PHYS 391 – Lab 3: Astronomical Image Data: Measuring the Distance and Age of a Stellar Cluster

Goals

This lab is designed to demonstrate basic astronomy data analysis of extracting stellar population information from images. With image analysis, we measure flux and determine the strength of signal through a concept called signal to noise (SNR). Using SNR we can distinguish between random noise and a faint star.

After preliminary tasks that acquaint you with pyRAF software, you will calculate the distance and age of an open cluster of stars using image data from Pine Mountain Observatory. If you are new to programming, there are some basic python scripts provided for you to hack. If you are more adept at another programming language – you may use it. If you are not sure of your programming skills you may use excel, however I encourage you to try python and check your results against excel. Python is widely used for many applications in science and business because of its versatility and ability to incorporate linux commands and other software. You will need to use PyRAF to take data.

Instead of a formal write up, you will use a template form included at the end of this lab to present your results. Email or hand it in to me.

I. Getting Familiar with terminal, data and software environments. Part I is an introduction to the software and data formats. There isn't any work to report for part I, but I suggest making notes where necessary for your own benefit.

Everything in ***bold italics*** is something you type at the prompt and underlined words following a command is something you put in based on your filenames, directory name, etc. ...

Setup and startup

Click on the virtual machine (VM) icon; click start. After the VM loads, type the following commands in the open terminal window (or any other terminal window in the VM):

- In the lab391 directory (you start in this directory), make your own directory using your email name or whatever as long as it's not confused for someone else. Use the command 'mkdir'

  e.g. ***mkdir*** elsa
- Copy the files from the directory labfiles/ to your directory using command 'cp' using the exact syntax except using your directory name:

  e.g. ***cp labfiles/**** elsa/
- Type:

  ds9 &

  at the prompt. This will bring up a window where you will view the astronomical images.

- In the main directory, (not your directory) type :

  pyraf

  PyRAF is essentially a python environment that contains an astronomical software package called IRAF (Image Reduction and Analysis Facility). For astronomers, this is very convenient because python can now call IRAF tasks which means you can load images, measure, analyze and plot data all in one handy python script.

- Once you are in the **pyraf** environment, change to your directory by using command 'cd'

e.g. ***cd*** elsa/

At this point you should have at least the ds9 window and a terminal running pyRAF

Gedit

Before we go any further, bring up another terminal window by clicking on the terminal icon. Change to your newly made directory and type:

ls

These are all the files you will need for the lab. To view and edit myscript.py, type at the prompt:

gedit myscript.py

This should bring up a text editor window with the file myscript.py. If you want to create a new file, just type gedit at the prompt.

Okay now go back to your pyRAF window…

Saving work

The virtual box has a linked folder that connects it to the rest of the computer called **pyraf_share.** If you wish to save your work you can copy your files to this folder and retrieve them outside the virtual box. You can also sftp your files to your duck account too.

PyRAF is potentially buggy. Write down measurements or save files/scripts in case you have to restart pyRAF.

DS9

FITS files are binary image files and thus can't be viewed with a text editor like Gedit or Word. All astronomical images and spectra are stored in this format. To view an image, go to the terminal running pyraf and type:

display m101_10.fits

After you press return, press return again (you can display up to 16 images at once in 'frames' on ds9 by typing in a frame number from 1-16). Bring up another image (select any fits file from your directory) and try different ways of displaying the frames. Click on an image, you should get a little green circle appearing on the image. Do the following to get familiar with the functionality of ds9. All of this is done through the ds9 window (no typing needed):

- Change the brightness and contrast (hint: try holding the mouse button down and dragging the cursor)
- change the scale (linear, log etc)
- zoom in and out
- click on a circle and change the radius, color, shape
- change the color of the image - for my own research, I find the rainbow color map most effective or inverted grayscale
- display both frames at once, blink them etc..

Note: to stop generating circles go under edit menu and select 'none', otherwise leave on 'pointer'.

As you move the cursor over the image you see numbers changing for 'X', 'Y' and 'Value'. X and Y - are simply pixel coordinates and 'Value' corresponds to the flux of photons in each pixel. Scroll over to an empty patch of sky - notice it isn't zero. The sky has photons and this must be subtracted from the starlight when we measure the flux of stars.

pyRAF Math

The pyRAF environment is like other scripting languages (e.g. R, Matlab) such that mathematical expressions are calculated right on the command line. To do math calculations in pyRAF type:

import math

Now try these calculations by typing in the following:

x=100
sqrt(x)
log10(x)
x**2

If you wish to use pi (fyi you will), you need to use math.pi
e.g.

r = 4.5
2*r*math.pi

(Ans: 28.274333882308138)

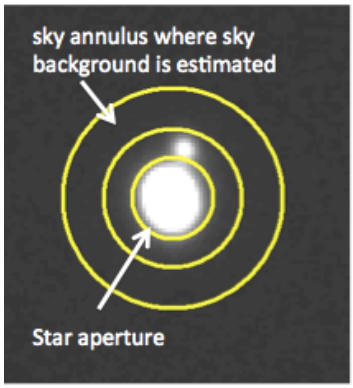
Turning off Virtual Box etc:

When you are ready to turn off the VM, exit out of ds9 and pyRAF. Close any gedit windows too. Shut off the VM by going under the VM menu item 'system' and select Shut Down... **Don't just click to close the window;** that may screw up the VM and any work you have contained in it. And it will also render the VM useless until we can fix it.

II. Photometry and Signal to Noise

Background:

Photometry is the term for measuring flux from any astrophysical object. The algorithm for stellar photometry goes as follows: An 'aperture' of a determined radius (or any shape for non spherically symmetric objects like galaxies) is centered about a star and all of the photons including the sky background and other sources of noise are summed up in this aperture. The sky background level is modeled and averaged based on a small piece of sky near the star (usually an annulus of about 3-10 pixels in width centered around the star and outside the aperture. The background is then subtracted leaving the flux. Below is a picture of this process.



In the image above, we have no doubt that there is a star in the middle of the aperture. But in the case of faint stars or galaxies it's much harder to distinguish between detector or sky noise and a distant signal. In order to quantify the strength of a faint astrophysical object Astronomers calculate signal to noise ratio (SNR), which is essentially the number of times the star (or galaxy) signal is greater than the noise.
SNR comes from counting statistics - standard deviation or noise goes as the square root of the counts. SNR is the signal count divided by the standard deviation:

$$N = Number\ of\ counts$$
$$\sqrt{N} = Standard\ Deviation$$
$$SNR \sim \frac{N}{\sqrt{N}} \sim \sqrt{N}$$

In photometry, SNR is the number of photons from the signal alone (i.e. star) divided by the standard deviation of the photons from the signal plus the background noise. For instance if you collect 10,000 photons in an aperture where 100 are from the star and 9900 are from noise, the SNR is:

$$SNR = \frac{100}{\sqrt{100 + 9900}}$$

$$SNR = 1$$

Conceptually, this means that the amplitude of your signal is as big as a random fluctuation of noise – the signal is indistinguishable from the noise. An SNR ~ 3 is the bare minimum for detecting object. A bright star will have an SNR of at least 1000 or have a signal that is 1000 times greater than a random fluctuation of noise. A large SNR means a small measured error for flux.
Note that noise takes many forms (light pollution, sky background, detector electronics, cosmic rays, bad pixels, etc.). We will be mainly concerned with sky background noise for this lab.

Astronomy Terminology and Equations:

- Flux (**F**) is the amount of energy/sec/area from a star. More specifically, it is the number of photons from a star or galaxy that intersects a detector in an interval of time.
- Background (**S**) refers to the sky photons contaminating the star signal, contained within the aperture. It has the same units as flux.
- Apparent brightness is also flux, but measured in a $\log_{10}$ scale based on how our eyes perceive different levels of brightness. It is denoted by **m** and measured in magnitudes.
- Absolute brightness is similar to apparent brightness, but it's the brightness measure of any object at a distance of 10 parsecs (32.6 ly or $3x10^{19}$ cm) away. It is denoted by **M** and measured in magnitudes.
- Gain is a scale factor that compares the counts registered on the CCD to actual photoelectrons. It is always a value greater than or equal to 1. For instance, if it takes 10 photoelectrons to register 1 count on a CCD, that CCD has a gain of 10. We measure flux in units of counts/sec, however we have to use photo-electrons for calculating SNR.
- Zero point (**zp**) refers to a magnitude calibration that is specific to the observing conditions, filters and telescope. Strictly speaking, it represents the magnitude of an object with a flux of one count per second, but it also serves as a term that encompasses all calibrations (e.g. gain, filter system) and wraps them up into one neat term. It is estimated by comparing measured magnitudes to catalogued values of known stars. You will derive it for your data set when you analyze M39.

These quantities are related:

i. $m = -2.5 \log_{10}(F) + zp$

ii. $SNR = Ft\sqrt{\frac{Gain}{(F+S)t}}$

iii. $m_{error} = 1.0875/SNR$

iv. $F = L/d^2$

v. $m - M = 5log_{10}(d) - 5$

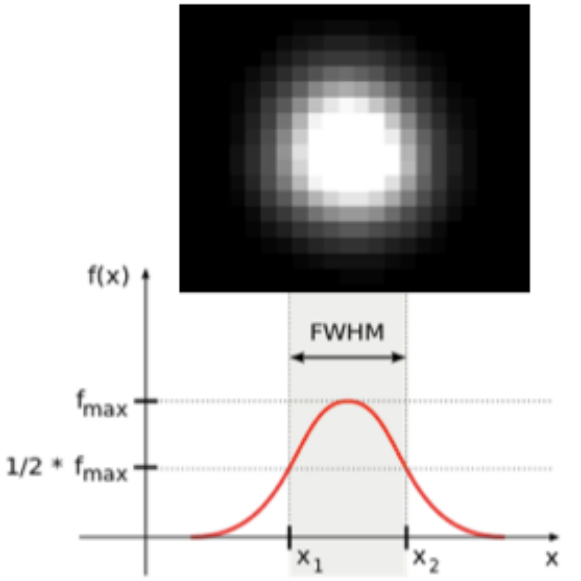
vi. $m_1 - m_2 = -2.5log_{10}(F_1/F_2)$

where d is the distance to the star, t is exposure time and m_{error} is the error associated with the star magnitude.

Imexamine

The main software task that you will use in this lab is called imexamine.
Imexamine does all of the basic photometry tasks automatically including:

- Finding center of the star based on the stellar profile
- Deriving an aperture radius based on the full width half maximum (FWHM) of the stellar profile (radius = 3xFWHM, see figure below)
- Calculates and subtracts the sky background.



Light from a star is fit to a Gaussian profile and FWHM is estimated. f is photon counts, the x axis a spatial dimension

<u>General Instructions:</u> Keep text files of output, your math and plotting scripts, calculation output. You will need to cut and paste these scripts and data into your lab where prompted. For your convenience, I've denoted any instructions that use calculations with a symbol ★.

A. Measure SNR of Faint and Bright Stars in single and combined images of different exposure times.

The goal of every astronomer is increasing the SNR of an object. There are two ways of doing this: take longer exposures or take several images with short exposure times and combine them. This exercise will demonstrate the connection between SNR and exposure time and the effectiveness of combining images.

Display these three UV images in 3 different frames and adjust the brightness/scale/contrast as needed.

- m101_10.fits (1-10 minute exposure)
- m101_15.fits (1-15 minute exposure)
- m101_4x15.fits (4 – 15 minute exposures added together – 60 total minutes)

**Note that each image pixel value has been divided by it's exposure time so that the units are counts/sec/pixel

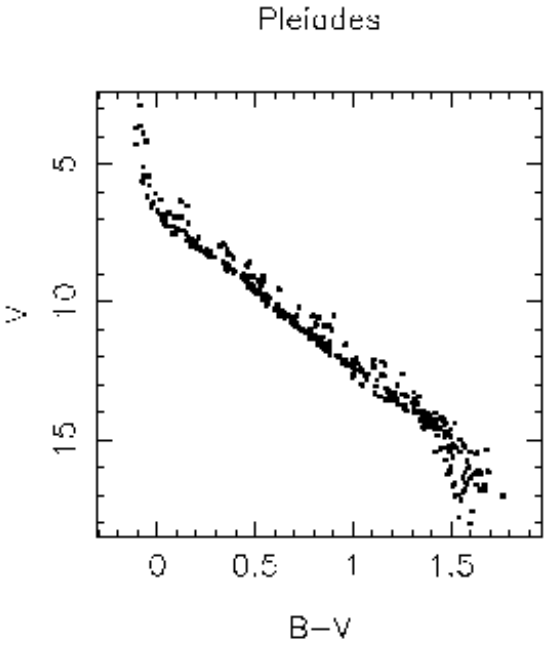
1. Type ***imexamine*** at pyraf prompt. When you press return the command prompt will not appear. Imexamine is an interactive tool to use with ds9. Notice that the cursor is round and blinking when hovered over the image. Pick out a bright star –find one isn't saturated which appears as spikes coming from the center. Hover the cursor over a star and type *a*
   (Note: To quit imexamine, type *q* while the cursor is in the image.)

You will get the following two-line output (highlighted values are the important ones):
COL (pixel column) LINE (pixel row) **COORDINATES** (a repeat of COL and LINE)
R (aperture radius derived from 3*FWHM) **MAG** (apparent magnitude) **FLUX** (counts/sec from object) **SKY** (sky counts/sec per pixel). The middle 3 terms are not important and the last 3 are derived values of the FWHM of the star. The apparent magnitude is calculated via equation (i) with zeropoint = 0.

2. Record COORDINATES (or COL, LINE), R, MAG, FLUX, SKY and exposure time (given above). Do the same star for all three images
3. Do this entire process again for the faintest star that you can find on the image. Again use the same faint star on all three images.
4. ★ Calculate the SNR. Use gain = 10. Note that the **SKY from imexamine is sky value per pixel and not for the entire aperture, which is needed for SNR (i.e. S = SKY×Aperture area in pixels); Flux = f; exposure time = t.** SNR for a bright star will range between 100-5000. For the faint star, aim for a value less than 50. When combining images, the SNR changes slightly; divide the flux in the denominator by the number of added images (n=4):

$$SNR = Ft\sqrt{\frac{Gain}{\left(\frac{F}{n}+S\right)t}}$$

B. Calculating the distance and age of M39
In order to measure properties such as the age and distance of a stellar population, astronomers create Hertzsprung-Russell (HR) diagrams from blue (B) and visual (V; green) data. Below is an example of an HR diagram of the nearby Pleiades cluster:



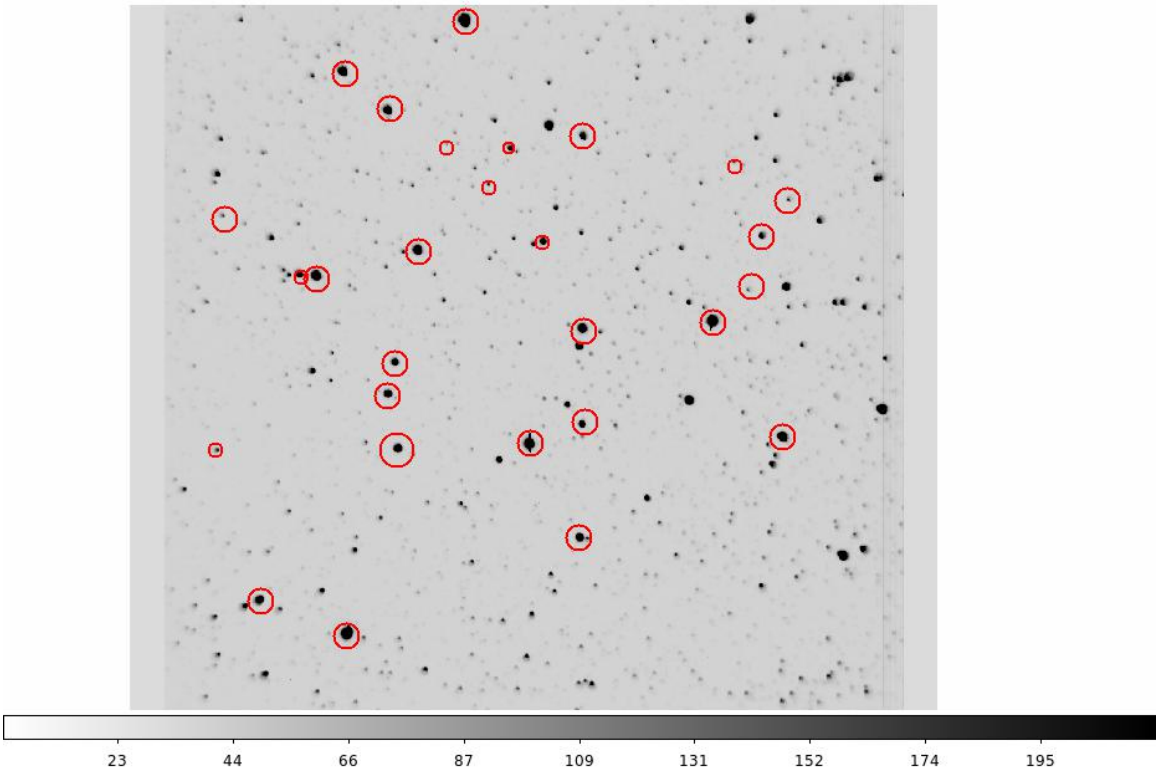
You will create an HR diagram of open cluster M39 by measuring B and V fluxes with imexamine. From the diagram you will determine the distance and age of these stars. I suggest that you refer to the lecture notes if you don't understand the astronomy portion. It won't be necessary but it will enhance your lab experience.

Files Used:

- m39B.fits
- m39V.fits
- myscript.py
- simpleplots.py

1. Display the two M39 files in your directory (you can close the frames from part A)
   m39B.fits (1 second blue exposure)
   m39V.fits (1 second visual exposure – effectively green)
   Change the scale as needed on ds9 to see the fainter stars.

2. Using the image below, measure the flux of the circled cluster stars in both the B and V images as you did in part A recording COORDINATES, R, MAG, FLUX and SKY. Be sure you keep track of each star so that you associate fluxes in B and V with the same star.



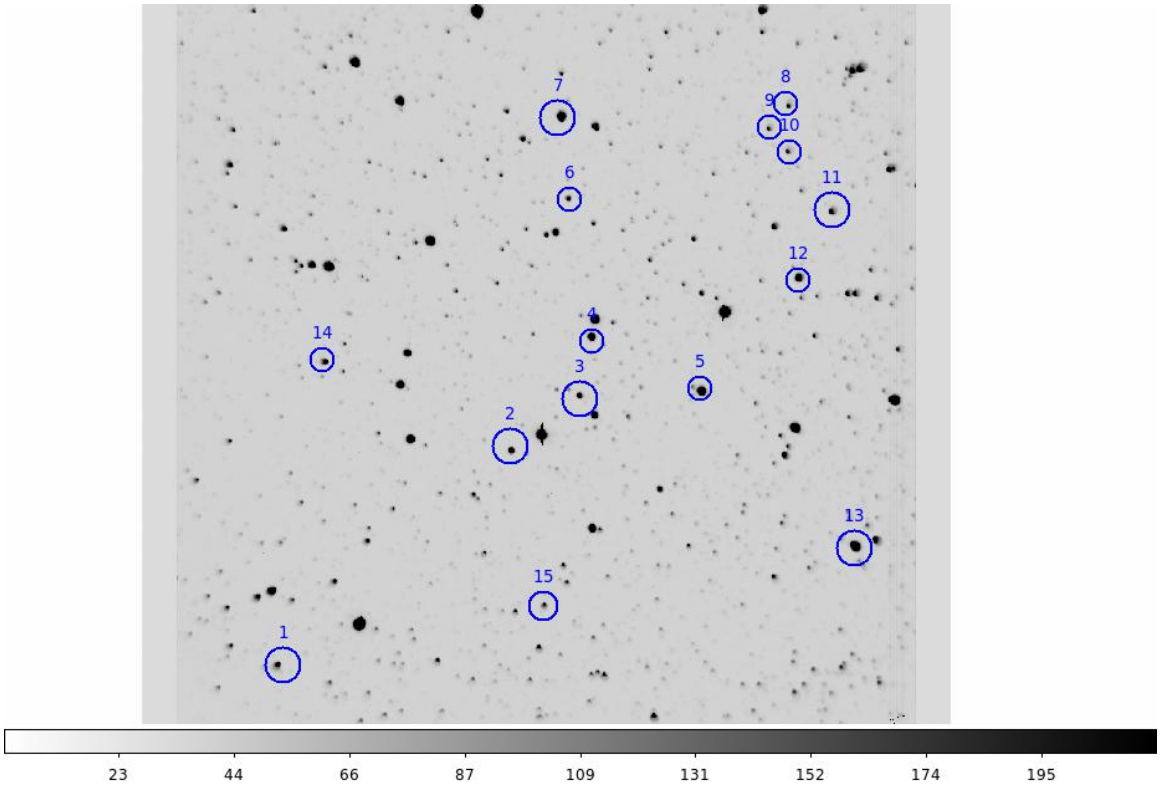
3. ★Calculate the magnitude error for each B and V. Note: it will be very small for most stars.
4. Find the zero point: In order to make sense of these fluxes, they need to be calibrated to a "standard".
   a. Using the image below of standard stars with (catalogued) magnitudes, measure the flux and magnitude of each (R, MAG, FLUX and SKY) circled star as you've done

before for both images. You don't need to record the coordinates; use the numbered labels

b. ★ Compare these measured magnitudes to the standard values using equation (i) and standard.txt (contains all the catalogue star values) to find the zero point. See myscript.py for calculations and arranging lists of data. (NOTE: If you feel confident about your python skills, write a little program and execute it in a terminal window by typing
./your_python_script.py
at the prompt. Note the period and the backslash before the file name. I strongly suggest copying file myscript.py and altering it with your own expressions)

c. ★Average these values to get the B and V magnitude zero points. Calculate the standard deviation for each zero point, this will be the error (don't worry about individual measurement errors as they will be small).

d. ★Apply these zero points to your cluster star data.



HR diagram: Now you are ready to create your HR diagram.

5. ★ Calculate B-V and errors (these add in quadrature).
6. ★ Plot V as a function of B-V with error bars. Use the Pleiades HR diagram above for guidance in terms of approximate B-V range. Use the scripts in simpleplot.py for help on plotting. Be sure that V goes in order of increasing brightness and B-V goes from smaller to

bigger numbers. Your plot should have data points from the bottom right corner to the top left corner of the plot along the main sequence. Save the plot to a file. In case you need to alter it – save the script so you can easily reproduce it.

Distance to Cluster

The B and V magnitudes you just measured are fluxes measured at Earth. We know what their relative brightnesses to one another are but don't know how they compare to other stars with known luminosity such as the Sun, Procyon, Sirius, etc. Therefore we convert this apparent magnitude (ie flux measured at Earth) to absolute magnitude (the flux of any astrophysical object standing 10pc away).

★Using the fact that the sun has a B-V =+0.6 and absolute visual magnitude of Mv = +4.8 (just to reiterate, this is the magnitude the sun would be 10pc away or about 2 million times it's present distance), estimate/extrapolate what the V band apparent magnitude would be for a star with a B-V=+0.6 in your cluster diagram. Using the equations given in the introduction of part II, find the distance to the cluster. Find the min and max distance based your errors.
→Google the actual value. How much bigger or smaller is your derived value (in percentage)?

Cluster Age:

★The age of the cluster is determined by the life expectancy of the most massive main sequence star. For example, a 2 solar mass star has a lifetime of about 1.3 billion years. If the most massive star in a cluster was 2 solar masses, then the cluster is at most 1.3 billion years old. Massive stars burn through their fuel faster than smaller main sequence stars because they require more internal pressure generated in their core to support greater overlying mass –even though they start off with more fuel than a smaller star. As a result, the most massive star in a cluster is the first to evolve off the main sequence or to "die" because the lifetime of a star is defined by its time fusing H into He in its core (main sequence). It is also the most luminous of all the main sequence stars in the cluster.
Using your diagram, locate the most massive main sequence star and calculate the luminosity. There are a few different ways to determine the luminosity of this star, I suggest the following way: compare the apparent magnitude of a sun-like star in this cluster to the brightest cluster star to find the relative luminosity in solar units L_{sun} (e.g. $5L_{sun}$, $1000L_{sun}$ etc – see eqns. on page 5).
Use the following relations to derive the cluster age:
$\mathcal{M}$ here is mass and in solar mass units and L is in solar luminosity units.

- $L \sim \mathcal{M}^{3.5}$
- $Cluster\ Age \sim {}^{\mathcal{M}}/_{L}$
- $Note$: ${}^{1\ \mathcal{M}_{Sun}}/_{L_{Sun}} = 10\ Billion\ Years$

Lab Write Up

Instructions: Cut and paste this template form and your results into a document. There are no other parts to turn in other than what is asked.

Part A

1) Paste your data for the bright and faint star in all 3 images below. It should be organized into a 6 row, 6 column table with column headings: COORDINATES, R, MAG, FLUX and SKY

2) Cut and paste your scripts used to calculate SNR and the SNR for each image below. If you used excel, type out the formula.

3) By what factor is the SNR greater for the 15 min exposure to the 10 min exposure. Based on the formula, is this what you expect? What about the added exposure vs the 15 min exposure? Did the SNR improve according to what you expect?

4) If there is a neighboring star in this annulus, how will that effect the flux estimated from the star?

Part B:

5) Paste your data for the cluster stars. It should be organized into 2 - 28 row, 6 column tables with column headings: COORDINATES, R, MAG, FLUX and SKY

6) Paste your table of SNR values and errors (you don't need to show the calculation scripts). Data should be organized with columns COORDINATES (can either be from B or V) B_{SNR} V_{SNR} m_{verror} m_{Berror}

7) Paste your data for the standard stars. It should be organized into 2 - 15 row, 6 column tables with column headings: COORDINATES, R, MAG, FLUX and SKY. Include the zero point average and standard deviation.

8) Paste your data for your corrected B, V, B-V values and errors

9) Paste your Hertzsprung-Russell diagram here

10) Show your calculation steps and answer for the cluster distance.

11) Percentage from actual value

12) Calculation steps and answer for cluster age:

13) How would the age change if dust lies between our line of sight and the cluster? Dust "reddens" starlight by significantly scattering blue light more so than red light.