

Messier 55 HR Diagram

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INTRODUCTION

On February 23, 2001, NASA released a Color Magnitude Diagram (CMD) of the Globular Star Cluster M55 (Fig. 1). The image contained information regarding the color index, effective temperature, absolute magnitude, and luminosity of the different stars in the cluster. A Color Magnitude Diagram is an important tool used by astronomers to study how a star changes over the course of time. Looking at the data in a CMD can also aid observers infer the age of a star cluster and knowing additional information about the cluster such as its apparent magnitude gives the observer information about the cluster's distance.

However, instead of a full blown Color Magnitude Diagram, this project will focus on plotting a CMD that leans toward a Hertzsprung-Russell Diagram (H-R Diagram) in terms of the number of variables. Compared to a CMD, the H-R Diagram will only contain two variables, usually these two variables are the luminosity or absolute magnitude and surface temperature of the stars in the cluster. However, for this project the two variables are color index and luminosity. Despite the lessened quantities in an H-R Diagram, it still holds the same amount of information as a CMD because the variables are interchangeable. Luminosity has the same scaling factor as apparent magnitude and absolute magnitude because magnitude is used to express the luminosity of an object at a particular distance so they are interchangeable in the y-axis. When one increases, the other variables increase as well. The values will be different but it can be fixed by adjusting the axis intervals. Effective temperature can also be replaced by surface temperature and color index on the x-axis, only the values on the axis need to be changed, because the color of a star indicates its temperature. The hotter the temperature of the star, the more negative the color index will be and the star will appear to be blue. The colder the temperature of the star, the more positive the color index will be and the star will appear to be red. These are the reasons why an H-R diagram is identical to a CMD.

Using data taken from the Las Cumbres Observatory (LCO), the project aims to create a Color Magnitude Diagram of the Globular Star Cluster M55 by plotting the luminosities of stars in the B-V color index to compare its age with other star clusters and observe any differences with the CMD released by NASA. Additionally, this paper will also present the images taken by the LCO and the code used to analyze the images. Discussion of results, error sources, and error propagation will also be included in the paper.

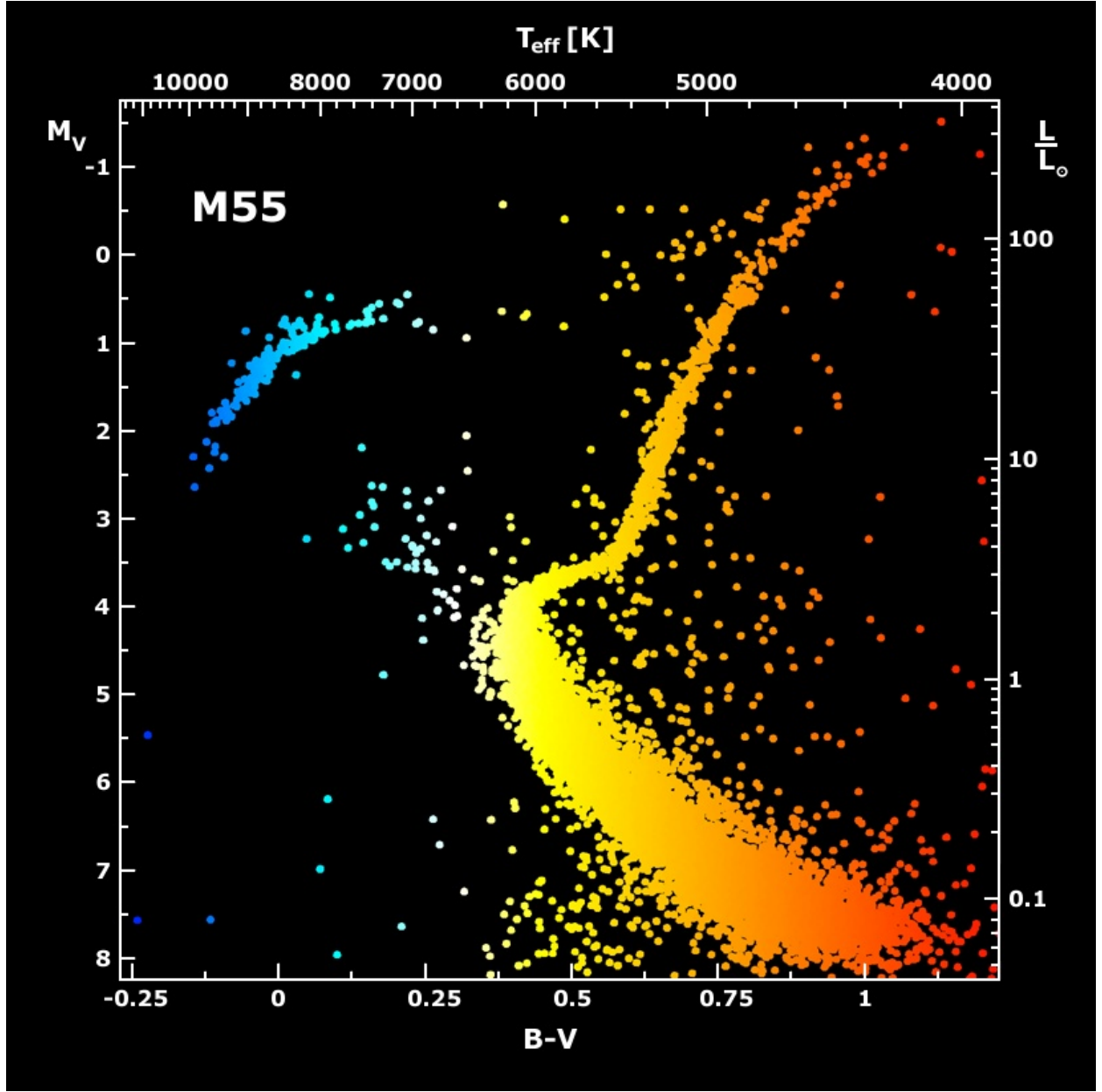


FIG. 1. M55's individual stars are represented as dots whose color indicates relative temperature, red (cool) to blue (hot). Position in the CMD corresponds to a measured astronomical color, (B-V color) read off the bottom scale, and a brightness in magnitudes (M) on the left hand scale. The temperature for each star can also be found by reading the equivalent scale at the top. Brightness relative to the Sun's luminosity (Sun = 1) is given on the scale at the right.[\[1\]](#)

HISTORICAL BACKGROUND

H-R Diagram

In reality, H-R Diagrams and Color Magnitude Diagrams are used interchangeably. The CMD is an offspring of the H-R Diagram and is more commonly used for star clusters while the H-R Diagram is more commonly used for individual stars. The Hertzsprung-Russell Diagram was developed by Ejnar Hertzsprung, a Danish chemist and astronomer, and Henry Norris Russell, an American astronomer, during the 1900's. It is a plot of the brightness of a star against its surface temperature, with the resulting position of the star in the diagram allowing astronomers to infer a wealth of information about the star's make-up, evolution, age and ultimate fate.[2] Luminosity is the total amount of energy that leaves the surface of the source per unit time in the form of photons.[3] Luminosity is usually measured in terms of the luminosity of the Sun. Before tackling absolute magnitude, it is important to first lay a foundation for apparent magnitude. Apparent magnitude is how bright an object appears from exactly where it is viewed by an observer from Earth. On the other hand, absolute magnitude is how bright the object is if it were 10 parsecs away from the observer on Earth. As mentioned earlier, it is used by astronomers to study stellar evolution. The major goal of stellar evolution theory is the interpretation and reproduction of the Hertzsprung-Russell Diagram (HRD) of stars in different astrophysical environments: solar vicinity, star clusters of the Milky Way and nearby galaxies, fields in external galaxies. The HRD of star clusters, in virtue of the small spread in age and composition of the component stars, is the classical template to which stellar models are compared.[4]

Figure 10 shows the primary regions where different stars reside. The diagonal region starting from the top-left of the diagram ending on the bottom-right region is the main-sequence stars. Most of the stars in this region are in a state of equilibrium where the radiation pressure pushing out from the fusion process is balanced by the inward pull of gravitational forces. After a period of time, when hydrogen in the core of main-sequence stars is depleted and radiation pressure decreases, the two forces become unbalanced thus resulting towards the star moving towards the regions of supergiants, giants, and white dwarfs depending on the mass of the star. The giant and supergiant regions of the diagram are filled with stars that have moved off of from the main sequence and are fusing heavier atomic nuclei.[5]

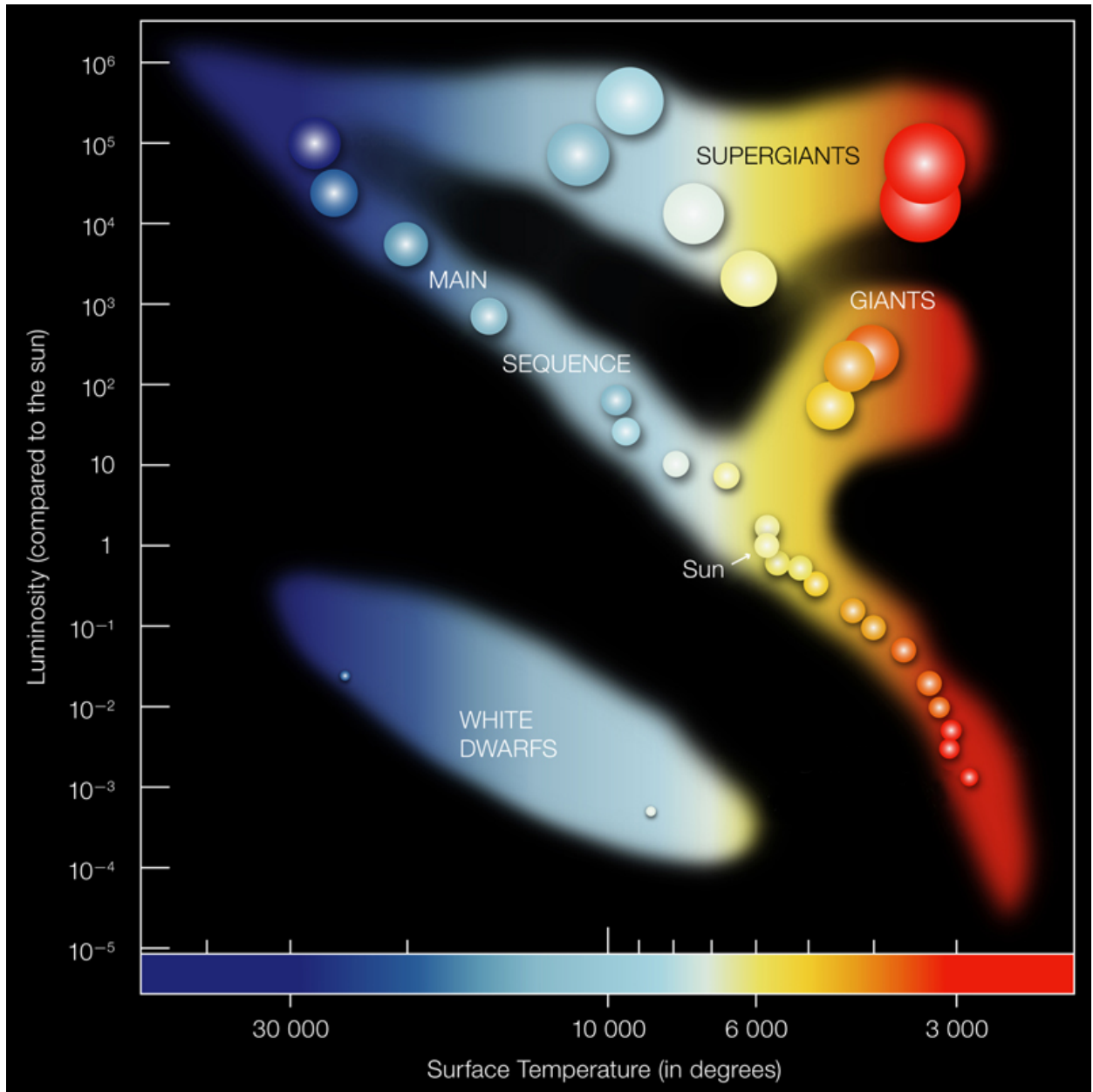


FIG. 2. Major Branches on the H-R Diagram.[5]

Globular Cluster M55

Globular Cluster M55, also known as The Summer Rose Star, was discovered between 1751 and 1752 by Nicolas Louis de Lacaille, a French astronomer, while observing the sky from South Africa since it is difficult to see from the northern hemisphere (Fig. 3).[6] The age of M55 according to a paper that was made last 1997 is 12.5 ± 1.0 Gyr.[7] It is located at about 4.5 kpc from the Sun.[8] It has a declination of $-30^{\circ}57'53.1''$, a right ascension of 19h 39m 59.71s, and it spans a radius of 48 light years. The apparent magnitude is +7.45. For comparison, the apparent magnitude of the Sun is -26.70 and the apparent magnitude of the moon is -12.69 which means that M55 is not very bright in the night sky.[9] M55 houses around 100,000 stars and has a mass that is 269,000 times the mass of the Sun.

Due to the age of the cluster, most of the stars in M55 are old and red. Old stars are red which is an indication that they are cooler. The basis of color temperature measurement started with William Kelvin in 1848 when he heated a block of carbon and noted the color changes as the temperatures increased. Initial colors detected were a slight glowing red that changed to yellow and finally reached blue shade white at its highest heat.[10] Some of the old stars in the cluster deceptively still are blue in color despite being old, these are called blue stragglers. Usually, blue stars can be correlated to young stars. But in the special case of old stars appearing blue, the reason behind this is that the core of the cluster is so dense that there are cases where stars that are both young and old interact and merge. The clusters with blue stragglers tend to be relatively redder than the others and the color red is usually attributed to older age thus reinforcing the old age of M55.[11]

The middle region of the cluster appears to be the brightest since that is where most of the stars reside and there are sprinkles of both red and blue stars surrounding the compact center of the cluster. According to historical accounts by William Herschel, a German-British astronomer, he described the cluster saying, “With 250 fairly resolved into stars; I can count a great many of them, while others are too close to be distinguished separately.”[12] In addition, John Herschel, a British astronomer and William Herschel’s son, gave a more specific description of the M55 cluster in his general catalog stating, “globular cluster; pretty bright; very large; round; very gradually little brighter toward the middle; diameter in RA 30.0s [7.5’]; all resolved into separate stars of 13 to 16 m...”[12]



FIG. 3. View of the globular star cluster Messier 55 in the constellation of Sagittarius. This image was taken in infrared light using the VISTA survey telescope at ESO's Paranal Observatory in Chile. M55 is located at a distance of about 17000 light-years from Earth.[\[12\]](#)

IMPORTANCE OF RESEARCH

In terms of a larger context in the study of the universe, this research provides helpful information in the field of cosmology, specifically in tackling the cosmic age problem. The cosmic age problem is a problem concerning the age of the universe. The problem was that at various times in the 20th century, some objects in the universe were estimated to be older than the age of the universe, as estimated from measurements of the expansion rate of the universe known as the Hubble constant. This would represent a contradiction, since objects such as galaxies, stars and planets could not have existed right after the Big Bang.[13] Although this problem is believed to have been solved, the results from this research reinforces the estimated correct value for the time that has elapsed since the Big Bang.

We can measure the age of the universe through the value of the Hubble constant which tells us how fast the universe is expanding and consequentially indicates that the universe has a finite age. Given the value of the Hubble constant, we can reverse the process of the expansion of the universe and trace back the time of the birth of the universe. However, there is another way to determine the age of the universe and that is to determine the age of the oldest stars in the galaxy. The oldest stars in the universe are mostly contained in globular star clusters like M55 which are used as cosmic clocks.[14] This is because globular clusters formed from giant molecular clouds, or huge masses of gas that form stars as they collapse and because there is less free gas available now than at the beginning of the universe, globular clusters generally cannot form today.[15] Also, when a globular star cluster is observed through a telescope the stars are generally dimmer compared to younger stars like the Sun and most of the stars appear to be red, both indications of the old age of the star cluster. Specifically, when compared to the Sun and other stars of the galactic disk, globular cluster stars appear to be deficient in heavy elements. This indicates that they are ancient objects, made from the pristine gas that condensed to form the galaxy long ago. Although chemical composition differs from one cluster to the next, all stars within a given cluster have similar compositions, indicating that they were born from the same cloud.[16]

In addition to creating an H-R diagram for the globular star cluster M55, the research determines the age of M55 using the H-R diagram created. This piece of information will give context and a lower limit approximation to the age of the universe.[14]

DATA COLLECTION

Filters

Two images of the Globular Star Cluster M55 were taken by the Las Cumbres Observatory using the Bessell B and Bessell V filters. When imaging an object, filters are attached to the telescope to measure the amount of electromagnetic flux incident on a detector at a specific waveband since there is no detector that is completely sensitive in all wavelengths. Each filter will let in different fluxes for an object. The Bessell B filter, B stands for Blue, admits light with a central wavelength of 445 nm and a full width at half maximum of 98 nm since this wavelength range corresponds to its blue color in the electromagnetic spectrum. This means that the image that will be shown using a B filter will mostly be filled with blue-colored stars. On the other hand, the Bessell V filter, V stands for Visual, admits light with a central wavelength of 550 nm and a full width at half maximum of 89 nm since this wavelength corresponds to the yellow color in the electromagnetic spectrum which the human eye is more susceptible to which is why it is called the Visual Color filter. This means that images produced by this filter will show the stars that are yellow. With each filter, the magnitude of the stars can be determined. In fact, the magnitudes of the stars in the Bessell V filter will be obtained and subtracted from the obtained magnitude of stars in the Bessell B filter. Once the subtracted values of the magnitudes of individual stars are determined, this will describe the relative color of the object. This difference in magnitude of the stars in two different filters is the color index. Now, it is possible to plot values since the two components that are needed to create the H-R Diagram, the B-V color index for the x-axis and the magnitude of the stars in the B-V color index for the y-axis have been determined. Table I shows the different filters and the corresponding wavelength that it will detect.

TABLE I. Basic filters of the Johnson-Morgan system.

Symbol	"Color"	Central Wavelength	FWHM
U	Ultraviolet	365 nm	68 nm
B	Blue	445 nm	98 nm
V	Visual	550 nm	89 nm

Signal to Noise Ratio

The images were taken with an exposure time of 100 seconds. It is important to have the right amount of exposure time when taking the images to obtain a clear and quality image of the object. The right exposure time is one that maximizes the Signal to Noise Ratio given by Eq. 1:

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

where

$$A_\epsilon = A\epsilon Q_e \quad (2)$$

The meaning of each variable is shown in Table II. The values of the variables A_ϵ , N_R , i_{DC} , and Ω are dictated by the specification of the Charge Coupled Device, CCD, which is the sensitive detectors of photon that can be used in telescopes to produce images and these values can be seen on the Las Cumbres Observatory website.[17] The value of the variable F_β is usually taken to be $F_\beta = 0.1$ which is ten times the ideal sky background flux since the sky is not always ideal. The variable F depends on the magnitude of the object of interest and several values are shown in Table III. Once the equation for the SNR has been simplified leaving only the exposure time term τ as the unknown, various exposure times are plugged into the equation to determine the exposure time that will maximize the SNR value. However, this does not mean that having a very huge exposure time will always provide a clear cut image of the object because the Charge Couple Device used by the telescope is limited in how many electrons it can store in each pixel during a given exposure before bleeding and ghosting effects start to affect the image quality.

Lastly, Equation 1 is useful when one is exploring multiple values of exposure time and signal to noise ratio and finding a suitable value that will produce a clear image with detectable data. However, finding the exact exposure time given a specific SNR can be obtained using Eq. 3:

$$\tau = \frac{S_N^2 N_T \pm \sqrt{S_N^4 N_T^2 + F^2 A_\epsilon^2 S_N^2 N_R^2}}{2F^2 A_\epsilon^2} \quad (3)$$

where

$$S_N = \frac{S}{N} \quad (4)$$

TABLE II. Variables relevant to signal to noise ratio value

Symbol	Quantity (Units)
N_R	Readout Noise (e^-)
i_{DC}	Dark Current ($\frac{e^-}{s}$)
Q_e	Quantum efficiency (dimensionless)
F	Point Source Signal Flux on Telescope ($\text{photon}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$)
F_β	Background Flux from Sky ($\text{photons}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}\cdot\text{arcsec}^{-2}$)
Ω	Pixel Size (arcsec)
ϵ	Telescope Efficiency (dimensionless)
τ	Exposure Time (s)
A	Telescope Area (cm^2)

TABLE III. Flux values given magnitude of the object

Magnitude	Flux ($\text{photons}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$)
0	3×10^6
5	3×10^4
10	300
15	3
20	0.03
25	3×10^{-4}
30	3×10^{-6}

TABLE IV. Observation Request Sheet

Target Name	Right Ascension	Declination	Filter	No. of Exposures	Exposure Time (s)
M55	19 : 39 : 59.71	-30 : 57 : 53.1	Bessell V	1	100
M55	19 : 39 : 59.71	-30 : 57 : 53.1	Bessell B	1	100

LCO Images

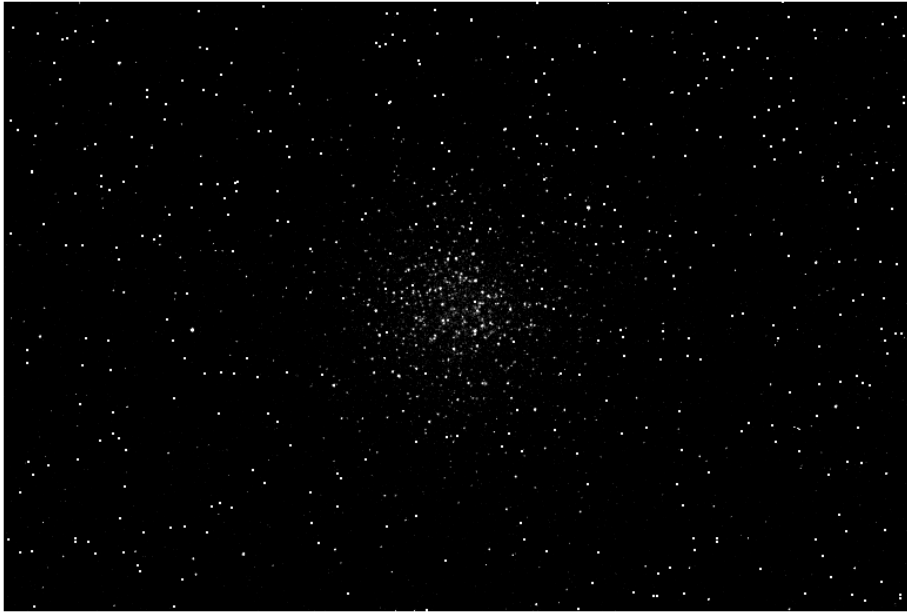


FIG. 4. M55 Bessell B filter with 100s exposure time. Image taken with 0.4m SBIG cameras operated by Las Cumbres Observatory

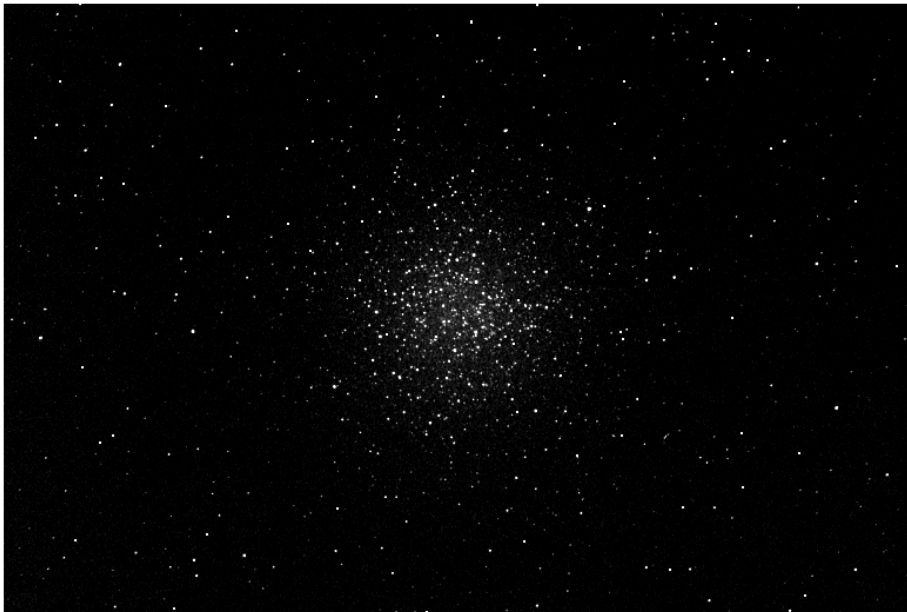


FIG. 5. M55 Bessell V filter with 100s exposure time. Image taken with 0.4m SBIG cameras operated by Las Cumbres Observatory

DATA ANALYSIS

Star Alignment

When the two images are first received, a star with coordinates (x, y) in the B filter will not have the same coordinates (x, y) in the V filter, it will most likely be another star or the black background. Before any stars are detected and analyzed for the purpose of the H-R diagram, the first step is to make sure that the stars in the Bessell B image is in the same position as the stars in the Bessell V image. This is to prepare for an important step in creating the diagram which is subtracting the magnitude of stars in the V filter from the same exact stars in the B filter and not aligning the position of the stars before subtracting will lead to inaccurate results. The magnitude of a star may be subtracted to the magnitude of the black background if not aligned properly. The process in aligning the stars is to determine the average difference in x position and y position, Δx and Δy , of the stars in the Bessell B and Bessell V images and using this value to later on shift the position of stars in the Bessell V image to align with the stars in the Bessell B image before subtraction.

In the M55 Bessell V image, four stars were taken as the calibration stars and their pixel coordinates were obtained using Astroart. Then, in Python, four 20x20 pixel square masks were created, one surrounding each of the four stars so each mask had its own set of coordinates. However, the mask that was created was an inverted mask where only the region inside the 20x20 square pixel would be detected and all the other regions in the Bessell V image would be masked. Then, the DAOSTarfinder source extractor in Python was used for the Bessell V image where the inverted mask was plugged in as a parameter. Combining this with the additional parameter called "brightest" where the value plugged in was four, the DAOSTarfinder was forced to detect only the four calibration stars that were chosen beforehand and give each of its x and y positions in order of brightest to dimmest. The coordinates of the masks that were used for the Bessell V image were not changed and were used on the M55 Bessell B image. The process was repeated to obtain the x and y positions of whichever star was detected in each of the four 20x20 pixel also in order of brightest to dimmest. The differences in the x and y positions of the brightest star detected in the Bessell B and Bessell V were subtracted, same with the second brightest star until the dimmest. Then, these differences were averaged to obtain the Δx and Δy values which were 2.5 pixels.

Source Extraction

After determining the Δx and Δy values which hold the key to the alignment of stars for both images, it is time to detect and analyze the stars seen in the two LCO images. In the end, the source extraction will provide information on the number of stars detected, the brightness of the stars, and the pixel coordinates of the stars.

First, the image needs to be processed using statistics to obtain the background median value of the image. The `SigmaClip()` function was used so that the values of the image that are a certain number of standard deviations, sigma, above the mean are removed from the image because they are stars and must not be part of the processing of the background. Then, the `MedianBackground()` function is used to specify which method of estimating the background the program uses to create the background. Then, the `Background2D()` function is used to create a background for the image whose value is the median value of the image. After the background for the image has been made, the median of the background value was obtained using the `background_median` method applied to the `Background2D()` function.

After obtaining the background median value, the finding of sources can now be started. Sources can be extracted using the `DAOStarfinder()` function. This function has two parameters which are the `fwhm`, which is the full width half maximum of the 'Gaussian kernel' of the starfinder in units of pixels, and `threshold`, which determines at what pixel value the starfinder will call something a source. The lower the values for both parameters, the more sources it will detect but the values cannot be too small since the source extractor will start treating noise as stars. Then, the `find_stars` method was used to print out the positions, magnitudes, flux of the detected stars and the `aperture_photometry` function was used print a table of the aperture sums (photon sums) of sources detected.

One obstacle met during the extraction of sources was that the source extractor was not detecting sources accurately in the Bessell B image. When the apertures were plotted, it can be seen that a lot of obvious bright stars in the image do not have apertures on them which means that it was not detected by the source extractor. To try to solve the problem, the threshold parameters of the `DAOStarfinder()` function was lowered from `4*std` to `3*std`. However, the problem was not solved and very bright obvious stars were still left undetected so a photometry table of the positions and photon sums of these bright stars are not present. The detected sources in the B and V images are shown in Figure 6 and Figure 7.

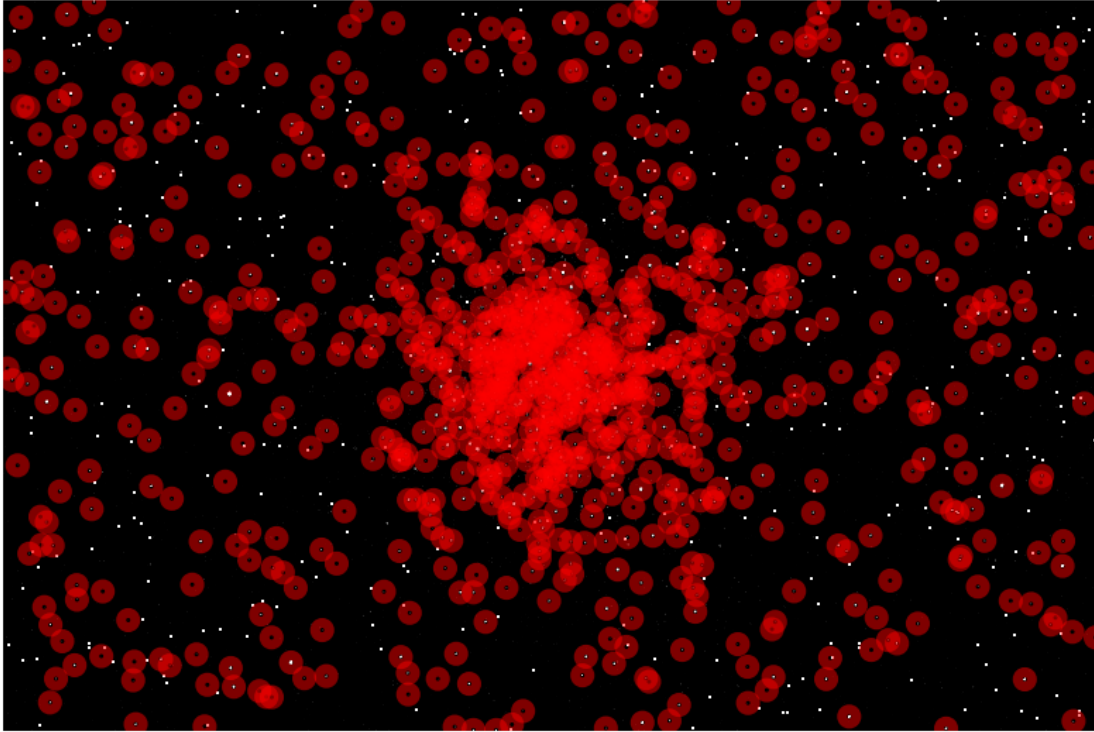


FIG. 6. 1700 sources detected in the M55 Bessell B image provided by the LCO

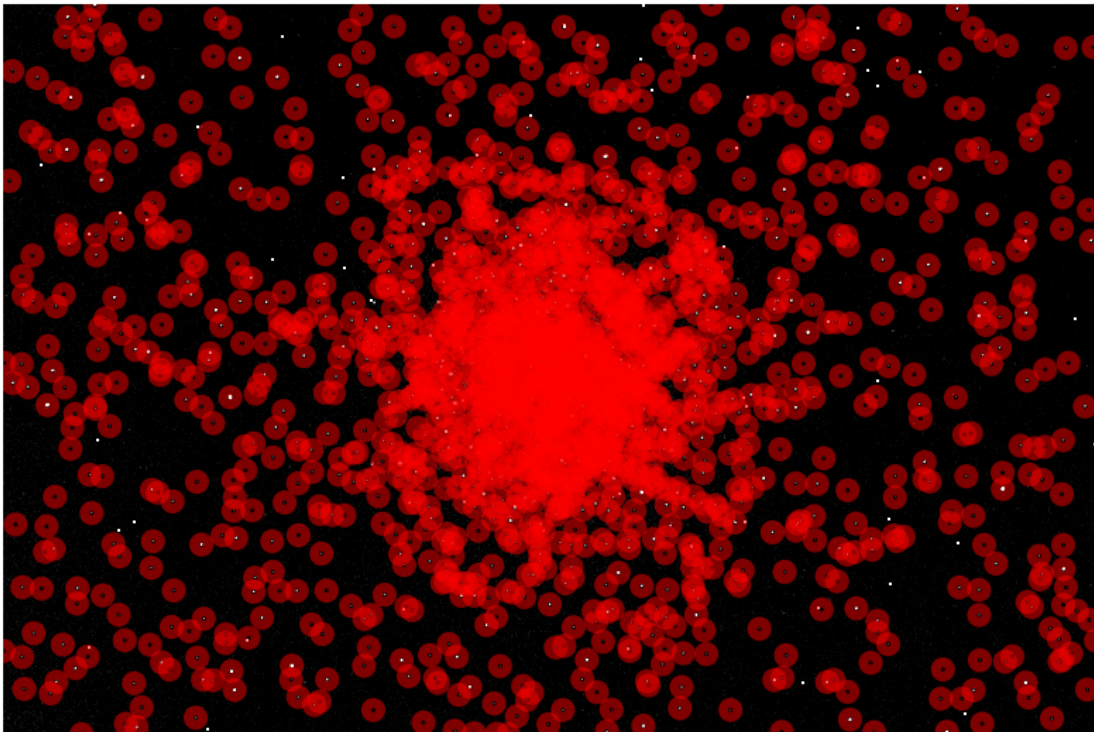


FIG. 7. 3000 sources detected in the M55 Bessell V image provided by the LCO

Plotting

As discussed in the subsection [Star Alignment](#), the stars in the Bessell B and Bessell V images are not aligned so simply subtracting the magnitudes of stars found in the V filter from the B filter will not work. Now that the Δx and Δy values are obtained along with the (x, y) coordinates of stars detected in the B and V filters, the Δx value was added to all of the x position of stars detected in the V filter and the Δy value was added to all of the y position of stars detected in the V filter to. This addition would result in the stars in the Bessell V image to have a new set of (x, y) coordinates and the position of the stars detected in the Bessell B and Bessell V images being aligned. Now, we can start subtracting the magnitude of stars in the Bessell V image from the magnitude of stars in the Bessell B image to get the color index. However before subtracting, it must be made sure that we are subtracting the same exact star on the two images. This was done by subtracting the (x, y) coordinates of every possible pair of stars in the Bessell B and V images using the data provided by the `find_stars` method and checking if the obtained value passes a certain threshold. If the difference in x coordinate of one star in the Bessell B image and one star in the Bessell V image is less than or equal to 1 pixel and also their difference in y coordinate is also less than 1 pixel, then we can assume that they are the same star and we can subtract their magnitudes. Out of the 1700 sources detected in the Bessell B image and the 3000 sources detected in the Bessell V filter, only 481 stars passed the threshold and can be assumed to be the same star in both filters. Thus, we will have 481 stars in the H-R diagram and it is the subtracted magnitudes in the Bessell B and Bessell V filters of these 481 stars that will make up the x-axis of the diagram, which is the B-V color index. The y-axis of the diagram will be the magnitudes of these 481 stars in the Bessell V image which can be obtained by indexing the star in the V image that passed the threshold and then using the index to take the magnitude of that star given by the `find_stars` method table for the Bessell V image. The magnitude of the stars detected in the Bessell V image is given by Eq. 6:

$$m = -2.5 \log \left(\frac{\text{peak density}}{\text{detection threshold}} \right) \quad (5)$$

or

$$m = -2.5 \log_{10}(N_{\text{aperture sum}}) \quad (6)$$

RESULTS

Signal to Noise Ratio

A graph of the SNR over different magnitudes in the B and V band is shown in Figure 8 and Figure 9. Basing from our graph, the good signal to noise ratio is all the way down to $m = 19$.

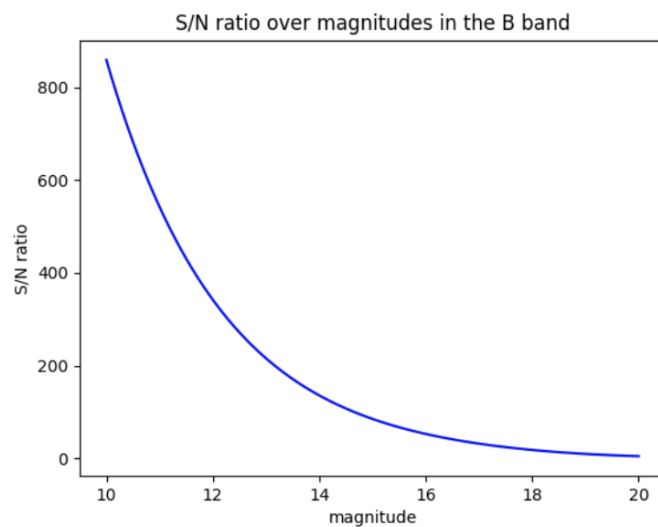


FIG. 8. A graph of the signal to noise ratio and magnitude relationship for the B filter band

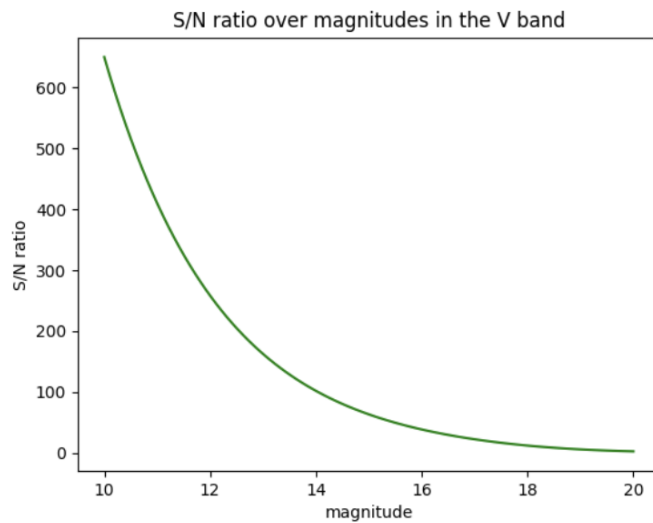


FIG. 9. A graph of the signal to noise ratio and magnitude relationship for the V filter band

H-R Diagram

The resulting H-R diagram is shown in Figure 10. It is important to note that the magnitude of the stars in the V band are not calibrated since we could not find reference stars to compare the magnitudes on SIMBAD astronomical database which may cause the B-V index values to be incorrect. A graph of the actual H-R diagram of M55 from a 1992 paper titled "BVRI CCD photometry of the globular cluster M55 (NGC 6809)" is shown in Figure 11 to be used as a reference for our created HR diagram.[18]. The H-R diagram we have created is not exactly similar to the actual H-R diagram based on the research paper but it slightly mirrors the shape of a small portion of the reference diagram which is the upward bend at around the 0.6 to 0.8 values of the x-axis.

ERROR ANALYSIS

The reason why the value of the mentioned threshold in the subsection Plotting is 1 pixel is due to error propagation. Ideally, for a perfectly aligned star in both images, which is the goal, the threshold is that the difference in x and y coordinates is equal to 0. However, a small room for error is provided to factor in the error that may be propagated from the new coordinates of stars in the V filter. Originally, the (x, y) coordinates of the stars detected in the V filter are very precise, however, the Δx and Δy values that were added is an average of the x and y position difference of the calibration stars. An average is treated as the best value within a certain range of values so there has to be an uncertainty in this average that becomes propagated into the new (x, y) coordinates of the stars in the V filter and then propagated into the obtaining the difference in x and y coordinates of two stars, one in the B and V image, to check if they are the same star. Another possible error may come from the extraction of sources using the DAOSTarfinder() function since there is a possibility that some of the sources being detected is just noise especially since we lowered the threshold to try and detect the bright and obvious stars in the Bessell B image. Lastly, interstellar dust and atmospheric interference may be two factors that would affect the brightness of the stars in the cluster when the image is taken by the telescope and possibly stopping us from getting the true magnitude of the stars.

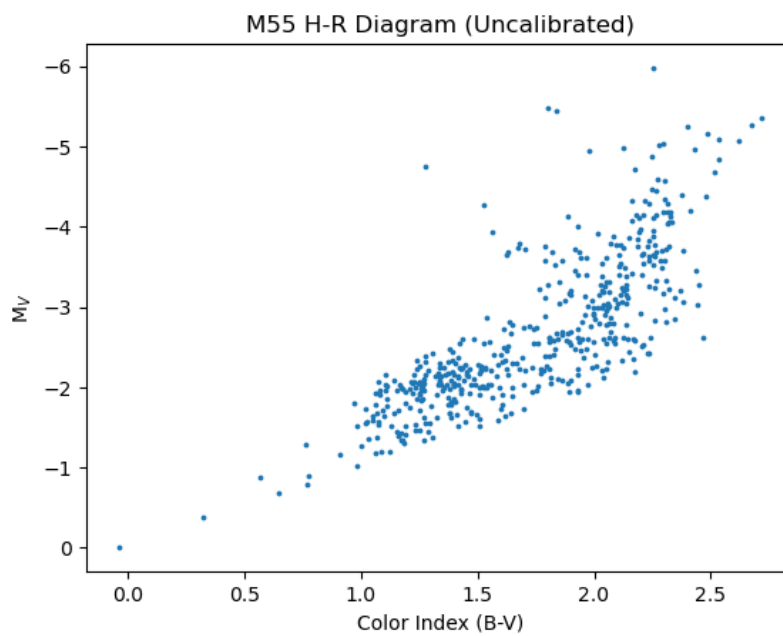


FIG. 10. Resulting H-R diagram of project

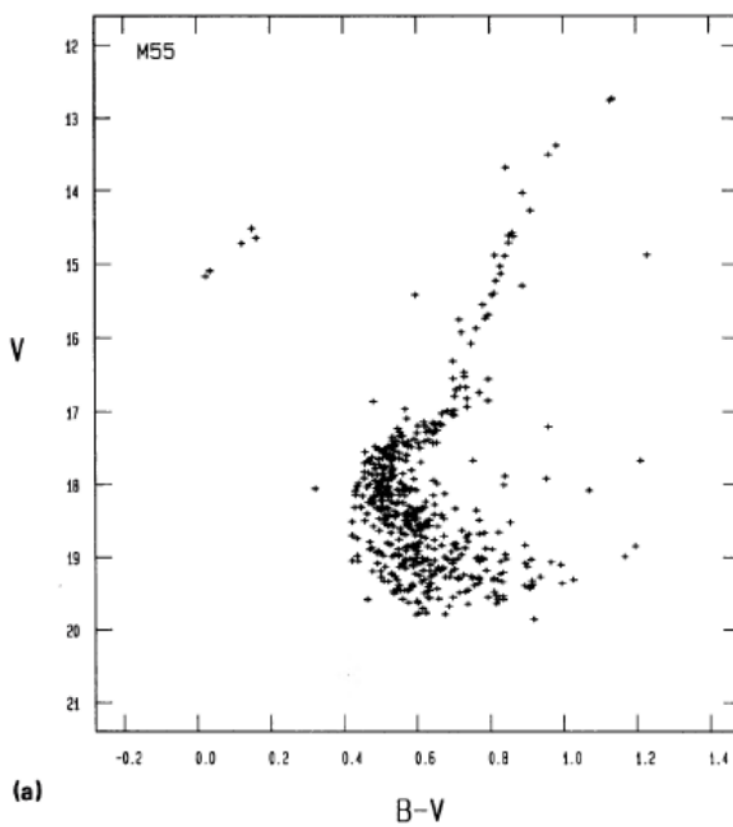


FIG. 11. H-R Diagram from research paper

DISCUSSION

Given that the H-R diagram that we produced is not exactly what we had expected since we were expecting it to look like Figure 11, there is still a silver lining found in our results in which there is a small portion of the plot of the reference H-R diagram which matches the shape of our results. Perhaps if more stars were detected and more stars passed the threshold then it would result to a graph similar to the reference and not just a small portion of it. A possible way for more stars to be detected is by slightly increasing the exposure time that the Bessell B and Bessell V images were taken but we cannot just increase the time to a very high value since we have to factor in noise. If we were to do this project again, we would definitely try to look for another way that the magnitudes of the stars can be calibrated since the method we tried, which was to look at the SIMBAD astronomical database and look for reference stars, did not work. I also wanted to discuss certain difficulties that I encountered along the way. A lot of the crucial steps like looking for reference stars and getting the pixel coordinates of reference stars can be easily done using Astroart and as an OS user, this was clearly a struggle for me since I had no access to Astroart.

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