Dissecting the True Age of the Ancient Globular Cluster Messier 55 / NGC 6809

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Abstract

Messier 55 (M55), a globular cluster located in the Sagittarius constellation, poses significant observational challenges due to its sparse core and ancient age. Utilising data from the Gaia mission, I have conducted a comprehensive study of M55, focusing on the collection and filtering of stellar data, analysis of colour magnitude diagrams (CMDs), and derivation of cluster parameters. Our analysis reveals refined CMDs, with clearer delineation of key features, such as the main sequence, main sequence turn off (MSTO), and red giant branch (RGB). By applying advanced filtering techniques, we have improved the precision of our measurements, resulting in estimated cluster age (12.218 ± 0.844 billion years) and distance (6609.9 ± 912.8 parsecs) that closely align with literature values. Our study underscores the importance of advanced celestial data filtering methods and the contributions of observation missions like Gaia in enhancing our understanding of stellar clusters and their evolution.

1. Introduction

Messier 55 / NGC 6809 (henceforth referred to as M55) is a relatively large and bright globular cluster located in the body of the Sagittarius constellation. Due to M55's lack of a dense core of stars and obscenely ancient age, it is notoriously difficult to resolve in sub-optimal conditions. Even renowned astronomer Charles Messier faced challenges in detecting this globular cluster during his compilation of the catalogue of Nebulae and Star Clusters. Initially discovered in 1752 by a French astronomer in what is presently South Africa, it wasn't until 1778 that Messier officially included it in his catalogue (1).

For observers in the northern hemisphere, M55 resides in a low position in the sky, leading to obstructed views due to a denser atmospheric layer, as well as the presence of water vapour and light pollution. These factors significantly impeded Messier's observations from his Paris observatory. In his cataloguing of M55, Messier remarked that "its [M55] light is even and does not appear to contain any star" (2).

The M55 cluster exists ≈ 5300 parsecs from Earth and has a radius of ≈ 31 parsecs. M55 contains an estimated 100,000 stars (55 of which are variable-type) and takes a spherical shape due to the intense gravitational attraction between the ancient stars (2). The cluster can be seen in Figure 2, where Hubble's clear view above Earth's atmosphere resolves individual stars in this cluster. Ground-based telescopes can also resolve individual stars in M55, but fewer stars are visible.

By leveraging data acquired from the European Space Agency's (ESA) Gaia mission, it is possible to use the fundamentals of astrophysics and data analysis to provide insight into the advanced age of M55, and study the process and distinct characteristics of stellar evolution on an incredibly vast scale.

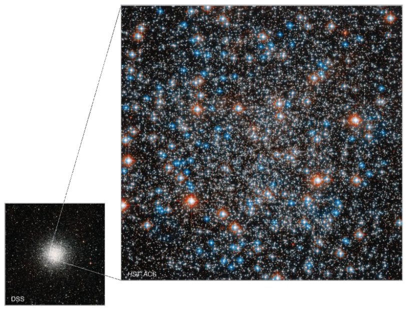

Figure 1: Messier 55 / NGC 6809 in DSS and HST ACB
NASA, ESA, A. Sarajedini (Florida Atlantic University), and M. Libralato (STScI, ESA, JWST); Image Processing: Gladys Kober (1)

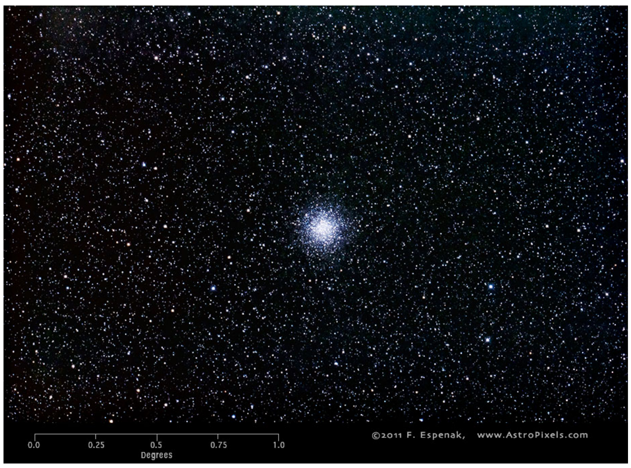

Figure 2: Messier 55 / NGC 6809
Fred Espenak (Takahashi Epsilon 180 ED Hyperbolic Astrograph); Image Processing: Fred Espenak (3)

2. Collection and Filtering of Gaia Data

The Gaia mission, colloquially known as the *'billion-star surveyor'*, is an ambitious space project undertaken by the European Space Agency (ESA) (4). Launched in December 2013, Gaia's primary objective is to create the most detailed and accurate three-dimensional map of our Milky Way galaxy to date. The mission aims to chart the positions, distances, motions, and other properties of approximately one billion stars in the Milky Way.

To achieve its goals, Gaia employs a specialised telescope equipped with sophisticated instruments to observe and measure the positions and motions of stars with unprecedented precision. The tiny angular shifts measured over time, known as stellar parallax, provide crucial information about the distances to the stars. Additionally, Gaia also gathers data on the brightness, colour, and other characteristics of stars using advanced filtering and observational techniques, which helps astronomers classify them and study their properties and evolution (5).

The M55 star data was collected from the Gaia Data Release 3 (5) with a collection radius of 15 arcminutes, which is beyond sufficient for the angular radius of M55 (≈8.5 arcminutes) (5).

2.1. Elementary Filtering of the Raw Data

To begin the filtering process, the raw data was first filtered for incomplete and non-physical inputs. Firstly, all stars with incomplete vital data points are disregarded. Secondly, a filter was introduced to disregard all negative parallax values and considerable parallax error values (>1mas).

Negative parallax values are stated to be an inherent outcome of the Gaia measurement process (6). Given that negative parallaxes result in nonsensical negative distances upon inversion, there is a necessity to simply discard these values. As mentioned in Section 1, the average distance of the cluster is ≈ 5300 parsecs with a radius of (≈ 31) parsecs (2), a condition on the distance of the stars was introduced to filter the star data based on the observed parallax using the relation between parallax in milliarcseconds and distance (Equation 1).

$$Distance_{parsecs} = \frac{1000}{Parallax_{mas}} \tag{1}$$

The filter was applied with a distance range of (5300 ± 300) to account for the relatively large parallax error (±0.189 mas). Following the meticulous application of filters, the extensive Gaia dataset underwent a significant reduction, shrinking from its initial count of 52,229 stars to a mere 966 stars that met the stringent criteria. This drastic culling was crucial to ensure the selection of only the most relevant and reliable data points for further analysis. Upon closer examination of this refined dataset, it was observed that the average distance to these selected stars settled at (5299.88 ± 175.88) parsecs, as determined through post-filter analysis. This average distance, with its associated uncertainty, serves as a pivotal metric in understanding the spatial distribution and characteristics of the stellar population under scrutiny.

The considerable reduction in the number of stars, coupled with the precise determination of average distance, underscores the efficacy of the applied filters in sieving out noise and focusing on the core subset of stars that exhibit the desired properties. This streamlined dataset forms the foundation upon which more detailed investigations and interpretations regarding the structure and dynamics of the stellar system can be built.

2.2. Proper Motion Filtering Techniques and Implications

As discussed in Section 2.1, the error on the parallax is very large (±0.189 mas), which could lead to a large bias in the data and inconclusive results during analysis. By determining the average proper motion velocity and direction of the distance filtered data, a conclusion can be made about the proper motion and direction of M55. Using equations 2 and 3, we can determine the proper motion in the angular direction, however, this filter is limited by the fact that the Gaia data does not contain the radial velocity for most of the stars (only ≈ 1.036 percent of the given stars have a radial velocity measurement attributed).

$$\omega_{mas/yr} = \sqrt{(\omega_{Dec})^2 + (\omega_{RA} cos(\theta_{Dec}))^2} \tag{2}$$

$$\theta_{pm} = tan^{-1}\left(\frac{\omega_{Dec}}{\omega_{RA}}\right) \tag{3}$$

As illustrated in Figures 3, 4 and 5, it is evident that the unfiltered data exhibits a considerable range in proper motion, indicating a wide spectrum of celestial movements. Conversely, upon applying the parallax filter to the stars, the data reveals distinct peaks in both proper motion and direction. Specifically, the proper motion peaks at (9.9 ± 0.5 milliarcseconds per year), while the direction exhibits a peak at (1.23 ± 0.35 radians). This clarity in the filtered data prompts the development of a more refined filter.

This enhanced filter is constructed by leveraging the data from stars falling within the ranges defined by the peaks of proper motion and direction identified in the parallax-filtered dataset. By focusing on this subset of stars, it is anticipated that more precise and reliable data can be obtained. This approach circumvents the significant uncertainties associated with parallax motion inherent in the Gaia dataset, thereby offering a more robust basis for analysis and interpretation, in the following section, both filtering methods will be analysed and compared (6).

This method, like parallax filtering, is burdened by the fact that the radial velocity dimension was forced to be omitted from the calculations. Although this method captures the stars that travel in the same angular direction, the M55 cluster is known to have a very significant redshift due its relatively large distance and advanced age. Estimates put the average radial velocity of stars in M55 to be 174.40 km/s (7), which would drastically affect the proper motion, and filter out more misfit stars.

More about this discrepancy and its calamitous effects on the final calculations, as well as a feasible solution before the updated Gaia data releases is discussed in detail in Section 4.

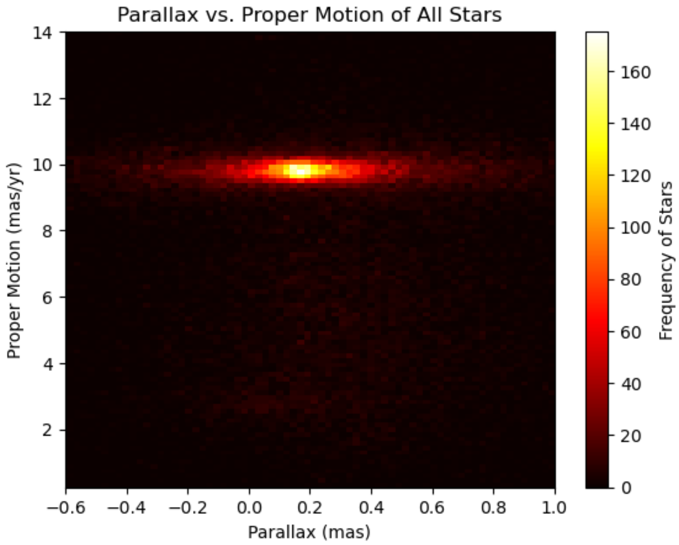

Figure 3: Parallax vs. Proper Motion of Stars (unfiltered) 2D Histogram

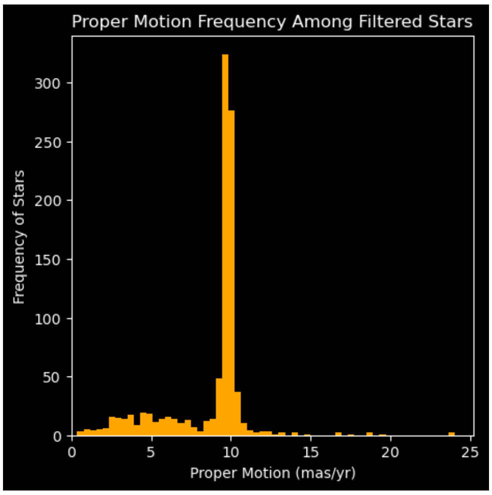

Figure 4: Parallax-filtered Star Proper Motion Histogram

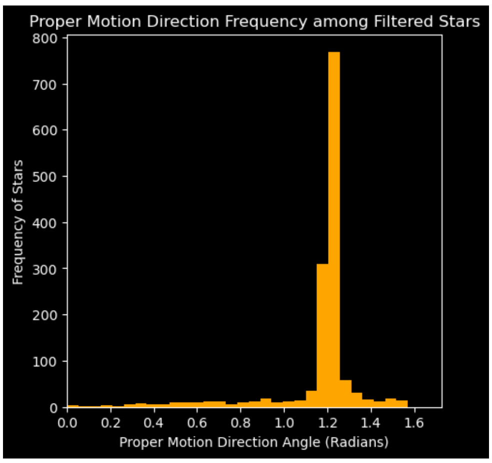

Figure 5: Parallax-filtered Star Proper Motion Direction Histogram

3. Colour-Magnitude Diagrams and Age Derivations

A colour magnitude diagram (CMD) is a powerful tool used in astronomy to study the properties and characteristics of stars within clusters of stars. It plots two fundamental parameters of stars: their apparent magnitude in a specific wavelength band (In the case of the Gaia data, the G-band ($\approx$ 330 – 1050 nm) filter (8)) on the y-axis, and their colour on the x-axis.

The colour of a star is determined by comparing its brightness in two different wavelength bands. Typically, astronomers use the difference in magnitudes between two filters, such as B (blue) and V (visual), however, the Gaia observatory uses the BP-RP pass-band filter, which provides the same vital information about the colour of the stars. This colour index provides information about the temperature of the star's surface (in general hotter stars appear 'bluer', while cooler stars appear 'redder').

The apparent magnitude of the star is a measure of its brightness in the G-band as observed from the Gaia observatory on Lagrange Point 2 ($\approx$1.5 million kilometres from Earth) (4). The apparent magnitude is significantly influenced by various factors, including the star's intrinsic luminosity, distance, and any interstellar extinction.

By plotting the colour of stars against their magnitude, a CMD reveals important information about the cluster under study, specifically, the distribution of stars in the CMD reflects their spectral types and evolutionary stages. Main sequence stars, giant stars, and white dwarfs occupy distinct regions of the diagram. The main sequence represents stars burning hydrogen in their cores (like the Sun), white giants, supergiants and white dwarf stars represent later stages of stellar evolution, where different fusion processes cause distinct physical features, mainly, colour and lower magnitude (brighter). These features also provide insight into the age of the cluster, as we can determine the magnitude at which the main sequence stars are beginning to expand into the red giant branch (RGB), called the main sequence turn off (MSTO), and estimate the time after creation at which these stars will leave the main sequence relative to the Sun.

The MSTO magnitude can be related to the age of the cluster by Equation 4, which is a derivation involving many approximations and equations:

$$G_{MSTO} = g_{MSTO} - 5log\left(\frac{d_{pcs}}{10pcs}\right)$$

$$G_{MSTO} - G_{sun} = -2.5log\left(\frac{L}{L_{sun}}\right)$$

$$\frac{L}{L_{sun}} \approx \left(\frac{M}{M_{sun}}\right)^{4}$$

$$t_{ms} \approx (10Gyrs) \cdot \left(\frac{M}{M_{sun}}\right)^{-3}$$

Combining these expressions, the final equation (Equation 4) is extracted, where the absolute magnitude of the Sun in the G filter is given by $G_{sun} = 4.68$ Mag:

$$t_{ms} = (10\ Gyrs) \cdot \left(10^{\left(1.872+2log\left(\frac{d_{M55}}{10pcs}\right)-\frac{2}{5}g_{MSTO}\right)}\right)^{-\frac{3}{4}} \quad (4)$$

Or, in terms of the absolute magnitude of the MSTO:

$$t_{ms} = (10\ Gyrs) \cdot \left(10^{\left(1.872-\frac{2}{5}G_{MSTO}\right)}\right)^{-\frac{3}{4}} \quad (5)$$

If the distance of the cluster is unknown, the tip of the red giant branch (TRGB) can be used as a standard candle, which yields the distance to the star (Equation 6) by the fact that $G_{TRGB} \approx -3$ Mag:

$$d_{M55} \approx 10^{\frac{(g_{TRGB}+3)}{5}+1} \quad (6)$$

3.1. Parallax Filtered CMD and Analysis

The CMD presented in Figure 6 was constructed by utilising the BP-RP colour index (x-axis) and apparent G magnitude (y-axis) from the refined data set outlined in Section 2.1 (Parallax Filtered).

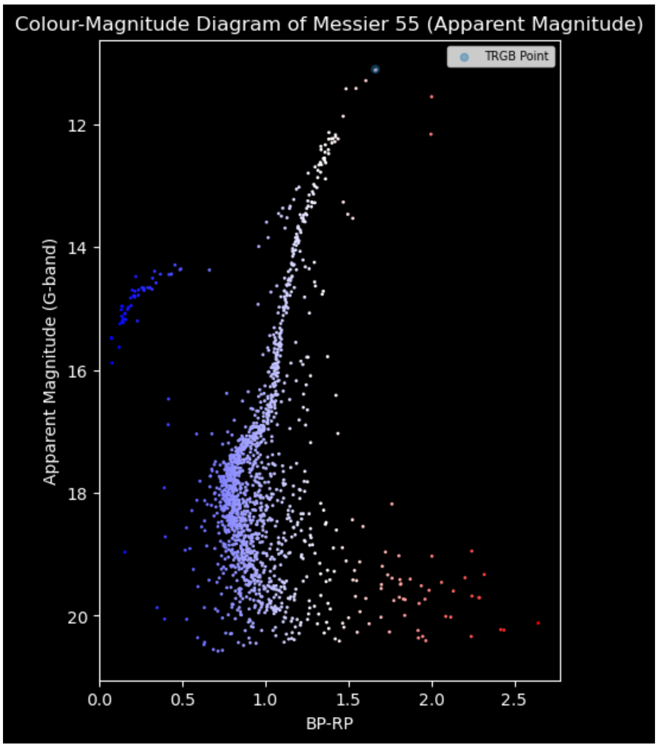

Figure 6: Parallax-filtered Star CMD (Apparent Magnitude)

The distinctive features delineated in the CMD are very evident; however, the CMD depicted in Figure 7 imbues a greater degree of physical significance. This heightened significance arises from the incorporation of absolute magnitude, which serves as a crucial reference point for a more comprehensive analysis of the CMD. Using the parallax data of the filtered stars to transition the apparent magnitudes into absolute magnitudes, and integrating the absolute magnitudes into the diagram, we are able to transcend mere relative brightness comparisons and delve deeper into the intrinsic properties of the cluster, as the absolute magnitude offers a standardised metric that accounts for the varying distances of stars, thereby facilitating a more nuanced understanding of their luminosity and evolutionary state.

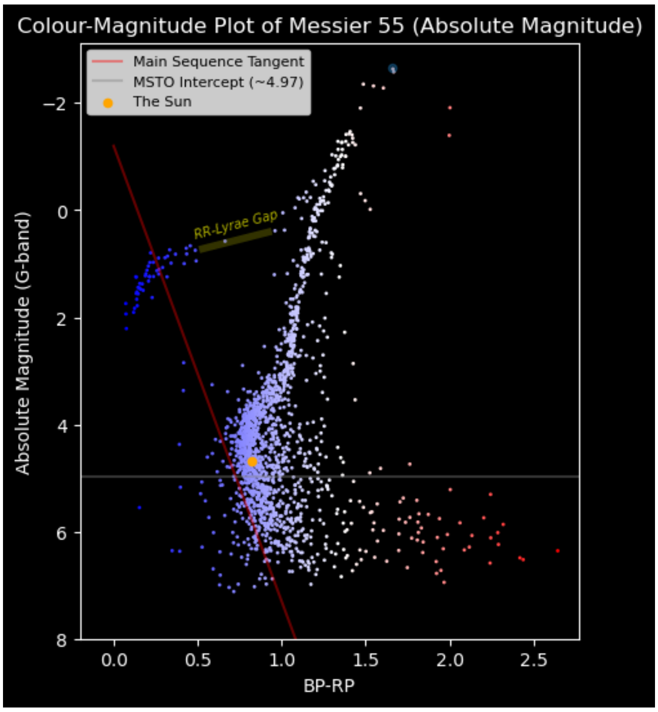

Figure 7: Parallax-filtered Star CMD (Absolute Magnitude)

The CMD presented in Figure 7 unveils a rich tapestry of stellar evolutionary stages and population characteristics. Prominent among these features is the unmistakably well-defined red giant branch, tracing a trajectory towards higher magnitudes and redder colours, indicative of stars in advanced evolutionary phases. Accompanying this, the CMD also showcases a relatively large horizontal branch, a testament to the archaic nature of M55.

Despite the clarity of these features, the main sequence and the main sequence turn off (MSTO) appear somewhat obscured by noise. Nevertheless, their presence is apparent, albeit with some degree of uncertainty. Notably, the MSTO is identified at $G_{MSTO} = 4.97 \pm 0.1$ Mag, a pivotal point denoting the transition from hydrogen-burning main sequence stars to more evolved phases. It's important to note that the position of the MSTO in M55 deviates from the typical placement observed in many stellar clusters. This discrepancy arises from M55's advanced age, which results in a lower MSTO magnitude compared to younger counterparts. Consequently, this deviation accentuates the slope of the main sequence tangent, an effect compounded by the inherent magnitude inconsistencies characteristic of stars residing in the lower main sequence.

Comparing this CMD (Figure 7) to literature (9) (Figure 8), it is evident that the parallax filtering method provides a sufficient data set to determine the key features, specifically, the MSTO, which is a crucial component in determining the cluster's age.

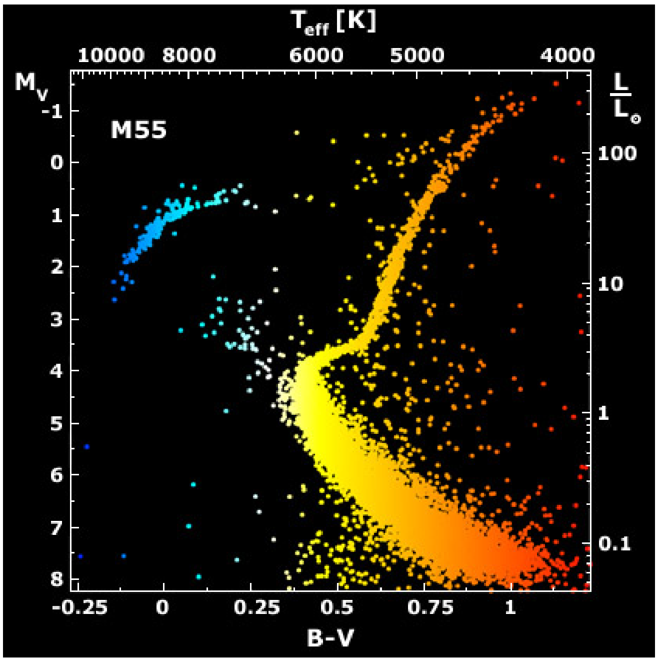

Figure 8: M55 Colour Magnitude Diagram
B.J. Mochejska, J. Kaluzny (CAMK), 1m Swope Telescope (9)

Utilising the MSTO determined from the CMD (Figure 7) and Equation 5, the age of the cluster is estimated to be 12.218±0.844 billion years old. Comparing this to the accepted literature value, which estimates M55 to be approximately 12.3 billion years old (2), it is evident that the estimation calculated from the CMD is well within the uncertainty of the determined estimation.

In Figure 6, we encounter challenges in resolving the tip of the red giant branch (TRGB) due to a distinct scarcity of stars in the upper reaches of the RGB. This disparity of data in the upper RGB region introduces a significant degree of uncertainty when pinpointing the precise location of the TRGB. To mitigate this uncertainty, we adopt a conservative approach by selecting the star with the lowest apparent magnitude within the RGB, which registers at 11.1 Mag. However, it's important to acknowledge the inherent limitations imposed by the lack of data in the upper RGB. Consequently, we incorporate a relatively high uncertainty of (±0.3) to account for the potential variability and imprecision in determining the TRGB.

Based on this methodology, the estimated distance to the cluster is calculated to be (6609.9 ± 912.8) parsecs from Equation 6. This estimate encapsulates both the measured value and the associated uncertainty, providing a comprehensive assessment of the distance to the cluster while acknowledging the inherent challenges posed by the sparsity of data in the upper RGB region. Despite the uncertainty, this distance estimation is within the literature value of (5300 ± 31) parsecs (2).

3.2. Proper Motion Filtered CMD and Discussion

The CMD presented in Figure 9 was constructed by utilising the BP-RP colour index (x-axis) and apparent G magnitude (y-axis) from the refined data set outline in Section 2.2 (Proper Motion and Angular Direction Filtered).

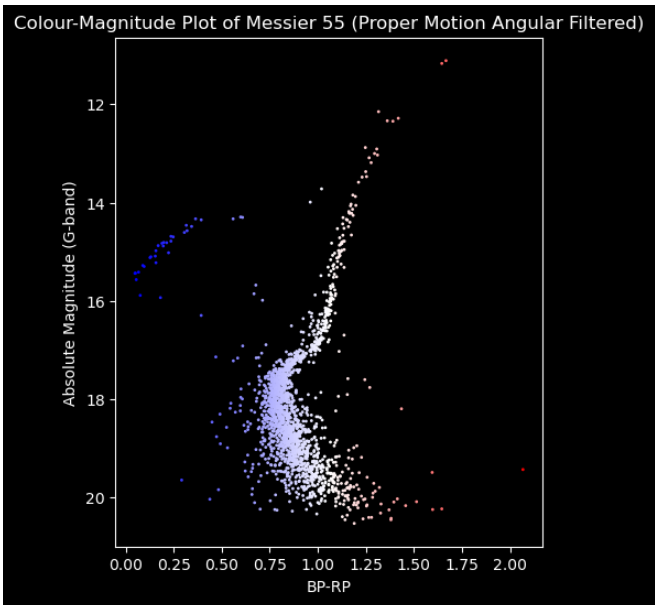

Figure 9: M55 Colour Magnitude Diagram with Motion and Direction Filtering

The infusion of this additional stellar data has imparted a newfound clarity to the features of the CMD, notably enhancing the discernibility of key stellar evolutionary features, particularly the main sequence. The augmentation of the data set has a profound impact on the CMD, refining the main sequence data and significantly reducing the amount of 'noise' by removing stars which are likely not part of the cluster. Moreover, the MSTO and RGB are now distinctly delineated, with substantially reduced noise, thereby eliminating the undesired broadening of the dataset seen in Figures 6 and 7. This infusion of additional data has not only refined the understanding of stellar evolution within the cluster but has also heightened the precision of our observational analyses. Although this refined data set does not change the calculated values or the positions of the MSTO or RGB, it serves to reduce the uncertainty of the measurements by providing more accurate and refined points of reference.

4. Inherent Challenges with The Proper Motion Dimension from Gaia Data Release 3

As mentioned in Section 3.2, the lack of radial velocity data for the stars observed by the Gaia observatory provides challenges with the filtering process. Although the proper motion filtering process significantly increases the accuracy and precision of the subsequent CMD, these missing values cause a noticeable bias in the proper motion calculations, which ultimately lead to the collection and processing of stars which are likely to exist independently of M55.

This bias is due to the fact that the Gaia observatory's advanced radial velocity spectrometer (RVS) is riddled with technical issues (10), thus, much of the readings from the radial velocity are omitted in the data release, especially for stars of apparent magnitude < 10 mag. Due to the fact that all of the stars from M55 are above this limit, the radial velocities are indeterminate.

From an independent paper written by Aneesh Naik (11) and Axel Widmark (12), the inherent issues with the Gaia Data Release 3 were addressed, and proposed a method to interpolate the missing data. This method of interpolation involved using a complex Bayesian neural network, which proved to be a highly efficient method of 'guessing' missing radial velocities as a function of the existing data associated with the star, and thus filling in the missing radial velocity dimension (13).

By integrating these radial velocities into the proper motion calculations, the proper motion filtered dataset becomes more comprehensive and complete. This ensures that a larger proportion of stars in the M55 cluster are accounted for in the analysis, reducing the likelihood of bias introduced by the inclusion of certain unsuitable stars.

This groundbreaking approach not only addressed the inherent limitations of the Gaia dataset but also contributed to the advancement of data interpolation techniques in astrophysical research. By bridging the gap in missing data, the Bayesian neural network method paved the way for more comprehensive analyses and interpretations, fostering a deeper understanding of stellar dynamics within M55 and beyond.

5. Conclusion

In conclusion, the study of Messier 55 (M55) presents unique challenges due to its location and age, making it difficult to observe and analyse. Despite these challenges, the integration of data from the Gaia mission has significantly enhanced our understanding of this globular cluster.

Through meticulous collection and filtering of raw data, we have refined our dataset to include only the most relevant and reliable stellar data points. This process has led to a substantial reduction in noise, allowing for clearer identification of key features within the Colour Magnitude Diagram (CMD). Notably, the main sequence, main sequence turn off (MSTO), and red giant branch (RGB) are now more distinctly delineated, providing valuable insight into the evolutionary stages of stars within M55, and the age of the entire cluster.

By leveraging both parallax and proper motion filtering techniques, we have further improved the precision of our observations. The incorporation of additional stellar data has not only enhanced the clarity of the CMD but has also reduced uncertainty in our measurements, providing more accurate estimates of parameters such as cluster age and distance.

Comparing our measured values to literature values, we find that the estimated age of the cluster, determined to be (12.218 ± 0.844) billion years old, closely aligns with the accepted literature value of approximately 12.3 billion years (2). Similarly, the estimated distance to the cluster, calculated to be (6609.9 ± 912.8) parsecs, falls within the literature value range of (5600 ± 31) parsecs (2). This consistency between our measurements and literature values underscores the reliability and accuracy of our data analysis techniques.

Overall, this study emphasises the importance of advanced data analysis techniques and the invaluable contributions of missions like Gaia in advancing our understanding of stellar clusters like Messier 55. Through continued research and analysis, we can further refine our knowledge of these fascinating celestial objects and unravel the mysteries of stellar evolution.

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