

Physics 134L Final Paper

Professor Lubin

Department of Physics

University of California, Santa Barbara

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Introduction

The aim of this project was to create Hertzsprung-Russel (HR) diagrams for two star clusters: Messier 44 (M44), or the Beehive Cluster, and Messier 13 (M13), or the Hercules Cluster. Additionally, an astrophotography project that captured M44 and M13 was also completed. These star clusters were chosen due to their ideal seasonal visibility from April to June. Python packages and AstroArt were used to process the data files from the Las Cumbres Observatory (LCO) telescope's Sloan Digital Sky Survey (SDSS) filters into plots and images. The four filters used for this project included SDSS Red, SDSS Green, SDSS Ultraviolet, and SDSS Infrared. These filters were stacked for each exposure to output the final plots and composite image files.

Historical Background

Hertzsprung-Russel Diagrams

Hertzsprung-Russel diagrams, or color magnitude diagrams, plot the luminosity versus the temperature of stars. They were first created in 1911 by Ejnar Hertzsprung who plotted stars' magnitudes against their colors. In 1913, using the same model Henry Russel plotted luminosity and spectral class. This resulted in plots that showed that the temperature of stars was not random and could be categorized into types of stars. HR diagrams show how stars evolve over time in what is known as evolutionary sequences. They give information on how the physical characteristics of stars change as they age. The various classes of stars is as follows: OBAFGKM. O-class stars are the hottest and most massive. From there, they descend in mass and temperature with M-class stars, or red dwarf stars, being the least massive and coolest. The main sequence of an HR diagram contains ninety-percent of stars. This is where thermonuclear fusion occurs with hydrogen forming into helium, and also where stars are in hydrostatic equilibrium. Stars with more mass mean they have a faster fusion rate, and thus they spend less time on the main sequence. On the other hand, less massive stars have a slower rate of fusion, so they spend more time on the main sequence. HR diagrams most importantly are used to determine the age of star clusters. When observing

HR plots, there is a main sequence turnoff where the stars begin the end of their life cycles by departing from the main sequence. Therefore, the age of a star cluster is equivalent to the main sequence lifetime of the turnoff stars.

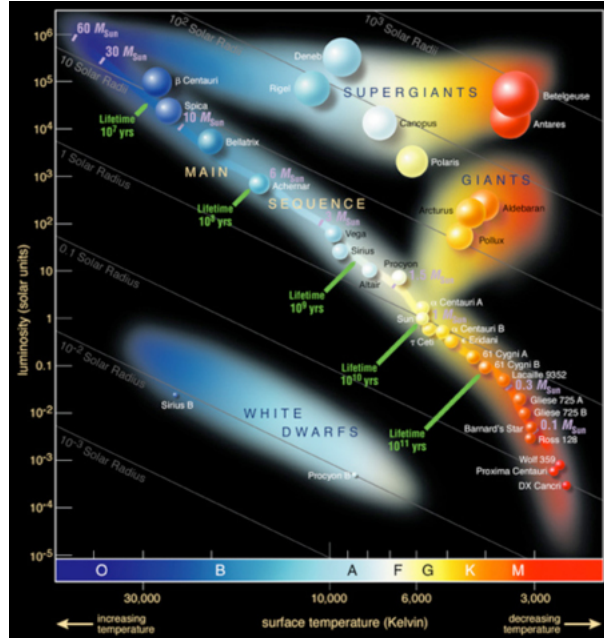


Figure 1: Major branches of the Hertzsprung-Russell diagram

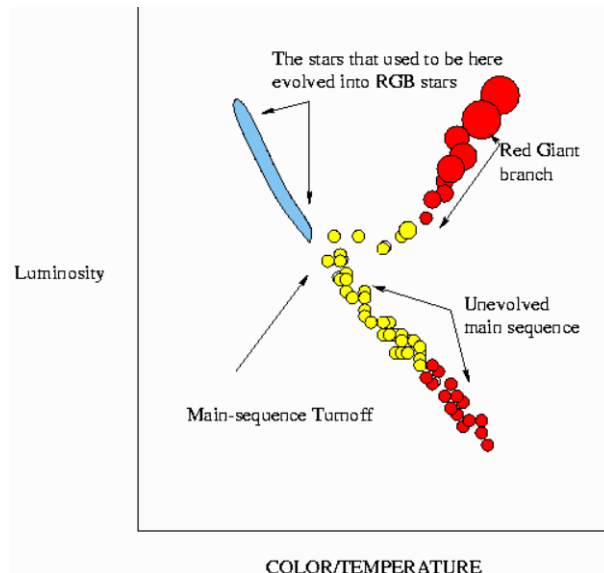


Figure 2: The main sequence turnoff shows where stars begin the end of their lives. Star cluster age is the main sequence lifetime of the turnoff stars

Messier 44

Messier 44 (M44), or the Beehive Cluster, is one of the closest star clusters to our solar system at six hundred light years away. It is an open cluster that spans fifteen light years and covers 1.5 degrees in the Cancer constellation. M44 has about one thousand stars, most of which are young stars six hundred million years old. These stars are mainly blue main sequence stars, red giants, and white dwarfs. The total mass of the Beehive Cluster is 500-600 solar masses. Furthermore, it originated from the molecular cloud that the star cluster Hydra also came from. Finally, M44 is visible to the naked eye, and the first person to observe it with a telescope was Galileo who found forty of its stars.

Messier 13

Messier 13 (M13), or the Hercules Cluster, is a globular cluster that is one of the brightest star clusters when viewed from the Northern Hemisphere. It is 25 thousand light years away from the Earth and best visible during the month of June. M13 was discovered by Edmund Halley in 1714. Furthermore, its stars are very densely packed together and can become so crowded that they will run into one another to form new stars called blue stragglers. The new stars are significantly younger than the rest of M13 and have many implications for astronomers.

Significance

Hertzsprung-Russel diagrams offer important information about stars and provide the most accurate models possible of clusters today. They not only estimate stellar ages, but other physical properties as well, such as diameter, mass, and evolutionary state. HR diagrams let astronomers determine which class a particular star belongs to, for instance, which ones belong to the main sequence or are white dwarfs. In a larger context, they address the cosmic age problem, which concerns the age of the universe. HR diagrams further confirm that there are no objects older than the Big Bang. This is shown by using the HR plots to find the age of the oldest stars in galaxies, which are mostly found in globular star clusters like Messier 13. Globular clusters were formed from molecular clouds of gas when stars collapsed at the beginning of the universe. So, the age of the oldest stars in a globular cluster is evidence for the age of the universe. Overall, HR diagrams are a way to conveniently study the birth and evolution of galaxies, form theories about galactic interactions, and contribute to the understanding of the age of the universe.

Data Collection

For both M44 and M13 clusters, observation requests were submitted to LCO for the SDSS filters. We requested the data to be collected between April 1 and May 1 for M44. During this time, the M44

cluster's best visibility was from 2:00 am to 8 am for the OGG - Haleakala, ELP - McDonald, and TFN - Tenerife locations. For M13, the data was collected between May 15 and June 9 with the best visibility being 6:00 am to 3:00 pm for OGG, 3:00 am to 11:00 am for ELP, and 9:00 pm - 5:00 am for TFN. The observation requests included the location of each star cluster, the filters to be used (red, green, infrared, and ultraviolet), ten exposures each for fifteen seconds, and the observation window for the data to be collected. Afterward, we received the data in the form of .fits files. These files included all four filters we requested, and for each filter were the ten exposures.

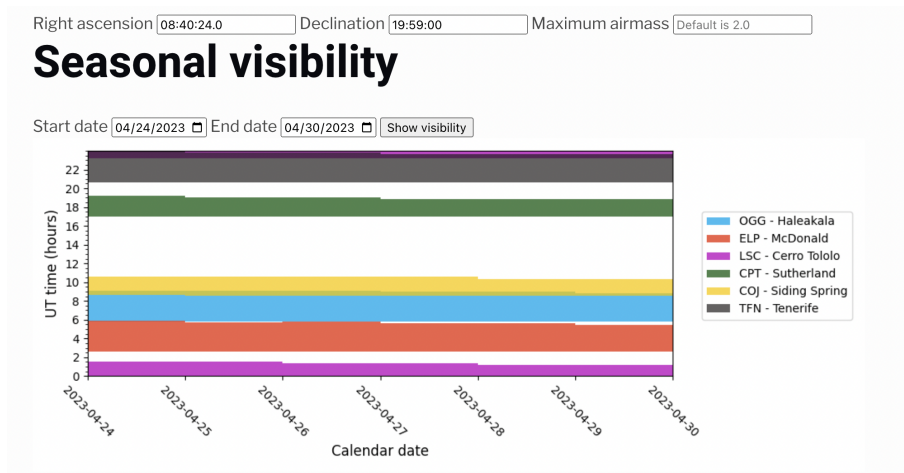


Figure 3: Seasonal visibility of the M44 cluster, determined by right ascension (08:40:24.0), declination (19:59:00), and maximum air mass of 2.0 (the default of the LCO Visibility Tool) from April 1 to May 1

Target Name	RA (J2000)	Dec (J2000)	Filter	# Exposures	Integration Time (s)	Observational Windows
M44 - red	08:40:24.0	19:59:00	SDSS r'	10	15	02:00 - 08:00
M44 - blue	08:40:24.0	19:59:00	SDSS g'	10	15	02:00 - 08:00
M44 - I	08:40:24.0	19:59:00	SDSS i'	10	15	02:00 - 08:00
M44 - u	08:40:24.0	19:59:00	SDSS u'	10	15	02:00 - 08:00

Figure 4: Summary of M44 observation parameters including right ascension, declination, telescope and filters, number of exposures, exposure/integration time, and time of data collection

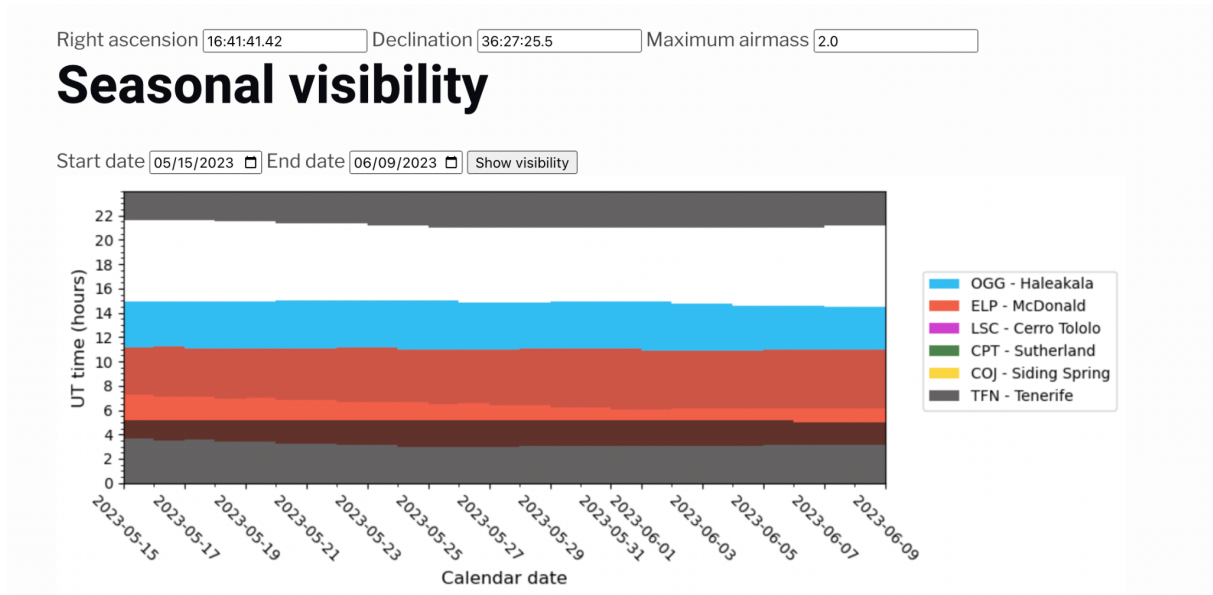


Figure 5: Seasonal visibility for M13 cluster determined by right ascension (16:41:41.42), declination (36:27:25.5), and maximum air mass of 2.0 (default of LCO Visibility Tool) from May 15 to June 9

Target Name	RA (J2000)	Dec (J2000)	Filter	# Exposures	Integration Time (s)	Observational Windows
M13 - red	16:41:41.42	36:27:35.5	SDSS r'	10	30	06:00-15:00 (OGG) 03:00-11:00 (ELP) 21:00-05:00 (TFN)
M13 - blue	16:41:41.42	36:27:35.5	SDSS g'	10	30	06:00-15:00 (OGG) 03:00-11:00 (ELP) 21:00-05:00 (TFN)
M13 - I	16:41:41.42	36:27:35.5	SDSS i'	10	30	06:00-15:00 (OGG) 03:00-11:00 (ELP) 21:00-05:00 (TFN)
M13 - u	16:41:41.42	36:27:35.5	SDSS u'	10	30	06:00-15:00 (OGG) 03:00-11:00 (ELP) 21:00-05:00 (TFN)

Figure 6: Summary of M13 observation parameters including right ascension, declination, telescope and filters, number of exposures, exposure/integration time, and time of data collection

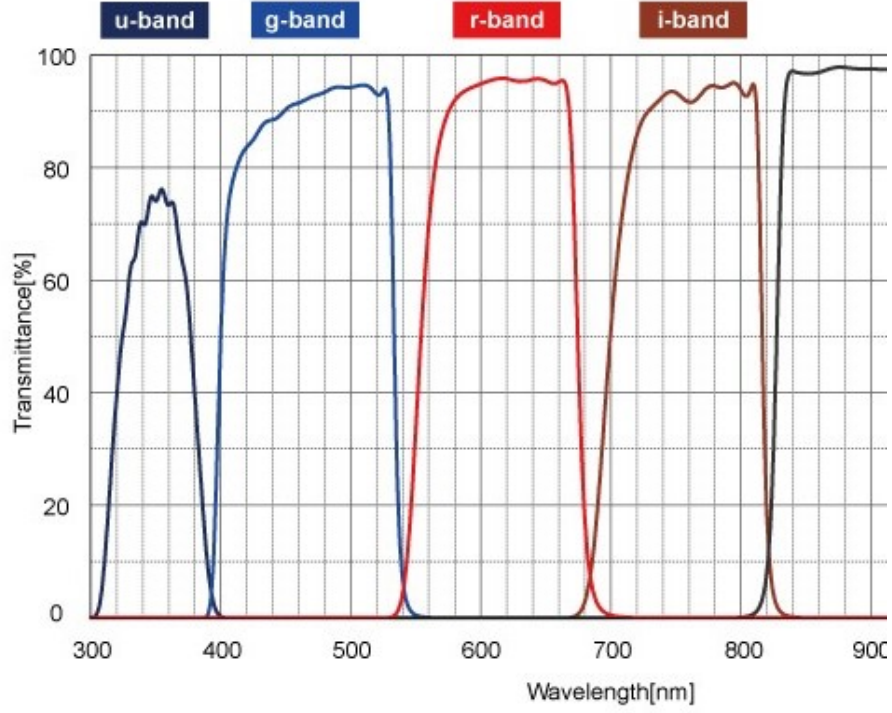


Figure 7: Sloan Digital Sky Survey (SDSS) filters including ultraviolet, green, red, and infrared

Images

For the astrophotography aspect of the project, we created composite images of the M44 and M13 clusters. Initially, we examined the raw images for each filter in an exposure. For each filter, the .fits file data was extracted and converted into an image file using Python and AstroArt. Below are the images for each filter:



Figure 8: M44 raw images of SDSS filters for infrared, red, green, and ultraviolet

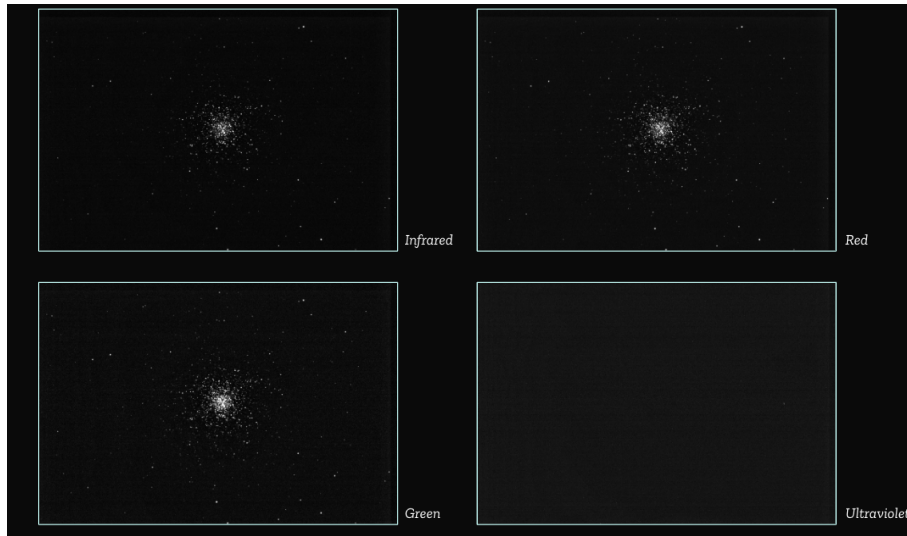


Figure 9: Messier 13 filtered images

Notice that the green filter is the brightest, while the ultraviolet filter captures the stars faintly. After examining the raw images, the filters were stacked using the Python package Astropy to create a composite for each exposure in the order of infrared, red, green, and ultraviolet. Initially, we only used red, green, and ultraviolet to create the RGB image. However, the resulting composites came out with more orange and no blues. After, stacking the filters to include the infrared though, the final composite then had a balance of colors with more of a bluish tint. See the Python code below for how the .fits files were stacked and converted to image files:

```
1 # stack RGB files
2 from astropy.io import fits
3 import numpy as np
4 import matplotlib.pyplot as plt
5
6 # for i in fit_files:
7 #   r_path=
8 r_file = '/content/drive/MyDrive/M44 project/fn130_mol85_exp3_filterrp.fits'
9 g_file = '/content/drive/MyDrive/M44 project/fn110_mol83_exp3_filtergp.fits'
10 b_file = '/content/drive/MyDrive/M44 project/fn140_mol86_exp3_filterup.fits'
11 i_file = '/content/drive/MyDrive/M44 project/fn120_mol84_exp3_filterip.fits'
12
13 r_data, r_header = fits.getdata(r_file, header=True)
14 g_data, g_header = fits.getdata(g_file, header=True)
15 b_data, b_header = fits.getdata(b_file, header=True)
16 i_data, i_header = fits.getdata(i_file, header=True)
17
18 rgbi_array = np.stack((i_data, r_data, g_data, b_data), axis=-1)
19
20 rgbi_array = (rgbi_array - np.min(rgbi_array)) / (np.max(rgbi_array) - np.min(rgbi_array)) * 65535.0
21 rgbi_array = rgbi_array.astype(np.uint16)
22
23 fits.writeto('irgb_stacked_16bit.fit', rgbi_array, header=r_header, overwrite=True)
24
```

Figure 10: Python code for stacking the filter .fits files of M44 exposure 3 using the Astropy package

```

26 # Open the FITS file
27 hdulist = fits.open('irgb_stacked_16bit.fits')
28
29 # Extract the data from the first extension
30 data = hdulist[0].data
31
32 # Convert the data to a 16-bit integer array
33 data_16bit = np.array(data, dtype=np.uint16)
34
35 # Plot the image using Matplotlib
36 plt.imshow(data_16bit, cmap='gray', vmin=0, vmax=2*16-1)
37 plt.axis('off')
38 plt.savefig('m44_irgb_exp3.jpg', dpi=300, bbox_inches='tight')

```

Figure 11: Python code for converting the M44 exposure 3 .fits file composite to a JPG image file

After using Python to process each exposure's image, AstroArt was used to confirm the image was not saturated and to adjust the levels of black point and white point in the image. After this step, we had our final images for each exposure. See below for the composite images for exposure 1:



Figure 12: Messier 44 Exposure 1 Composite Image



Figure 13: Messier 13 Exposure 1 Composite Image

Furthermore, we noticed that the final composites were still not as vibrant and the signal to noise ratio did not have enough of signal. This meant we had to either increase the exposure time for the data or combine all of the exposures to get a better signal to noise ratio, and thus a vibrant image with more stars visible in the M44 cluster. However, when we began to combine all the filter bands according to their color and then stack all exposures, we were unable to complete a working code that accomplished this.

Plots

HR diagram plots were created for both the M44 and M13 star clusters using Python and the Python package Astropy. The data is taken from each filter's .fits file with the data being extracted from all four filtered images per exposure out of the ten total exposures per filter. It is then flattened, and the color indices and absolute magnitude were calculated from the data. Absolute magnitude was calculated with infrared data using this equation:

$$M_{abs} = m - 2.5 \log (ADU)$$

For the purpose of this project, $ADU = 1000$ and m is given by the equation below:

$$m = -2.5 \log \left(\frac{peak\ density}{detection\ threshold} \right)$$

Each color index is then plotted against the absolute magnitude to create the final HR diagrams. The Python code is shown below:

```

1 import numpy as np
2 import matplotlib.pyplot as plt
3 from astropy.io import fits
4
5 # Read the FITS files
6 r_data = fits.getdata('fn073_mol36_exp1_filterrrp.fits.fits')
7 g_data = fits.getdata('fn053_mol34_exp1_filtergrp.fits.fits')
8 u_data = fits.getdata('fn083_mol37_exp1_filterup.fits.fits')
9 i_data = fits.getdata('fn063_mol35_exp1_filterip.fits.fits')
10
11 # Flatten the data arrays
12 r_flux = -2.5*np.log10(r_data.flatten())
13 g_flux = -2.5*np.log10(g_data.flatten())
14 u_flux = -2.5*np.log10(u_data.flatten())
15 i_flux = -2.5*np.log10(i_data.flatten())
16
17 # Calculate the color index
18 U_V1 = u_flux - g_flux
19 V_R1 = g_flux - r_flux
20
21 # Calculate the absolute magnitude
22 abs_magnitude1 = i_flux - 2.5 * np.log10(1000) # Assuming a distance of 1000 parsecs
23
24 # Plot the HR diagram
25 plt.scatter(U_V1, abs_magnitude1, s=1, c='black')
26 plt.gca().invert_yaxis()
27 plt.xlabel('Color Index (u-g)')
28 plt.ylabel('Absolute Magnitude (i)')
29 plt.title('HR Diagram for Exposure 1')
30 plt.grid(True)
31 plt.show()
32 # Plot the HR diagram
33 plt.scatter(V_R1, abs_magnitude1, s=1, c='black')
34 plt.gca().invert_yaxis()
35 plt.xlabel('Color Index (g-r)')
36 plt.ylabel('Absolute Magnitude (i)')
37 plt.title('HR Diagram for Exposure 1')
38 plt.grid(True)
39 plt.show()

```

Figure 14: Python code for extracting .fits data, calculating color indices and absolute magnitude, and plotting the final HR diagrams

After running this code, two HR diagrams are output: one for the color index u-g and the other for the color index g-r. See below for the HR diagrams for both M44 and M13:

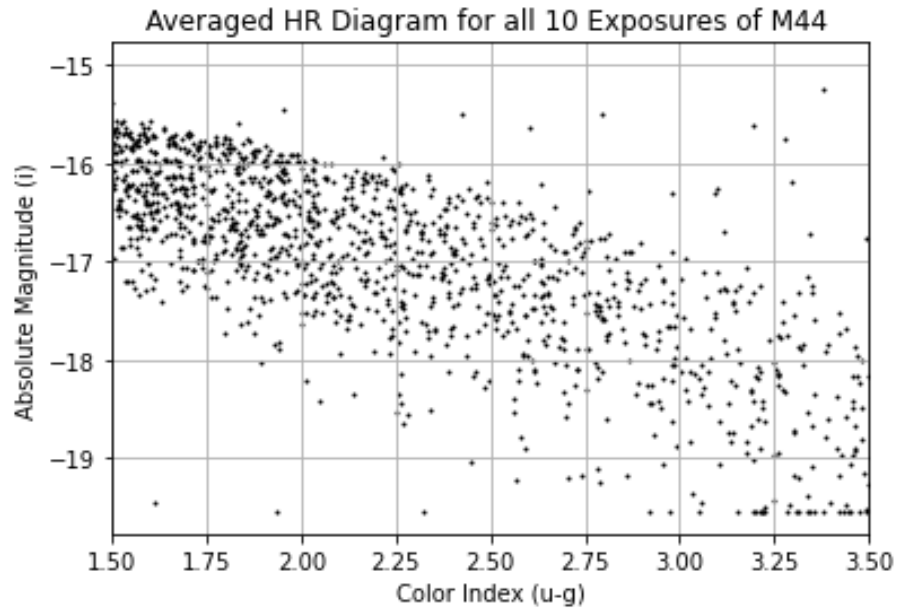


Figure 15: Messier 44 averaged HR diagram with color index $u-g$

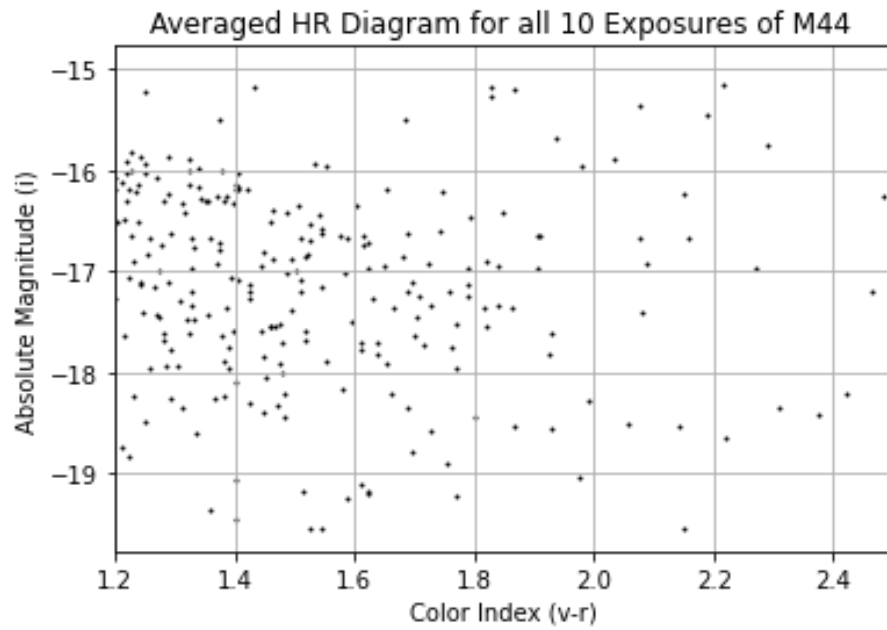


Figure 16: Messier 44 averaged HR diagram with color index $v-r$

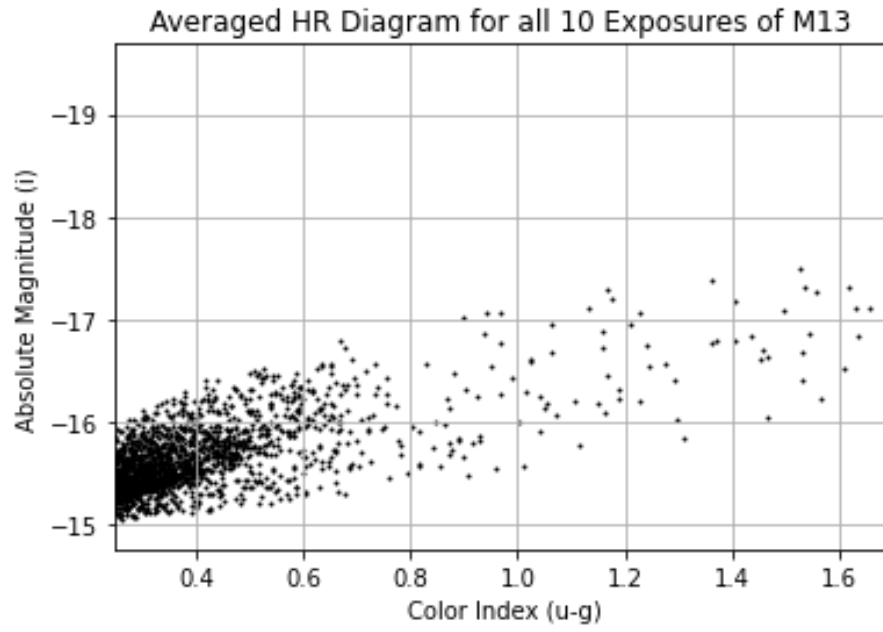


Figure 17: Messier 13 averaged HR diagram with color index u-g

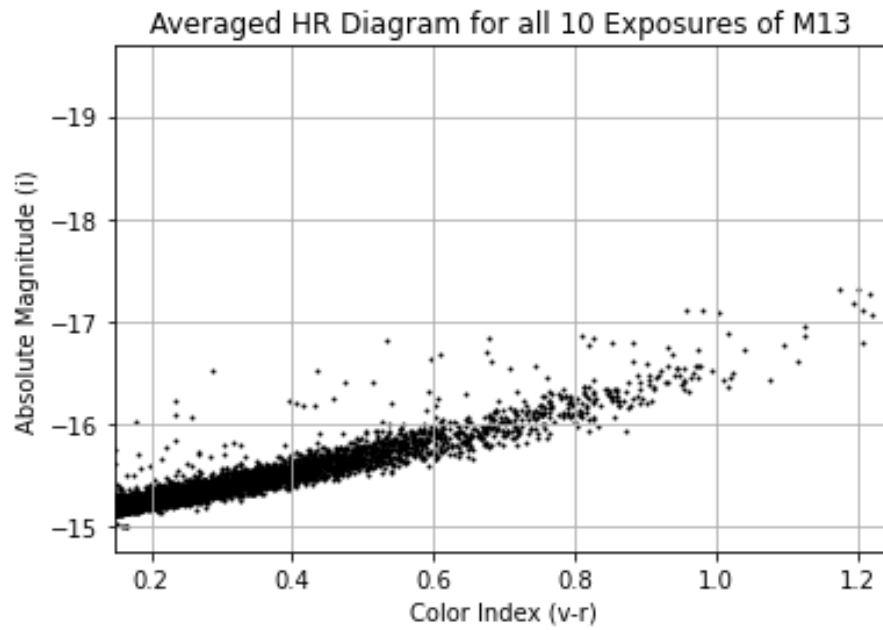


Figure 18: Messier 13 averaged HR diagram with color index v-r

Data Analysis

For both Messier 13 and Messier 44, the strongest results are in the SDSS Green filter because this is visible light. This is apparent when observing the raw image files of each filter for both clusters, since the green filter has the brightest stars. On the other hand, the ultraviolet filtered images lacked the most data, since it is not visible light. This can be also be seen in the individual images of the filters where the ultraviolet band pictures' stars are the duller.

Signal to Noise Ratios

To ensure we had good data for the astrophotography project and the HR diagrams, we had to calculate the peak signal to noise ratios. The equation for this is:

$$\frac{S}{N} = \frac{FA_{\epsilon}\sqrt{\tau}}{\left(\frac{N_R^2}{\tau} + FA_{\epsilon} + i_{DC} + F_{\beta}A_{\epsilon}\Omega\right)^{\frac{1}{2}}}$$

where F is flux, A_{ϵ} is the telescope effective area, τ is integration time, N_R is readout noise, and Ω is pixel size. To convert from magnitude to flux, the following equation was used:

$$\frac{b_1}{b_2} = 10^{0.4(m_2 - m_1)}$$

where b_1 and b_2 are the fluxes of two stars and m_1 and m_2 are those stars magnitudes. For this project, the signal to noise ratio was calculated for each filter band (red, green, blue, and infrared) for both M44 and M13. See below for a summary of the ratios:

Magnitude (M44)	SNR (M44)	Magnitude (M13)	SNR (M13)
10.496	452.4	11.379	297.4
11.733	250.5	11.733	250.5
11.741	249.5	12.746	150.0
11.779	244.9	13.016	129.8
11.944	225.8	13.363	107.1
12.547	166.4	13.537	97.5
12.552	166.0	13.563	95.5
12.748	149.9	13.750	85.5
12.933	135.8	13.875	79.3
13.152	120.5	13.878	79.1
13.346	108.1	13.930	76.7
13.673	89.5	13.978	74.4

Figure 19: Signal to noise ratios for each of the SDSS filters for M44 and M13

Additionally, the S/N ratios for M44 and M13 can be plotted versus magnitude as seen below along with the Python code used to generate the plots:

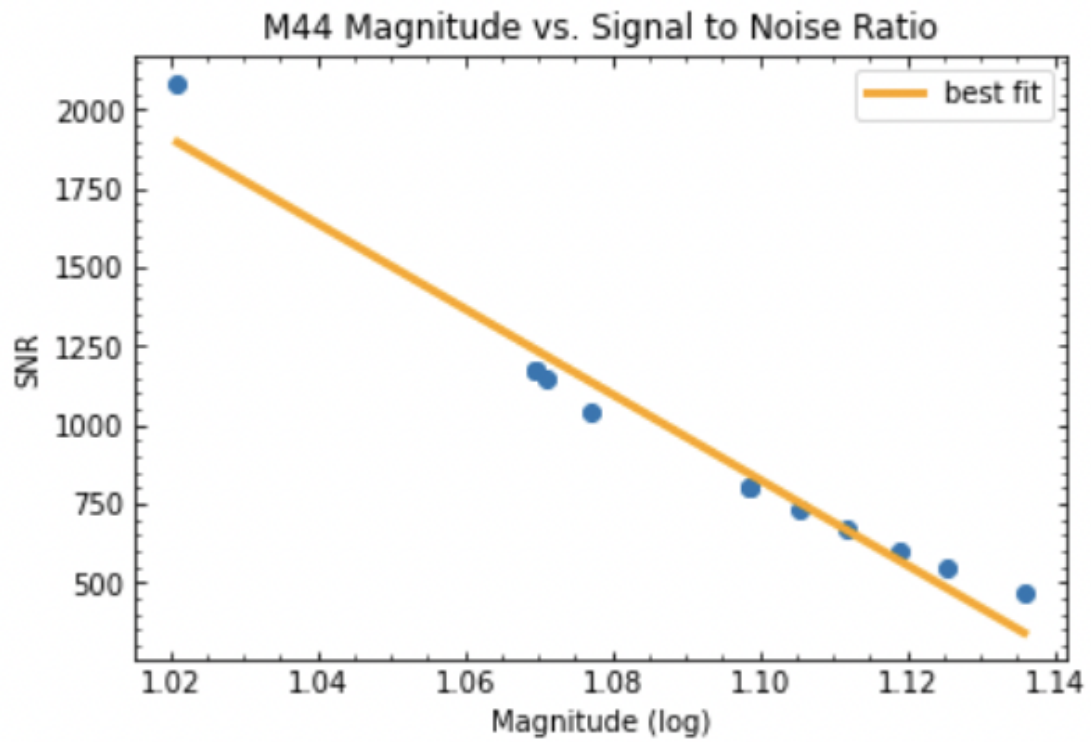


Figure 20: Magnitude versus S/N ratio for M44

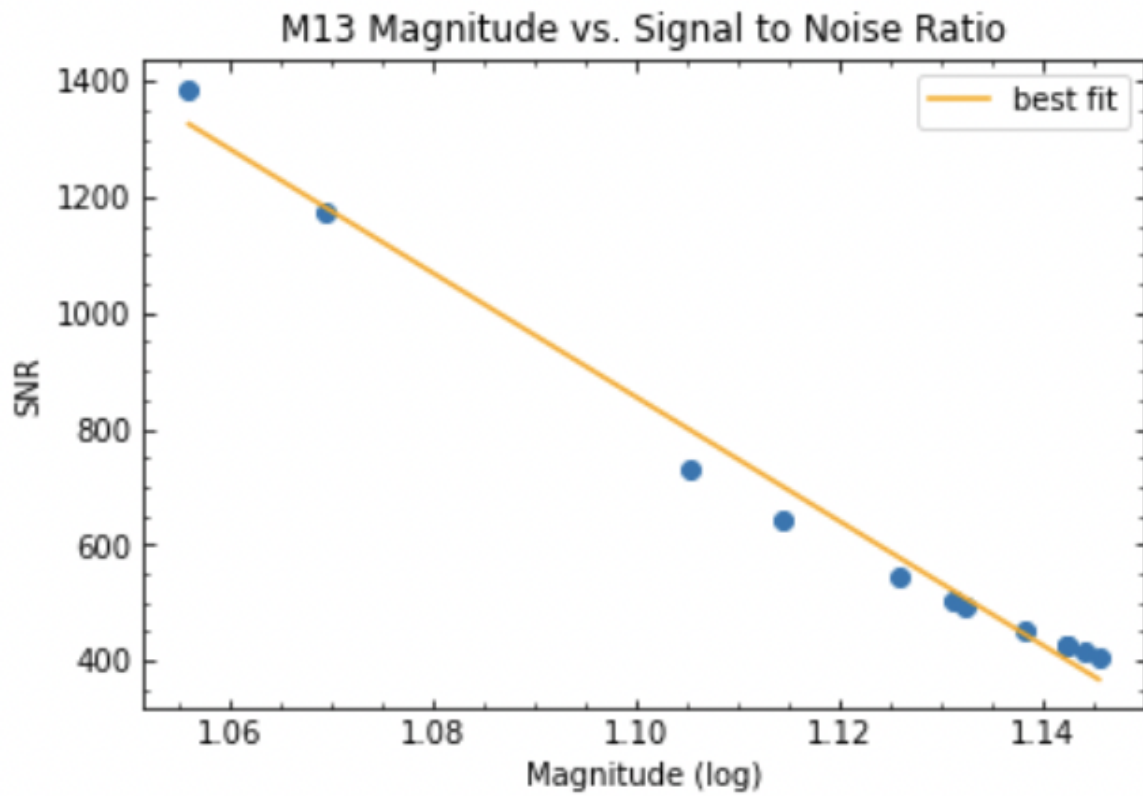


Figure 21: Magnitude versus S/N ratio for M13

```

import numpy as np
import matplotlib.pyplot as plt
from matplotlib import rc

x = np.array([10.496, 11.733, 11.741, 11.779, 11.944, 12.547, 12.552, 12.748, 12.933, 13.152, 13.346, 13.673])
y = np.array([2085.9, 1174.9, 1170.5, 1149.9, 1040, 801.9, 800, 729, 667.5, 600.9, 547.1, 466.2])
# magnitude data from AstroArt
# SNR data from LCO calculator
xlog = np.log10(x)
curve = np.polyfit(xlog, y, 1)

rc('xtick', **{'direction' : 'in', 'top': True, 'minor.visible' : True}) # tick marks go in and adding minor ticks
rc('ytick', **{'direction' : 'in', 'right': True, 'minor.visible' : True})

plt.plot(xlog, -13551*xlog + 15733, color = "orange", label = "best fit")
plt.scatter(xlog, y)
plt.legend()
plt.xlabel('Magnitude (log)')
plt.ylabel('SNR')
plt.title('M44 Magnitude vs. Signal to Noise Ratio')

plt.show()

```

Figure 22: Python code for M44 magnitudes versus S/N ratios plots

```

import numpy as np
import matplotlib.pyplot as plt
from matplotlib import rc

x = np.array([11.379, 11.733, 12.746, 13.016, 13.363, 13.527, 13.563, 13.750, 13.875, 13.878, 13.930, 13.978])
y = np.array([1386.5, 1176.2, 731.8, 643.9, 545.4, 503.8, 495.1, 451.9, 425, 424.4, 413.6, 403.9])
# magnitude data from AstroArt
# SNR data from LCO calculator
xlog = np.log10(x)
curve = np.polyfit(xlog, y, 1)
print(curve)

rc('xtick', **{'direction' : 'in', 'top': True, 'minor.visible' : True}) # tick marks go in and adding minor ticks
rc('ytick', **{'direction' : 'in', 'right': True, 'minor.visible' : True})

plt.plot(xlog, -10722.*xlog + 12649, color = "orange", label = "best fit")
plt.scatter(xlog, y)
plt.legend()
plt.xlabel('Magnitude (log)')
plt.ylabel('SNR')
plt.title('M13 Magnitude vs. Signal to Noise Ratio')

plt.show()

```

Figure 23: Python code for M13 magnitudes versus S/N ratios plots

For both the M44 and M13 plots, there is a clear trend of the S/N ratio descending as the magnitude increases. Additionally, based on the graphs, there is a good signal to noise ratio all the way to a magnitude of 1.14.

Error Analysis

There are a number of ways to improve the results of both the HR diagrams and astrophotography project. One improvement would be to increase the exposure time for M13, so more stars are visible in the final composite image. Even though M44 has a better final composite image than M13, longer exposures for it could also help make the image clearer. Moreover, another way to make the photos better would be to combine all ten exposures for the data we received. First, we would have to stack the IRGB filters together for each exposure. Then, take the composites and stack for all ten exposures. This would be a simpler way to adjust the code to output images with more visible stars. We began

to make this change, but simply did not have enough time to complete the new code. Furthermore, we did not compute the apparent magnitude using reference stars, since it is difficult to find and calculate with this method. Finding the apparent magnitude with reference stars as opposed to flattening the data would produce more accurate HR diagrams. However, this method would consume a lot of the time spent on the project, since it uses AstroArt and requires more calculations. Thus, we were not able to start attempting to use reference stars for our data, calculations, and plots. If we were to though, we should have started this approach earlier. Additionally, using Bessel filters for the images may have offered a simpler way to create the pictures as opposed to the SDSS filters. This is because Bessel filters are more compatible with standard magnitudes. These given magnitudes can simply and easily be used to make Bessel images. On the other hand, there is more conversion that has to be done in the calculations for the SDSS filters. To convert between Bessel and SDSS magnitudes the following equations can be used:

$$B = g + 0.3130(g - r) + 0.2271$$

$$V = g - 0.5784(g - r) - 0.0038$$

There were a number of complications with this project and errors that arose, and many of these errors could have been mitigated by simply altering the procedures we carried out had we planned better and accordingly in the beginning of the project.

Conclusion

Overall, we successfully put together the astrophotography images and produced Hertzsprung-Russel diagrams for Messier 44 and Messier 13. We were able to write Python code that created composite images of both the star clusters in realistic color, even though there was still a lack of brightness in both images, and we also output the pictures for each SDSS filter. For the astrophotography aspect of the project, we had to use the Python package AstroPy, which made outputting the composites simpler and more efficient. We also successfully wrote code that output four HR diagrams which show the life cycles of Messier 44 and Messier 13 by plotting the data we received from LCO; magnitude was graphed versus color index for the star clusters. However, there were a number of errors in the project that could be improved upon to produce even clearer images and make HR diagrams with more useful information. Future work for this project includes adding color to represent temperature for the HR plots for easier reading, altering the Python code to combine all the exposures for the astrophotography project in order to achieve clearer final composite images, combining all exposures for the HR diagram code as well for more accurate plots, and requesting longer exposure times or integration times for both Messier 44 and Messier 13. Most of these changes could be accomplished if we had started them earlier or had more time to complete the project. Additionally, analysis of the ages of Messier 44 and Messier 13 could be carried

out based on the final HR diagrams and a comparison of these ages to known values would be beneficial as well. The star cluster ages could also be compared to one another to denote any physical differences between M44 and M13 due to their age difference.

References

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