Hertzsprung-Russell Diagram of Messier 67

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Abstract

The purpose of this lab experiment is to create a Hertzsprung-Russell (HR) diagram of the open cluster Messier 67 (M67) and from it, determine its age. To create an HR diagram of M67, the 48 inch telescope at the Fred Lawrence Whipple Observatory in Arizona is used to take images in multiple filters and exposure times of the open cluster using a charge coupled device (CCD). After performing aperture photometry on the images, the flux from each source is converted to a magnitude and plotted versus the color of each source. The HR diagram can be used to measure the age of the cluster because open clusters are well-calibrated, meaning all of the stars were created at the same time. Since more massive stars do not live as long as lower mass stars, as time goes on, the HR diagram becomes truncated to lower and lower mass stars. This point, called the main sequence turnoff, can be used to determine the age of the cluster. In this experiment, isochrones are manually fit to the data to determine which isochrone best matches the main sequence turnoff. From the results, M67 is approximately 4.17 billion years old.

1 Introduction

Open clusters are loosely-gravitationally-bound groups of hundreds to a few thousand stars.[7] Since the stars are not closely bound by gravity, open clusters usually survive for only a few hundred million years, but there are exceptions.[7] The stars in open clusters are all formed from the same molecular cloud meaning open clusters contain stars that are all similar in age, chemical makeup and approximate distance to the Sun, but there are a range of masses.[7]. Due to the characteristics of an open cluster, the main sequence lifetime of the most recent stars to leave the main sequence are an indication of the cluster's age. Open clusters are also important in astronomy because they can be used to study the formation and evolution of stars, the interactions between stars and the structure and evolution of the disk of the Milky Way.[6]

The main sequence on an HR diagram is the band of stars that are powered by the nuclear fusion of hydrogen in their cores. The fusion of hydrogen to form helium creates an outward pressure that counters the force of gravity, supporting the star. Around 90 percent of the stars in the Universe are main sequence stars, including the Sun.[11] The Sun's main sequence lifetime is estimated to be 10 billion years.[11] But more massive stars will have a shorter lifetime, while less massive stars will spend more time on the main sequence. Although larger mass stars may have larger fuel reserves, they must fuse the hydrogen faster than lower mass stars in order to stabilize themselves against the greater inward force of gravity.[11] Once stars run out of hydrogen to fuse, they begin to move off the main sequence and many become red giants, which compose the red giant branch of the Hertzsprung-Russell diagram.

The lifetime of a main sequence star is dependent on its mass. An isochrone is a curve that plots the predicted locations of stars, which were all created simultaneously, as a function of mass. In this experiment, the isochrone plots absolute magnitude versus mass. By plotting isochrones with different ages overlaid on the data, it can be manually determined which appears to be the best fit. This method can be used to determine the age of an open star cluster; in this case, M67.

2 Observations and Analysis

2.1 Telescope

The telescope is a 48 inch reflector, imaging optical telescope located at the Fred Lawrence Whipple Observatory on Mount Hopkins in Amado, Arizona. Keplercam, the CCD, is a single-chip CCD with a Fairchild CCD 486 detector. It produces images that are 4096 x 4096 pixels and the chip saturates at around 65,000 counts per pixel.[3] Each pixel is 15 μ m x 15 μ m. The CCD has 100% fill factor and a readout noise of less than 5 e^- at 50k pixles per second.[4] The primary mirror is a honeycomb, borosilicate mirror.[9] The focal length is 369.7011 inches and the focal ratio is 7.7021.[2]

2.2 Coordinate System

The coordinate system that is used to point the telescope is the equatorial coordinate system. Coordinates are specified using right ascension (α) and declination (δ). Right ascension is measured in hours along the celestial equator, which is a projection of the Earth's equator onto the celestial sphere. There are 24 hours in total and one hour is equal to 15°. On the Vernal Equinox, 0^{h} right ascension points towards the Sun in the Northern Hemisphere. Declination is measured in degrees from the celestial equator. Declination ranges from δ = -90°to δ = 90°. The current epoch is J2000.0.

2.3 Conditions

The observations were taken on March 20, 2019 beginning at 03:29:48 UT. It was cloudy at the start of observing so the first two images are poor due to cloud cover. The clouds began to clear so the remaining images are usable. The airmass was 1.06. Observing was done on the night before the full moon so the sky was too bright to see fainter sources.

2.4 Filters

The filters used for observing are the V, B and R filters. The V, which stands for visible, lets through light with the frequency in the green part of the spectrum. The B filter allows blue frequencies of light to pass through and the R filter allows red frequencies of light to pass through. Multiple filters are used to observe the cluster because the difference in a source's magnitude as measured in two different filters is an indication of the color of the source.

2.5 Target and Imaging

M67 is located at $\alpha = 08 : 51 : 18$, $\delta = +11 : 48 : 00$. It is an open cluster that is 800-900 parsecs away, or approximately 2700 light years. Sixteen images are taken of M67. Seven images are taken in the V filter, five images are taken in the B filter and four images are taken in the R filter. Exposure times range from two seconds to five minutes. The brightest stars are saturated in the five second images, but multiple exposure times are necessary for photometry to be done on stars of varying brightness.

Image	Filter	Exposure Time (sec)
0135	V	5
0136	V	5
0137	V	5
0138	V	2
0139	V	30
0140	V	120
0141	V	300
0142	B	5
0143	B	2
0144	B	30
0145	B	120
0146	B	300
0147	R	5
0148	R	30
0149	R	120
0150	R	300

Table 1: Observing log of M67 on March 20, 2019. Sixteen total images are taken in the V, B and R filters with varying exposure times.

2.6 Data Reduction

Data reduction is performed on the raw science images using flat-fields and biases. Flat-fields are images that are taken with a uniform illumination in order to measure the imperfections that appear in every image. On the inside of the dome of the of the 48 inch telescope at the Whipple Observatory, there is a large area that is painted white in order to take flat-fields. Flat-fields are taken in the V, B and R filters. A bias is an image that is taken with zero exposure time to measure the noise of the CCD. Biases are taken in the V, B and R filters. The first step in the data reduction process is to create a

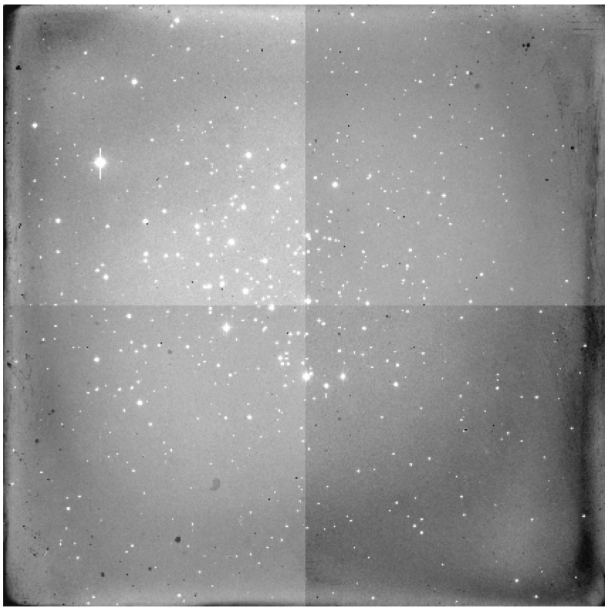

Figure 1: Raw science image #0148 of M67 taken in the R filter with an exposure time of 30 seconds.

combined bias image for each filter. Then a combined flat-field image is created for each filter and the bias is subtracted from the flat-field to remove the noise. The combined flat-fields are then normalized by dividing each by the median value of one of the original flat-fields in the respective filters. Finally, the science images are corrected by subtracting the combined bias from each image and then dividing by the combined flat-field, all in the respective filters. This process refines the raw science images by removing any existing detectable imperfections and noise due to the telescope and CCD.

Figure 2: Corrected image #0148 of M67 taken in the R filter with an exposure time of 30 seconds.

2.7 Adjusting the Images

Three adjustments are made to the corrected images before photometry is done. The Keplercam CCD creates mosaic images, meaning each image is comprised of four separate quadrants that create the full image. These four quadrants are stitched together and compiled into one image. Each full image is also shifted slightly compared to all of the other images. The images must be exactly aligned so that all of the sources in each image are located at the same physical coordinates. Third, each image is cropped to the same dimensions to eliminate the fringing on the edges that may by falsely identified as stellar sources.

2.8 Photometry

Photometry is done using the "photutils" package in python. One image from each filter, all with the same exposure time, is used. For one of the images, "DAOStarFinder" is used to find all of the sources with a count-threshold above three times the standard deviation of the image. These sources are then applied to the images in the other two filters so that the x and y coordinates of each numbered source are consistent for all three images. The function "CircularAperture" is used to place an aperture around each source whose size (r) is 2.5 times the full width at half maximum (FWHM) of each image. The function "CircularAnnulus" is used to place an annulus around each source whose inner radius (r_{in}) is three times the FWHM and whose outer radius (r_{out}) is five times the FWHM of each image. The function "aperture_photometry" is used on both the apertures and annuli at each source in all three images. The photometry done within the apertures calculates the sum of the counts of the source inside each aperture. The photometry done within the annuli calculates the sum of the counts of the sky background surrounding each source.

2.9 Magnitudes

Performing photometry calculates the sum of the counts from each source aperture (sum_{ap}) and the sum of the counts from each sky annulus (sum_{an}) in all three images. The number of counts per pixel of the sky ($msky$) for each annulus are calculated using:

$$msky_v = \frac{sum_{an,v}}{\pi(r_{out,v}^2 - r_{in,v}^2)}. \tag{1}$$

The flux ($flux$) of each source is then calculated by subtracting the total counts due to the sky from the sum of the counts calculated in the aperture.

$$flux_v = sum_{ap,v} - (\pi r_v^2)(msky_v) \tag{2}$$

The calculated fluxes are converted to magnitudes (m_1) using the zero-point magnitude ($zmag$) and the exposure time ($itime$). The zero-point magnitude, also known as the photometric zero point, is the magnitude of a source that produce one DN per second.[1] Since the zero-point can only be calculated using standard stars with known magnitudes in each filter, it is arbitrarily set to zero in the first magnitude calculations.

$$m_{v,1} = -2.5 * \log(flux_v) + 2.5 * \log(itime_v) \tag{3}$$

After the initial magnitude calculations, the zero-points for the V filter ($zmag_v$), B filter ($zmag_b$) and R filter ($zmag_r$) are found using the difference between the known magnitudes ($v(k)$ and the measured magnitudes for each standard star (k).

$$zmag_v = \frac{[v(1) - m_{v,1}(1)] + [v(2) - m_{v,1}(2)]}{2} \tag{4}$$

The following magnitudes are calculated for two standard stars using the NOMAD optical catalog. These standard stars are used to calibrate the magnitude calculations from the observed sources.

Standard Star (k)	Known Magnitude V Filter ($v(k)$)	Known Magnitude B Filter ($b(k)$)	Known Magnitude R Filter($r(k)$)
1	10.076	10.030	10.110
2	10.676	11.491	10.160

Table 2: The known magnitudes for four stars in the V, B and R filters, obtained using the NOMAD optical catalog.

The calculated magnitudes are lower than the actual magnitudes by about 21 magnitudes.

Standard Star (k)	Calculated Magnitude V Filter ($m_{v,1}(k)$)	Calculated Magnitude B Filter ($m_{b,1}(k)$)	Calculated Magnitude R Filter($m_{r,1}(k)$)
1	-11.74	-11.65	-12.17
2	11.02	-9.91	11.98

Table 3: The calculated magnitudes for the same four stars in the V, B and R filters in a five second exposure, obtained using Equation 3.

Equation 4 gives the following zero-point magnitudes in each filter:

Exposure Time (sec)	Zero-point V Filter ($zmag_v$)	Zero-point B Filter ($zmag_b$)	Zero-point R Filter($zmag_r$)
5	21.757	21.544	22.210

Table 4: The calculated zero-point magnitudes in the V, B and R filters for a five second exposure, obtained using Equation 4.

The initially calculated magnitudes are calibrated using the zero-point magnitudes in Table 4. The result is the calculated apparent magnitude (m) of each of the sources in the three images:

$$m_v = zmag_v - 2.5 * \log(flux_v) + 2.5 * \log(itime) \tag{5}$$

The apparent magnitude is a measure of how bright the star is seen from Earth; it is not a measure of its intrinsic luminosity. In astronomy, magnitudes are measured on a logarithmic scale with a lower number corresponding to a higher brightness.

	V Filter	B Filter	R Filter
Minimum m	8.193	8.805	8.151
Maximum m	16.912	16.997	16.987

Table 5: The minimum and maximum apparent magnitudes of sources in the V, B and R filters.

The apparent magnitudes are converted into absolute magnitudes, which are a measure of how bright each star is intrinsically. To calculate absolute magnitudes, the distance to M67 is approximated as $d \approx 2700$ light years or $\approx$ 827.8238 parsecs. The approximation for the distance comes with some uncertainty, because the exact distance cannot be measured precisely. Absolute magnitude (M) is calculated using:

$$M = m_v - 5 * \log\left(\frac{d[pc]}{10[pc]}\right) \tag{6}$$

The absolute magnitude is dependent on the apparent magnitude and the log of the distance, so the uncertainty in these two factors is propagated to the absolute magnitudes. When plotting the absolute magnitude in the HR diagram, the error bars do not take this into account because the uncertainty in the distance is outside of the scope of this paper. Since absolute magnitude is measured as observing the star from a distance of 10 parsecs rather than the actual distance to M67 ($\approx$ 827.8238 parsecs), the absolute magnitudes are brighter (lower) than the apparent magnitudes.

	V Filter	B Filter	R Filter
Minimum M	-1.396	-0.784	-1.439
Maximum M	7.322	7.408	7.398

Table 6: The minimum and maximum absolute magnitudes of sources in the V, B and R filters.

2.10 Color

The color of a source is calculated by subtracting its apparent magnitude in one filter from its apparent magnitude in another filter. The color used in this paper is $B - V$:

$$B - V = m_b - m_v \tag{7}$$

Since a lower magnitude corresponds to a greater brightness, a more positive $B - V$ color means that the star is brighter in the V filter than in the B filter, so the star emits more in the green frequency of the electromagnetic spectrum. A more negative $B - V$ color means that the star is brighter in the B filter than the V filter, so the star emits more in the blue frequency of the electromagnetic spectrum. The maximum calculated $B - V$ value is 1.85 and the minimum $B - V$ value is -1.93. There is a higher degree of uncertainty in the color calculation because color is a combination of two apparent magnitudes. In this case, the uncertainty from both m_b and m_v must be propagated through.

3 Results

3.1 HR Diagram

An HR diagram for M67 is created by plotting the apparent magnitude in the V filter versus color for each of the sources in the cluster (Figure 4). The value of the apparent magnitude is decreasing up the y axis because the lower magnitudes indicate brighter stars. The magnitude error for each source is higher for larger magnitudes, or fainter stars. The HR diagram created from the data looks similar to the documented HR diagram of M67, which was created in 1955 and published in Astrophysical Journal.[5]

An HR diagram is also created using the calculated absolute magnitudes in the V filter (Figure 5). The absolute magnitude versus color graph is used to calculate the main sequence turnoff. The error bars are identical to the ones plotted for the apparent magnitudes because the uncertainty in the distance, which is used to calculate absolute magnitude, cannot be obtained.

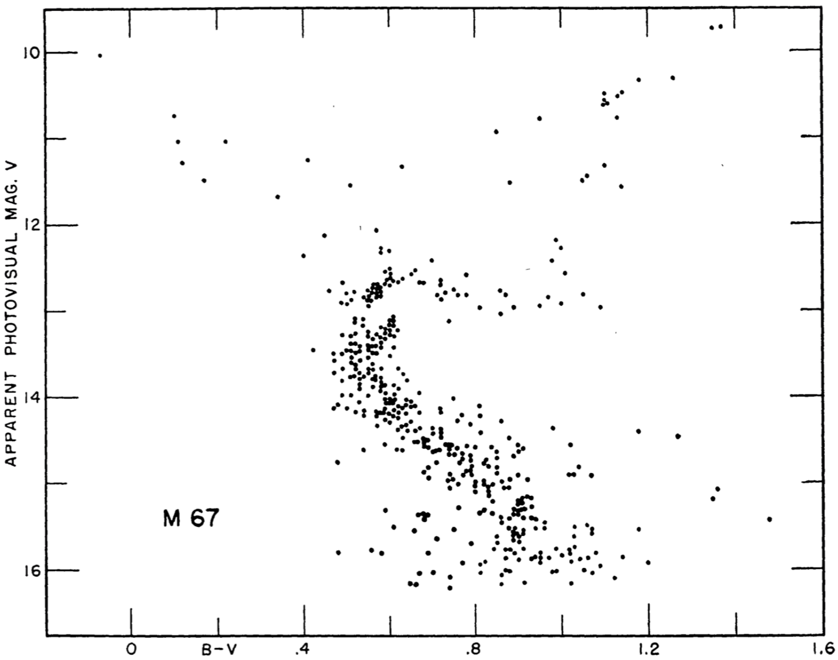

FIG. 3.—The color-magnitude diagram for M67

Figure 3: Hertzsprung-Russell Diagram of M67 plotting the apparent magnitude in the V filter versus the $B - V$ color. Created in 1955 by Harold L. Johnson and Allan R. Sandage. Their results were published in the Astrophysical Journal.

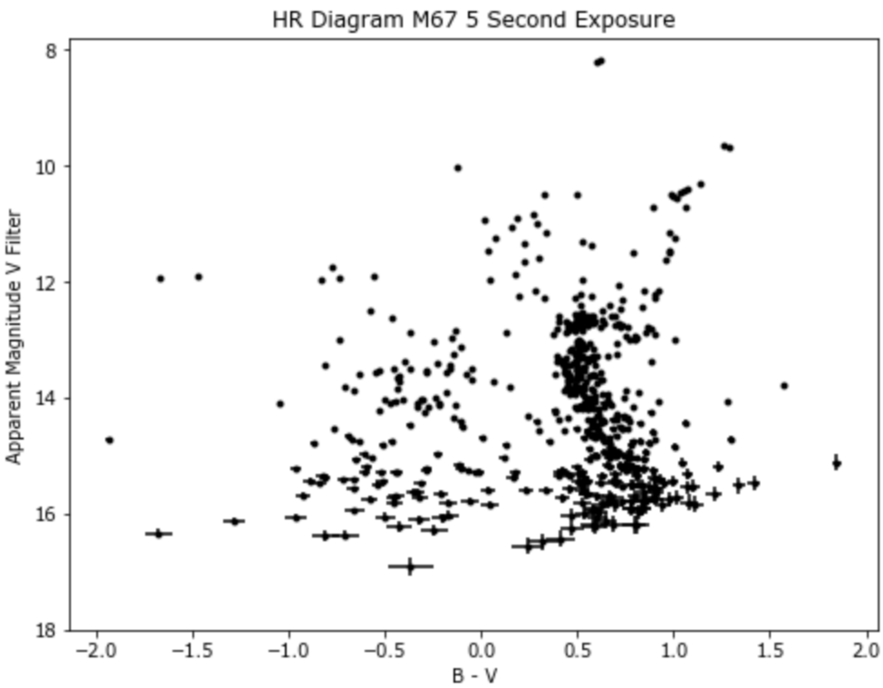

Figure 4: Scatter plot of the apparent magnitude vs. color of M67 for five second exposures in the B and V filters. The plot color is centered near 0.6 and the apparent magnitude ranges from 16.912 to 8.193.

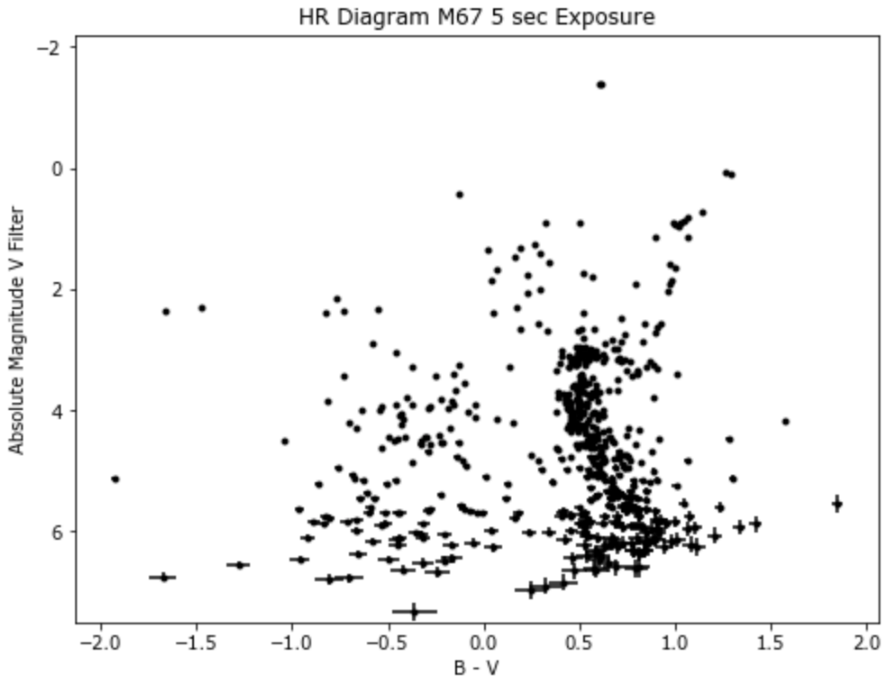

Figure 5: Scatter plot of the absolute magnitude vs. color of M67 for five second exposures in the B and V filters. The plot color is centered near 0.6 and the absolute magnitude ranges from 7.322 to -1.396.

3.2 Age

The main sequence turnoff is where the cluster's HR diagram begins to deviate from the main sequence. Since the stars in an open cluster were all born at approximately the same time, making them all very close in age, the stars that are just deviating from the main sequence are an indication of the age of the cluster. This characteristic of open clusters means that isochrones can be fit to the Hertzsrpung-Russell diagram to determine the age of the cluster. An isochrone is a curve that plots the predicted locations of stars of varying masses given a specified time.[10] In this case, the isochrone predicts the absolute magnitude for each mass. For this experiment, the isochrones are fit by hand. The documented range of ages of M67 is 3.2 Gyr to 5 Gyr.[8]

The isochrone with an age of 3.2 Gyr fits the data well on the main sequence, but once the stars begin to leave the main sequence the isochrone is not the best fit. The isochrone's main sequence turnoff appears to be slightly higher than the actual main sequence turnoff, meaning 3.2 Gyr is an underestimate for the age of the data of M67.

On the other end of the spectrum, the isochrone plotting stars that are 5 Gyr old also fits the main sequence stars well, but deviates from the data the closer the mass of the stars is to the main sequence turnoff. Contrary to the 3.2 Gyr isochrone, the 5 Gyr isochrone shows a main sequence turnoff that is slightly lower than the data, meaning it is an overestimate for the age of M67.

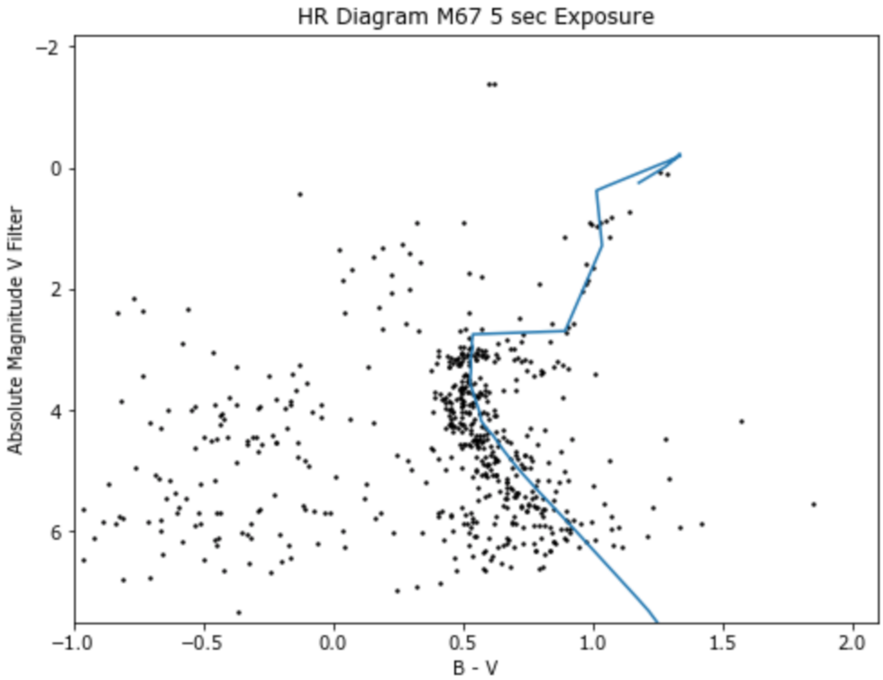

Figure 6: HR Diagram with an isochrone plotted showing the predicted absolute magnitudes of stars with an age of ≈ 3.2 Gyr, which is the low end of the range of documented ages for M67.

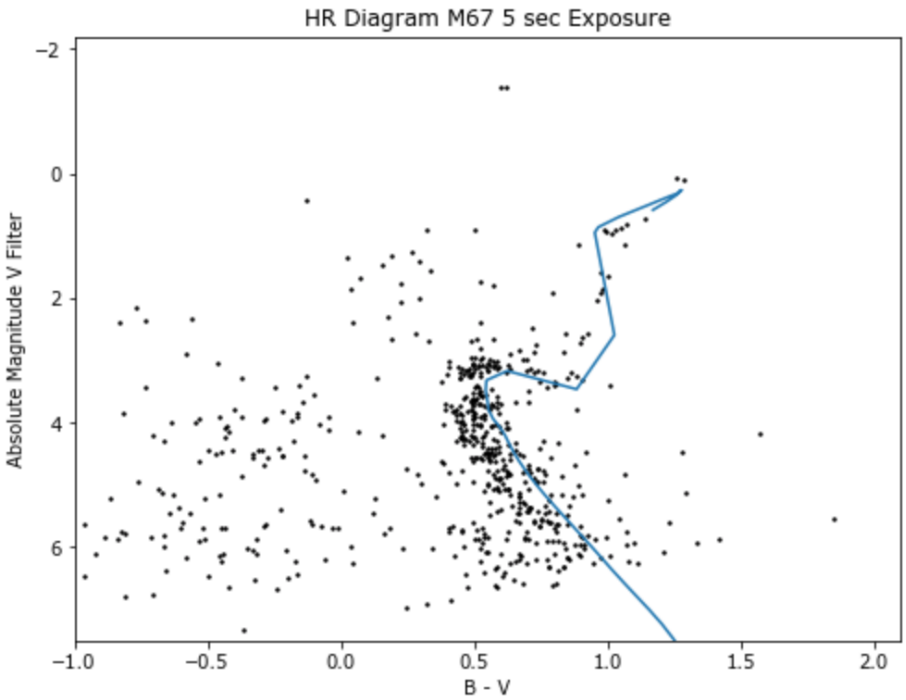

Figure 7: HR Diagram with an isochrone plotted showing the predicted absolute magnitudes of stars with an age of ≈ 5 Gyr, which is the high end of the range of documented ages for M67.

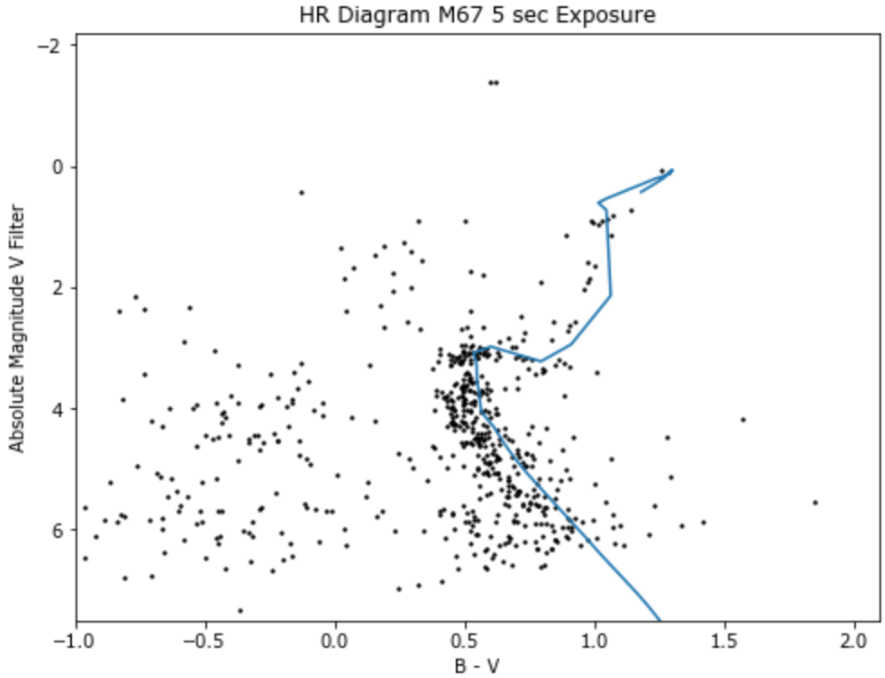

Figure 8: HR Diagram with an isochrone plotted showing the predicted absolute magnitudes of stars with an age of ≈ 4.17 Gyr. The main sequence turnoff of the isochrone matches the data well. The main sequence turnoff is at approximately $M_v = 3.2$

By manually fitting isochrones between 3.2 Gyr and 5 Gyr, the best fit is determined to be a isochrone that plots the predicted absolute magnitudes for stars that are ≈ 4.17 Gyr old. The main sequence stars follow the path of the isochrone, and most importantly, the main sequence turnoff matches what the isochrone predicts. Looking at the data and the isochrone, the absolute magnitude of the main sequence turnoff is $M_v \approx 3.2$

4 Discussion

In this experiment, data is gathered by taking optical images of the M67 open star cluster in the V, B and R filters over multiple exposure times. Data reduction is performed on every image by subtracting the bias frame and dividing by the flat frame. Photometery is done on the corrected images of the same exposure times in each filter to get the counts from each star source. After correcting for the background, the flux from each star is converted to a magnitude in each filter. Using the difference between the B and V magnitudes as a measure of color, the apparent and absolute magnitudes of each source in the V filter is plotted versus the color to create HR diagrams of M67 (Figure 4 and Figure 5). By manually comparing the HR diagram to isochrones that plot the predicted absolute magnitudes for stars of varying masses (Figure 6, Figure 7 and Figure 8) , the best-fit isochrone is determined.

The method used creates uncertainties in the measurements. Although the data is representative of former HR diagrams constructed for M67, not all of the features are completely distinguishable. One factor that contributes to this is the stars that lie along the line of sight to M67 but are not part of the open cluster. The magnitudes, distances and ages of these stars are not correlated with those of the stars in M67, but they are still counted as sources because it is not possible to precisely distinguish these stars from the rest. The data collected is also not ideal due to the observing conditions (Section 2.3). The two second exposures have the least number of saturated stars, but the fainter stars in the cluster are not bright enough in the shorter exposures to be detected above the background noise. When the exposure time is lengthened to five seconds and above, many stars become saturated which may cause error in the photometry. For this reason, only the five second exposures are used when constructing an HR diagram. The sources that are detected but have an apparent magnitude of less than 17 skew the data and are disregarded because it cannot be determined with confidence whether they are very faint stars or just background noise. Furthermore, human error may influence the results. Subjectivity is introduced when manually fitting an isochrone to the data.

The error bars on the HR diagrams (Figure 4 and Figure 5) are calculated using the uncertainty in the apparent magnitudes (Equation 7). The uncertainty in the color is propagated from both the apparent magnitudes in the V and the B filters. The uncertainty in the absolute magnitude is due to its dependence on the apparent magnitude and the distance to M67 (Equation 6). The error bars for the absolute magnitudes are only representative of the uncertainty from the apparent magnitudes in the V filter because the uncertainty in the distance cannot be calculated from the methods used in this experiment.

Even with the uncertainties present in the experiment, the HR diagram that is created resembles a common HR diagram. The red giant branch is prominent and there is a clear main sequence turnoff at $M_v \approx 3.2$ (Figure 8). In the five second exposure in the V filter 585 sources are found to be above the noise. This gives a rough estimate for the number of stars in the open cluster. It is an overestimate though due to the extraneous stars along the line of sight. An isochrone is able to be manually fit to the data which closely resembles the HR diagram and includes the most prominent and important features, including the main sequence turnoff at approximately $M_v = 3.2$. Since stars of this brightness are just about to leave the main sequence, their lifetime is an indication of how old the entire cluster of stars is. Using isochrones, the age of M67 is measured to be approximately 4.17 Gyr, which is within the accepted range of 3.2 Gyr to 5 Gyr that has been determined by multiple sources.[8]

5 Conclusion

The purpose of was experiment is to take optical images of the open star cluster Messier 67 in the V, B and R filters in multiple exposure times and use the data to create a Hertzsprung-Russell diagram of the cluster. After reducing the raw science images using bias and flat frames, performing photometry on the images to determine the flux from each source, converting the fluxes to magnitudes and plotting them versus color, the objective was achieved. A Hertzsprung-Russell diagram was created (Figure 5), showing the two prominent features of an HR diagram: the red giant branch and the main sequence turnoff. The main sequence turnoff of Messier 67 is approximately at an absolute magnitude of 3.2 (Figure 8). The accepted age of Messier 67 is between 3.2 and 5 billion years.[8] Using isochrones to manually fit a curve to the data, the age of Messier 67 is calculated to be 4.17 billion years.

References

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