Measuring the age of Globular Cluster M15 using a Colour-Magnitude Diagram to make an estimate for the age of the Milky Way

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This report displays a colour-magnitude diagram (CMD) of (B-V) vs V of the globular cluster M15 otherwise known as NGC 7078. The observations were made by the Las Cumbres observatory using a Spectral, 2-meter telescope with a field of 10’ × 10’. With the determined location of the main sequence turnoff, an estimate for the age of the cluster was found. The measured age of M15 from this study is $13.013 \pm 0.355\ Gyrs$. The inferred estimate of the Milky Way based on the upper limit of GC age is $13.4 \pm 0.1\ Gyrs$.

Introduction

Globular clusters are star clusters usually observed with a spherical shape where the density of stars decreases with increasing radius. Their dense centres may be a result of a process called core collapse, caused by more massive stars meeting their companions resulting in migration from the centre out. Globular clusters are usually found in close orbit to galactic cores and are most importantly measured to be some of the oldest astronomical objects in existence.

This report focuses on the well studied globular cluster M15 found in the constellation Pegasus (conveniently placed below the galactic plane), otherwise named NGC 7078. Having the target below the galactic plane makes observations easier as it reduces saturation from background light. M15 can be seen with the naked eye despite a distance of 33,600 light years from Earth as it holds an absolute magnitude of -9.2. (The brightness of 360,000 suns) [8]

Globular clusters are widely studied yet not fully understood; especially where they come from. GC’s are common objects among galaxies and only form with the birth of their galactic home. It is generally assumed that all the stars within the cluster form at around the same time. Therefore, when plotted on a Hertzsprung-Russel diagram the data has a candlestick like effect over time.

The current understanding is that GC’s formed during the early universe around the time of reionization (one billion years after the Big Bang) which is the second of two major phase transitions of gas. [2] GC’s are known for having poor metallicity levels, due to their age. This makes sense because the early Universe had a low abundance of heavy elements due to the small number of stars undergoing nuclear fusion. Due to the nature of a GC’s origin their age relates strongly to the age of the galaxies they sit in. GC’s have been measured in other galaxies due to their brightness, allowing for age measurements to be taken over a large survey of GC’s and therefore, age estimates for the Universe. However, studies of GC’s in galaxies beyond the local group tend to be biased towards brighter (more massive) clusters [1]; so, one cannot not be completely sure on the accuracy of these measurements.

My hypothesis is that the age of M15 measured in this study can be used to infer an estimate for the age of the Milky Way. This is justified by the nature of GC’s and how they form near the beginning of a galaxy's life not any later. To investigate my hypothesis, this report estimates the age by plotting a colour-magnitude diagram (CMD) of M15. Using the CMD, the main sequence turn-off can be located. The mass of the stars remaining at the turn-off can be used to calculate their main sequence lifetime and therefore the age of the whole cluster. The CMD data will be compared to a previous study (Scilla Degl'Innocenti's paper 'Age of the oldest Globular Clusters') to weigh up the similarity of the turn-off location.

Procedure

Messier-15 was observed by the Haleakala observatory using a 2-m telescope in the B and V spectral band widths. Observation date, 2019-12-09 (y/m/d), UTC-10 at elevation: 3055m. The observation sought to make observations of the globular cluster M15 to extract isophotal magnitudes in both filters; exposure time of 60 seconds each. Further details on the telescope can be found via the Las Cumbres Observatory website under 'sites and instruments'.

Reduced data was extracted from the observation archive within the LCO website. There were sixteen total files; eight for each filter. The files were transfered into a linux based operating system into two main directories for each filter, 'B-filter' and 'V-filter' respectively. The image files are then formatted for stacking. Stacking greatly increases the removal of noise as there is a reduction in the differences in the digital representation of light that hits and excites the camera sensor. [3] Before stacking can start, two star link commands need to be initialized, 'kappa', and 'convert' for formatting and to allow photometry software to understand the files. The final command 'wcsmosaic' was then used to stack the images. Final results of the two filters can be seen in fig 1.

During the stacking for this study, it became evident that there was an observation issue with the B-filter images. Individually the images are satisfactory, however, when stacked the image of the cluster becomes unusable for measurements as it creates an almost woozy effect (seen in figure 1). The decision was made not to stack the B-filter images and only use the best out of the eight images. This will reduce the quality of measurements but should not greatly scrutinise the final outcome of the investigation.

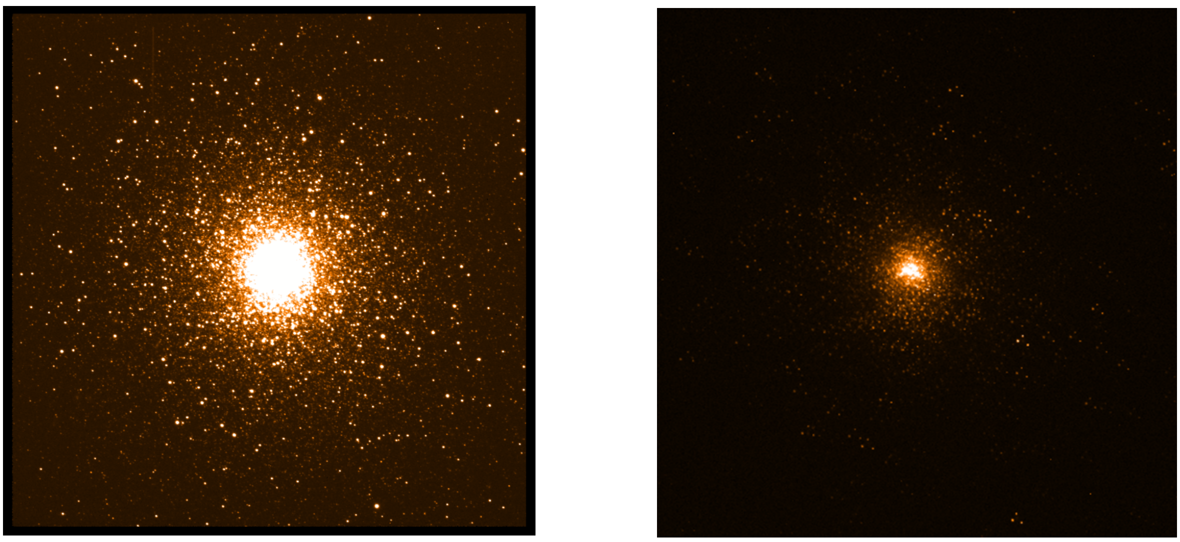

Figure 1 - Stacked V-filter image (left), stacked B-filter image (right)

Starlink GAIA::Skycat was the software used to display the stacked images, calibrate and perform photometry throughout this study. This was the main reason for importing the images into Linux as the software used is not available in other operating systems.

$$m_{apparent} = m_{instrument} + Z + kX \quad (1)$$

Equation (1) was used to identify the zero point, where k is the atmospheric extinction coefficient and X is the air mass. Therefore, to calibrate the images the apparent and instrumental magnitude had to be measured. The SIMBAD via ESO database was used to identify known standard stars within the FOV of the image. Once a catalogue of objects was created a standard star was selected with known RA, DEC and apparent magnitude.

$$m_{instrument} = -2.5log_{10}(N_{star+sky} - N_{sky}) \quad (2)$$

Equation (2) was used to calculate the instrumental magnitude, the second variable needed to find the zero point. Equation (2) contains $N_{star+sky} - N_{sky}$ which is known as the sum aperture. This takes the total counts of the star and the sky and subtracts the sky count; identifying the star count. GAIA calculates the sum aperture after performing manual aperture photometry on a bright star in the cluster image.

Eventually a zero point was calculated using equation (1), Z = 28.523 ± 1.403. Error values were provided by the software used. Apparent magnitude error was equipped with the SIMBAD database for each filter. Instrumental magnitude was calculated within the photometry tool. These errors were carried through equations (1) and (2) to produce a final error for the zero point. The final values for both magnitudes can be found in fig 2.

The zero point is required in the automated detection. 'Automated object detection' is a tool within the GAIA software and was utilised in this study to resolve data for the CMD. After the correct magnitudes are requested the tool automates the detection of objects in the image; providing the required data for this investigation. It is especially important to provide 'X_WORLD' and 'Y_WORLD' coordinates in order to match data between the two filters.

TOPCAT was the catalogue software used to match the data tables of both filters into one master catalogue. The catalogue was then exported to my native operating system using the WinSCP software and transferred into a Microsoft Excel spreadsheet. It was then edited down to the B and V isophotal magnitudes along with a calculated colour index column. The table was then read and plotted in Python using the Numpy and Matplotlib libraries to produce the final CMD.

	Mv	Mb	M(instrument)	Zero-point
V-filter	13.21 ± 0.01	n/a	-15.313 ± 1.403	28.523 ± 1.403
B-filter	n/a	14.35 ± 0.02	-14.087 ± 2.110	28.437 ± 2.110

Figure 2 - Apparent and instrumental magnitudes found for each filter

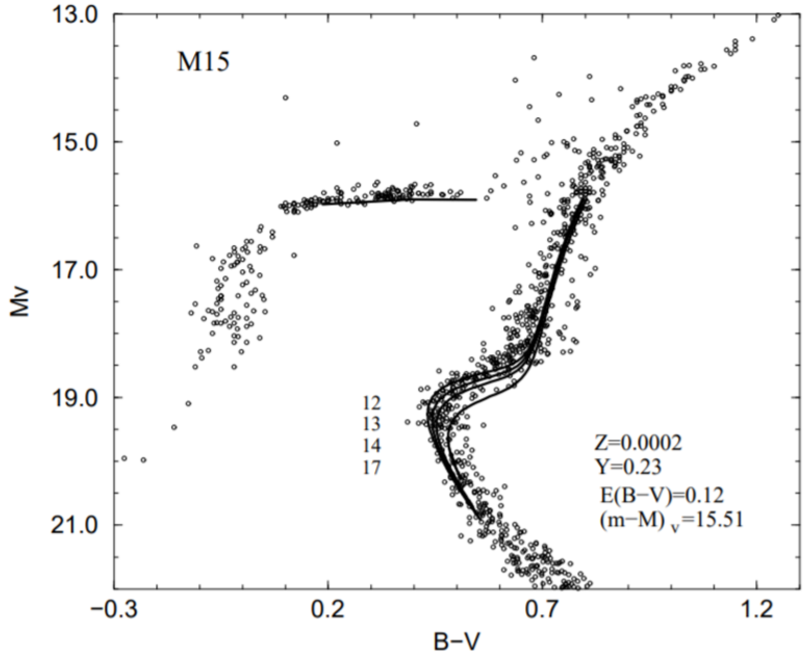

Figure 3 - Isochrones of different ages (given in Gyrs) fitted to the CMD of M15 plotted by Scilla Degl'Innocenti

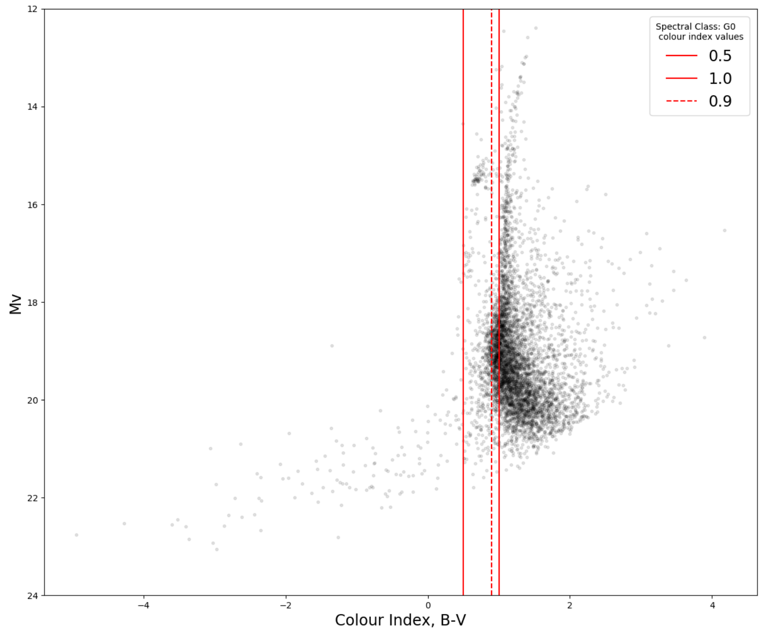

Figure 4 - CMD of M15 with colour index B-V and magnitude V. Consisting of 5,542 stars. Position of main sequence turn-off represented by vertical lines.

Data analysis

Fig 4 shows that M15 has no stars on the main sequence hotter than the spectral class G0; this implies the cluster is in fact an ancient object. The plot does not show any bluer, bright giants or supergiants; only dimmer more red stars. White dwarfs are the only existing blue/white stars left in the cluster shown in the lower left section of the graph between colour index: -4 to 0. Due to the lack of blue stars in the cluster one can imply little to no star formation occurring in the cluster.

The tall branch between M_V: 18-12 suggest most stars in the cluster that are no longer on the main sequence are now within the red-giant branch of their lifetime. These stars will remain for a few million years more before meeting the same fate of the stars before them. The red giant branch leads to the location of the main sequence turn-off.

Due to a large spread of data points around the main sequence, (including those who are not yet on the main sequence) vertical lines are plotted on fig 4 to show a clearer location of the main sequence turn-off. The turn-off is identified by the dashed vertical line with a colour index value of 0.9 (Along with the corresponding star class).

As spoken about in the introduction it is assumed that all stars in the cluster were born at roughly the same time. Therefore, identifying the star class at the turn-off and using theorised estimates for their lifetime, one can make a measurement for the current age of those stars and so the rest of the cluster.

$$\tau_{MS} = 10^{10} yrs \left[\frac{M}{M_\odot}\right]^{-2.5} \qquad (3)$$

Equation (3) is a theoretical estimate for the lifetime of a star of mass M on the main sequence [4]. It is an estimate based on solar evolutionary models which considers how long a star burns its fuel for at each stage in its life. 90% of a stars life is spent on the main sequence [4] and the rest in the red giant branch, for example the sun has currently been on the main sequence for 4 billion years and will continue for another 6 billion hence $10^{10} yrs$ in equation (3).

The mass range of the main sequence turn-off is determined using the colour index as seen in fig 5 along with the Harvard Spectral Classification table [10]. It is therefore found that the turn-off has a mass of $0.90 \pm 0.01\, M_\odot$. This is used with equation (3) to calculate an age for M15 of $1.3013 \pm 0.0355 \times 10^{10}\, yrs$ (13.013 0.355 Gyrs).

The age measured from my CMD in fig 4 agrees well with isochrone data plotted in fig 3. Isochrone plots in fig 3 were produced by Scilla Degl'Innconeti in their paper 'Age of the oldest Globular Clusters' The isochrones show the location of the turn-off to match the location in fig 4. The ages of the isochrone can be seen in fig 3 and match the age calculated for M15 in this study (Within range of 12-14 Gyrs). However, the colour index in fig 3 is much lower at the turn-off when compared to fig 4. This may be due to the weakness of the B-filter data used in this study.

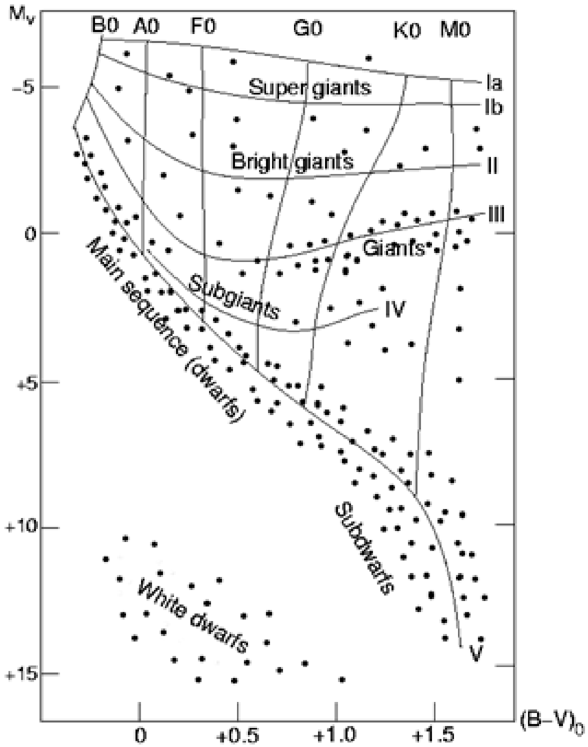

Figure 5 - CMD with labeled star classes and associated B-V colour index [10]

Discussion

Analysis of the CMD produced in this study looks to agree well with previous studies (fig 3). The resulting age of the M15 from the CMD came to be $13.013 \pm 0.355\ Gyrs$. The error was calculated using equation (3) by substituting the upper and lower bounds of the stellar mass measured at the turn-off. This final measurement agrees and fits within the upper and lower limits of the isochrone data plotted in fig 3.

This all leads to the final result of this study, an estimate for the age of the Milky Way. Using the upper limit of the error propagation produced in the measurement for the age of M15: 13.368 Gyrs. I have estimated that the age of the Milky Way is $13.4 \pm 0.1\ Gyrs$. This fits within the boundaries of ESO's report 'How Old is the Milky Way?' with a measured value of $13.6 \pm 0.8\ Gyrs$ [6] The error in this estimate is not calculated as it is an inferred value from the results of this study. The estimate is based on the assumption that stars do not exist at the very beginning of a galaxy's birth and takes into account star formation time. Galaxies are a result of lumped together gas in the early universe which have collapsed on themselves to form the galactic structures we know today [7] This means there is a lag time between the birth of a galaxy and the birth of its stars. Regular solar star formation takes around 10 million years, but stars of mass much greater will take much longer; one cannot have a star cluster until there are stars to cluster.

The ESO report was based on the study "Be in turn-off stars of NGC 6397: early Galaxy spallation, cosmochronology and cluster formation" by *L. Pasquini.* Pasquini's paper used a combination of astrophysical plots of the globular cluster NGC 6397 and the very useful cosmic clock isotope, Beryllium-9. There is a uniform distribution of cosmic rays originating from the interaction between Beryllium-9 and the ISM when the galaxy was first forming. The amount of Beryllium increased with time acting as a "Cosmic clock". This allowed useful data to be combined with CMD data from NGC 6397 to make an estimate for the galactic age.

The ESO study makes it obvious what might be missing from my own investigation. My study of an estimate of age for the Milkyway only used one sample; M15. To confidently state an estimate for the age of the Milky Way, one would use more than one GC by taking an average of a survey of globular clusters.

A possible weakness of my study of M15 is the sample size of stars taken from the cluster. For example if the observations focused on the centre of the GC there may have been a greater presence of blue stars in the CMD plot. This would have perhaps made for a younger estimation of the age of the cluster and therefore, the Milky Way. However, as the observations were conducted over the whole of the cluster, the data shows that on a whole there are mainly more yellow/red stars in the cluster. The observations field of view could have increased but this may have jeopardized the results by including stars not within the cluster. The sample size for the number of stars observed in M15 was a good sample size to make a justified age estimate. (Number of stars used to plot CMD: 5,542). Of course reproducing the data would make for more accurate data but is not justifiable within the time scale of this project.

Another possible weakness of this study was the corruption of the B-filter data during observation. Analysis of the data concluded the observations made in the B-filter were not aligned with all eight images taken (fig 1). This could have made contributions to the higher colour index values than first expected. In Vandenberg & Bell's 'Theoretical Isochrones for globular clusters' paper they estimate index values between 0.2 and 0.4 for the location of the main sequence turn-off; the colour index of the turn-off for this study was 0.9. Thus, the V-filter data may have been more concentrated than the B-filter data creating a bias for the redder stars in my data and would explain the higher colour index.

One other weakness of this study was the lack of isochrone plots on my CMD. Many CMD studies of globular clusters use isochrone data to plot best fits along their main sequence turn-off's to easily compare with other studies such as Vandenberg & Bell's paper. Isochrone plots also provide a good indication of visually representing error. They were not included in this study due to technicalities.

The purpose of this study was to make an estimate for the age of the Milky Way. This was based on the knowledge that globular clusters are a product of galaxy formation. The age concluded from data analysis of this study comes close to the known age of the Milky Way. One may conclude this to be the end of the study and make a conclusion. However, upon reading a review by Duncan A. Forbes [1] new ideas on the origin of GC's could suggest that I have not considered the whole picture.

In the review, Forbes discussed the formation of high and low mass galaxies. Low mass galaxies are dominated by local growth (*in situ)* and high mass galaxies go through a stage of mass growth through accretion of neighbouring galaxies or other bodies (*ex situ).* The review goes on to discuss direct evidence of accretion of GC's brought to the Milky Way's halo region through accretion/disruption of the Sgr Dwarf galaxy. These discussion points could completely change the perspective on how accurate age estimations are of GC's and to conclude them the age of the Milky Way. Some stars in the Milky Way could have been accreted from other neighbouring bodies.

Forbes goes on to talk about the number of GC's within the Milky Way (of an external origin) is highly uncertain; 30-100. Although this may seem a low number of clusters, this is in fact an incredibly large proportion of the Milky Way's GC population. The Milky Way holds approximately 160 GC's suggesting that ⅔ of the GC population could be of external origin.

As this study focuses on M15 and is a well studied GC, I am confident that the results made in this study are well justified and are a good estimate for age of the Milky Way.

Conclusion

There are three products of this study: CMD containing 5,542 plotted data points, a measurement of the age of the M15 and finally an inferred estimate for the age of the Milky Way.

The resulting CMD (fig 4) of this study agrees well with Scilla Degl'Innocenti's plot in fig 3 providing confidence in the outcome of the plot. The measured age from the CMD of M15 is $13.013 \pm 0.355\, Gyrs$. This value was estimated by measuring the location of the main sequence turn-off and comparing the associated star class. Thus, the mass was identified allowing the use of equation (3) for the estimate for the lifetime of this star. Error was estimated using the upper and lower limits for the mass of the star in the class. This method for error generated an agreeable result for the age of M15 when compared to isochrone data and related ages in fig 3.

This all leads to the result of this study, an estimate for the age of the Milky Way. As discussed, the estimate for the age of the Milky Way made in this study used a combination of the upper limit for the measured age of M15 and consideration for the time of star formation. The inferred age of the Milky Way made from this study is 13.4 ± 0.1 Billion years old.

There are two main ways this study could be improved. Firstly, make isochrone fits to a CMD allowing for error to be visualised and easily compared to theorised plots. This would back up my conclusion with more precision. Secondly, reproduce this study for a survey of globular clusters in the Milky Way for a better understanding of our galaxy. It could be taken further by undergoing this study for a survey of known globular cluster populations within the local group and grant an estimate for the age of the Universe.

References

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