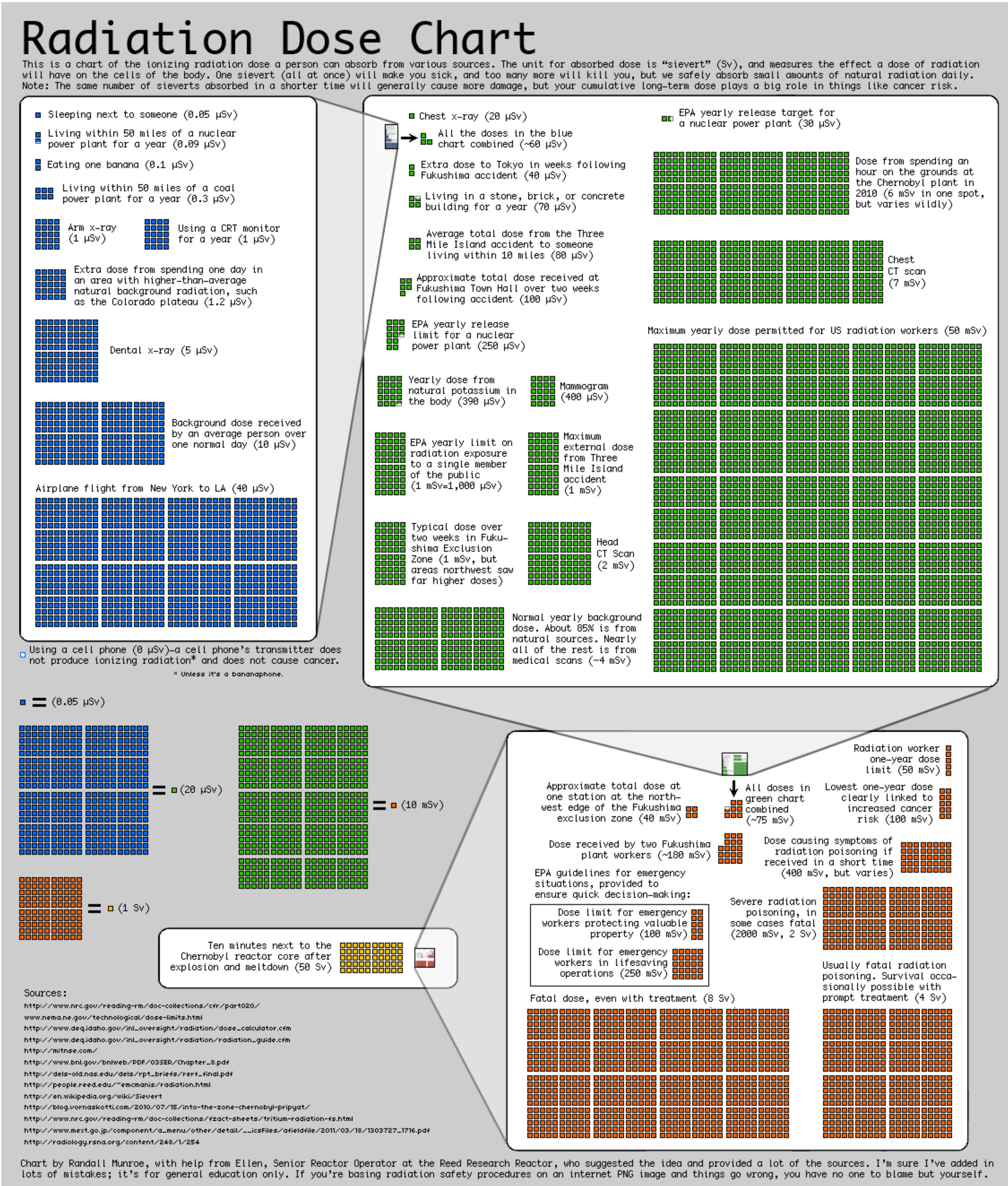

Figure 3.1: A chart of ionizing radiation dose from various sources. Source: https://xkcd.com/radiation/

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).

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 $\sqrt{N}$.

The Apparatus.

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.**

3.3 Procedure

Your task is to measure the half-life of ^{108}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.

1. 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.

2. 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.

3. 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
$$R_{\text{bkg}} = N_{\text{bkg}}/t \tag{3.3}$$
with an uncertainty given by Poisson statistics. **Report both the background rate and uncertainty in your lab report.**

4. While the samples are being irradiated, set up your measurement apparatus.

5. 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.You will need to use the watch to record times rather than timer built into the Geiger counter. **Record your data.** *You may want to take a video of the stopwatch and counter to get more precise readings of the 30-second intervals.*

3.4 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

$$R = \lambda N \,, \tag{3.4}$$

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

$$\frac{N}{N_0} = e^{-\lambda t} \,, \tag{3.5}$$

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

$$R = \lambda N_0 e^{-t \ln(2)/T_{1/2}} \,. \tag{3.6}$$

Taking the logarithm of both sides and substituting for N gives

$$\ln(R) = -\left(\frac{\ln(2)}{T_{1/2}}\right) t + \text{const} \,. \tag{3.7}$$

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

6. 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.

7. 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.**

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

8. 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.

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

10. 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?

11. 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.

12. 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.

3.6 Report checklist and grading

Each item below is worth 10 points, and there is an additional 10 points for attendance and participation.

1. Background rate and uncertainty (Step 3)
2. Plot of $\ln(R)$ vs. t with the trendline and equation listed. (Step 6)
3. Calculation of slope of above plot and work of solving for the half-life, with the final half-life determination. (Step 7)
4. Answers to questions in Steps 8–9.
5. Answers to questions in Steps 10–12.

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 (like Microsoft Excel, LibreOffice Calc, or Google Sheets), 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 ± 3 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

Lab Report Format

B.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 members of your lab team.

B.2 Organizing the report

The report should follow the sequence of the report checklist. Answers to questions and inclusion of tables and figures should appear in the order they are referenced in the manual. In general, include the following:

- For any calculations that you perform using your data, and the final results of your calculation, 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. Each answer requires providing justification for your answer.

B.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.