Isochrone Fitting of the NGC 6362 Globular Cluster

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We present the isochrone fitting to the colour–magnitude diagram of the Galactic globular cluster NGC 6362 using Gaia DR3. We use models and isochrones from the Bag of Stellar Tracks and Isochrones (BaSTI). We report fits of 12 Gyr and [Fe/H] = −1.20 and [Fe/H]= −0.90 for $E(B-V)$ of 0.090 and 0.056 respectively.

I. INTRODUCTION

Globular Clusters (GC) provide snapshots in stellar evolution. The stars in a GC have their origin from the same molecular cloud, and hence have the same age and metallicity. GCs are found in galaxy halos and bulges, making the size of a GC negligible compared to the distance to it. This allows us to approximate for an equal reddening for all the stars, in a given wavelength. These properties make them an ideal target for stellar evolution studies.

The Hertzsprung-Russel diagram (HRD) gives insight into the evolution of stellar populations. This diagram plots the luminosity (L) as a function of surface temperature (T) in logarithmic scale, with the hottest stars to the left. Its observational analogue is the colour-magnitude diagram (CMD). Stars have specific positions in these diagrams and form branches, and are not randomly distributed. This indicates that different branches are driven by different internal engines and energy transport mechanisms in the stars.

By doing photometry on a GC and fitting it with stellar evolution models, we can derive the non-observable properties of the cluster. Isochrones serve this purpose. These are theoretical colour-magnitude diagrams derived from stellar evolution models and are used to describe and study Simple Stellar Populations (SSP), like a GC [17]. We perform such a study on an inner-halo Galactic GC, NGC 6362. Figure 1 displays a picture of the NGC 6362 cluster. It is located in the IV Galactic quadrant. Figure 2 shows the position of the cluster in the Galaxy. Its general properties are shown in Table I. This GC is relatively well known and has been extensively studied in the past [5, 10, 12–14].

In this report, we will estimate the age and metallicity of NGC 6362 as an exercise to gain insight into stellar evolution studies.

FIG. 1. NGC 6362. Credits: MPG/ESO 2.2-meter telescope at ESO's La Silla Observatory, Chile. Optical (B and V bands) and infrared (I band).

II. DATA ACQUISITION

A. Photometry: Gaia

Gaia [6] is a space mission of the European Space Agency (ESA), launched on December 19, 2013, to perform measurements of astrometry, photometry and spectroscopy. Gaia's spatial environment and design allows for a combination of precision, sensitivity and coverage of the sky that is only possible from space. The latest Gaia data release, GAIA DR3 [8], was collected between July 25, 2014 and May 28, 2017 (34 months). For comparison, the previous data release Gaia DR2 is 22 months of data, and Gaia DR1 is 14 months of data.

GAIA DR3 provides data from three different instruments [8]: astrometric measurements in the G-band (330–1050 nm), the red and blue prism photometers (RP and BP, 330–680 nm and 640–1050 nm respectively), and the Radial Velocity Spectrometer (RVS). Gaia DR3 contains astrometry and photometry measurements for 1.8 billion sources brighter than magnitude $G = 21$, supplemented by the Gaia DR2 radial velocity.

Using the source search from the Gaia archive [2], the mean G, G_{BP}, G_{RP} magnitudes and respective flux over errors, right ascension (RA), declination (dec), and proper motion for the stars of NGC 6362 cluster were downloaded.

B. Isochrones: BaSTI

In this project, we use the Bag of Stellar Tracks and Isochrones (BaSTI) [1]. It is a database for stellar evolutionary models and isochrones that covers metallicities from -3.2 to 0.4, with a solar-scaled metal distribution (i.e. with a heavy element mixture that has been

α	δ	l	g	μ_α	μ_δ	D	r_{half}	$E(B-V)$ [11]	$E(B-V)$ [10]	[Fe/H]
17:31:54.99	-67:02:54.0	325.55452	-17.56977	-5.50	-4.74	7.65 ± 0.07	2.05	0.09 ± 0.01	0.056 ± 0.002	-0.99 ± 0.1

TABLE I. Properties of NGC 6362: equatorial coordinates (J2000) right ascension α and declination δ [9], Galactic longitude l ($^\circ$) and latitude b ($^\circ$), proper motions μ_α and μ_δ (mas/yr) [7], heliocentric distance D (kpc) [4], half-light radius (arcmin) [11], color excess $E(B-V)$ (mag) by [11] and [10], and iron abundance [Fe/H] [11].

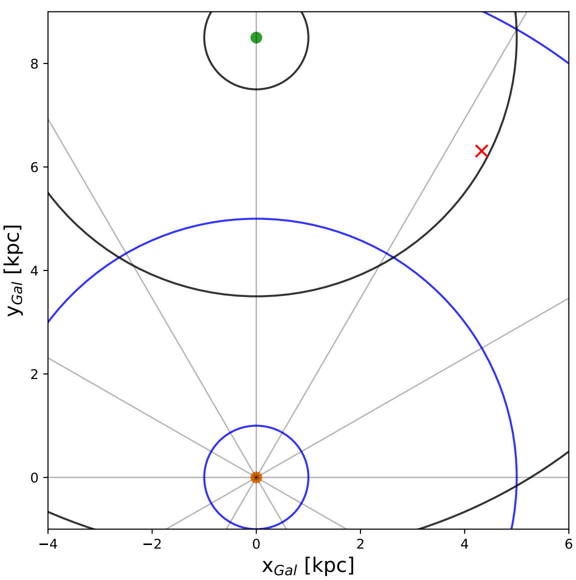

FIG. 2. Galactic position of NGC 6362 (red cross). The orange point corresponds to the Sun and the green point to the Galactic center.

scaled with Solar metal abundancies [15]) and stellar masses from 0.5 to 10 $M_\odot$. This database also contains isochrones for α-enhanced metal distribution [16], white dwarfs [18] and includes all evolutionary stages. The complete set of evolutionary models can be used to compute isochrones with ages from 30 Myr to 20 Gyr.

We downloaded many sets of isochrones with different combinations of age ranges and metallicity. We mainly tried metallicities close to -0.99 [11] and -1.04 [10].

III. PROCEDURE

Here, we describe the steps taken to obtain a good isochrone fit.

A. Cluster Selection

First we plot the proper motions of the stars, μ_α and μ_δ, to find the cluster (see Figure 3). We use elliptical select in TOPCAT to manually select the denser area (plotted in blue), which corresponds to stars that have similar proper motions and therefore belong to the cluster. The rest of the stars were discarded from the analysis as they correspond to background or foreground Galactic stars.

B. Treatment of Errors

We plotted the errors in magnitude against magnitude (see Figure 4) to understand the error distribution of the data. The magnitude errors were calculated from flux over errors by:

$$M_{err} = \frac{2.5}{\ln 10}\frac{F_{err}}{F}, \tag{1}$$

where M_{err} is the magnitude error, F is the flux and F_{err} is the flux error. This is an approximation, as this formula assumes a symmetric distribution of the errors.

We selected data points that are over 3σ, where σ is the standard deviation of the errors, and plotted the map of the cluster to check for possible biases 5.

We noticed that there were less points with high errors towards the centre. We hypothesised that this could be due to the apparent brightness of central sources in the cluster. Despite its remarkable resolution Gaia, suffers from blending effects where it cannot effectively resolve neighbours in dense regions. This causes the sources in the center to have higher astrometric errors, and Gaia's on-board software discards these points as poor detections. In the end, the sampling of the center appears to be less dense, as there are less good detections chosen by Gaia's software.

The low errors can bias our 3σ filtering and to avoid this, we crop out the centre of the cluster using the same elliptical method employed for the cluster and recomputed σ. We report no improvement in σ or the overall CMD. So, we chose to keep the sources in the center, as they were not introducing a bias.

The criterion of 3σ cropped the tail of the main sequence (MS) branch in our CMD, so we decided to discard the points over 5σ. The red points in Figure 4 were removed. In addition, in spite of having high errors, the blue crosses with high errors were not discarded (see Section V E).

C. Colour-magnitude diagram

We then plot the apparent magnitude in G band against the colour $G_{BP} - G_{RP}$. Figure **??** shows the

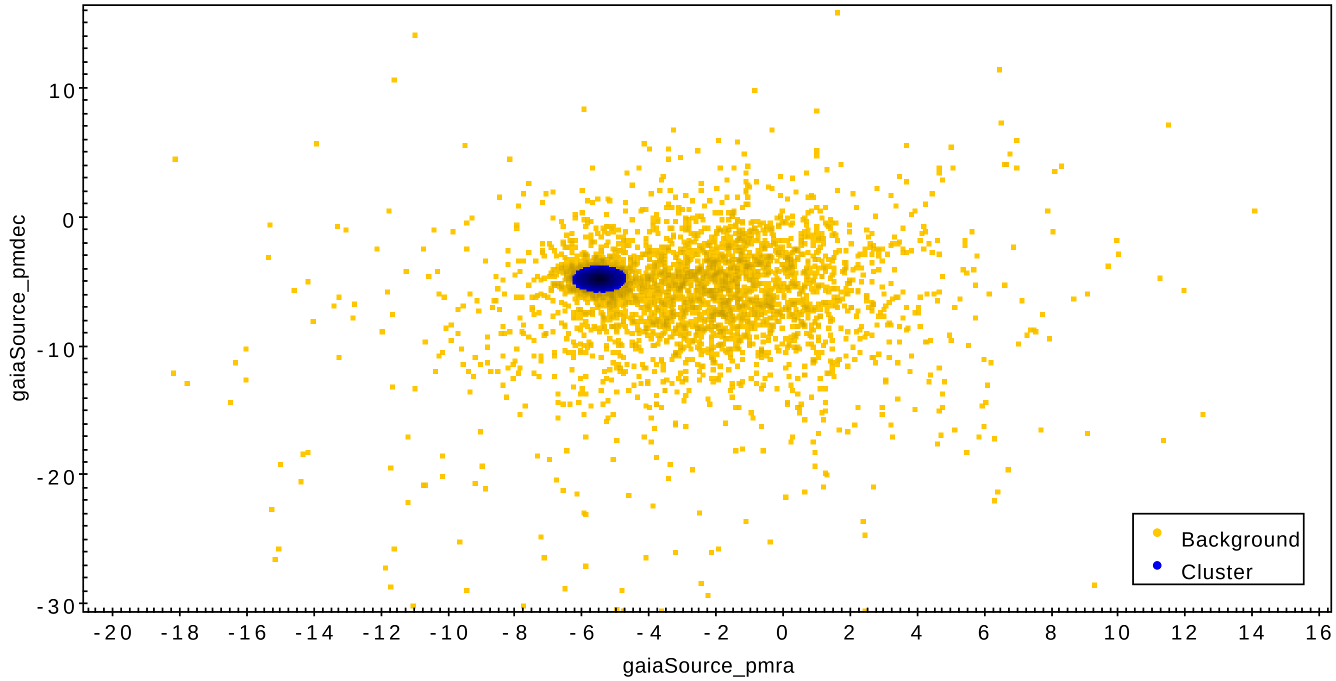

FIG. 3. Proper motion map of the data. Blue points correspond to the GC. The yellow points are background or foreground stars.

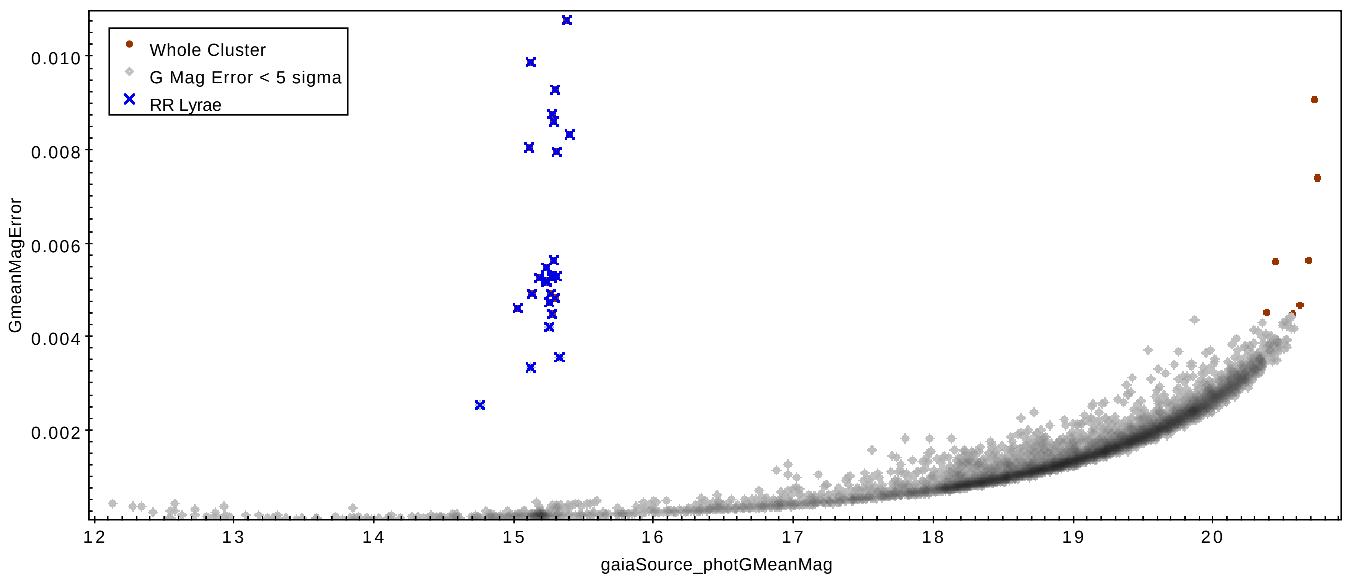

FIG. 4. Error distribution of G band data. Grey points have an error lower than 5σ. Red points have high errors and were excluded. Blue points may be RR Lyrae stars and were not excluded from the analysis.

obtained CMD. It shows a clear turn-off point, a red giant branch (RGB) and a horizontal branch, which serves as a sanity check.

D. Isochrone Fitting

1. *Adjustment for Extinction*

In order to perform the isochrone fitting, we must correct for the effects of absorption by dust in the interstellar medium (ISM), in both magnitude and colour. We adjusted the isochrones for extinction with two color excess

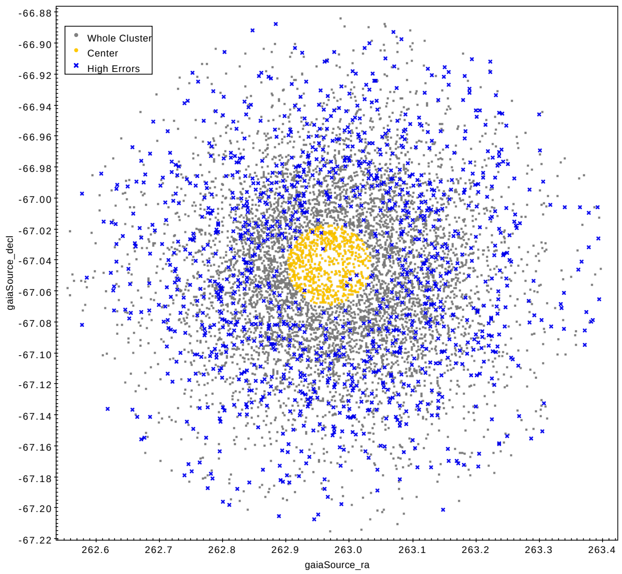

FIG. 5. Center selection in yellow. Blue crosses are points with errors higher than 3σ. The rest of the cluster is plotted with gray points.

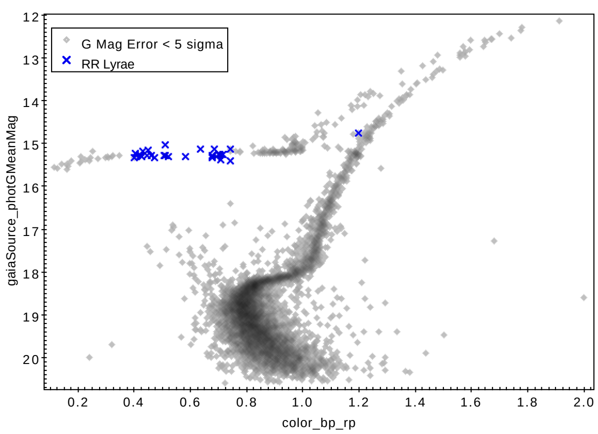

FIG. 6. CMD of the cluster. Blue points have errors above 5σ. They possibly are RR Lyrae stars (see Section V E).

$E(B-V)$ values: one from [11] and the other from [10]. We decided to do this to work with results from more recent studies and with less uncertainty.

We add extinction A_v to the isochrone:

$$A_v = R_v \cdot E(B-V), \tag{2}$$

where v is the given band and R_v is the coefficient that takes colour excess $E(B-V)$ to extinction in desired band. For Gaia, the R values for each band are $R_G = 2.740$, $R_{BP} = 3.374$ and $R_{RP} = 2.035$.

In the case of the magnitude, we have to account for the distance modulus DM as well 3:

$$DM = 5\log_{10}\left(\frac{d}{10}\right), \tag{3}$$

where d is the distance in parsecs.

The final G magnitude and colour $G_{BP} - G_{RP}$ of the isochrones are:

$$G_c = G + DM + R_G \cdot E_G(B-V) \tag{4}$$

and

$$(G_{BP}-G_{RP})_c = (G_{BP}-G_{RP})+(R_{BP}-R_{RP})\cdot E(B-V), \tag{5}$$

where the c sub-index stands for “corrected”.

2. *Fitting*

To fit the isochrone, we potted them on top of the CMD of the cluster. We tried many different combinations of age and metallicity, iterating between downloading BaSTI isochrones with different age and metallicity ranges, and testing them.

We consistently chose an α-enhanced element mixture $[\alpha/\text{Fe}]$ of 0.4 and He abundance of 0.247. A metal distribution is α-enhanced when the abundance of the α elements (Ne, Mg, Si, S, Ca, Ar, and Ti) have been uniformly enhanced with respect to Fe by $[\alpha/\text{Fe}]$. Since our cluster is in the inner halo of the Galaxy, we have chosen an α-enhanced metal distribution, which is suitable for populations in galactic halos, spheroids and dwarf galaxies [16]. The best-fitting isochrones were chosen manually.

IV. RESULTS

Our results are displayed in Table II and Figures 7 and 8.

$E(B-V)$	Age	[Fe/H]	Z
0.090 [11]	12	-1.20	0.001975
0.056 [10]	12	-0.90	0.003920

TABLE II. Parameters of the fitted isochrones: color excess $E(B-V)$, age (Gyr), iron abundance [Fe/H] and metallicity Z.

A. Comparison of the Fits

After obtaining the best fits, we evaluated their goodness-of-fit and compared to see which value for the colour excess allows for a better isochrone fit.

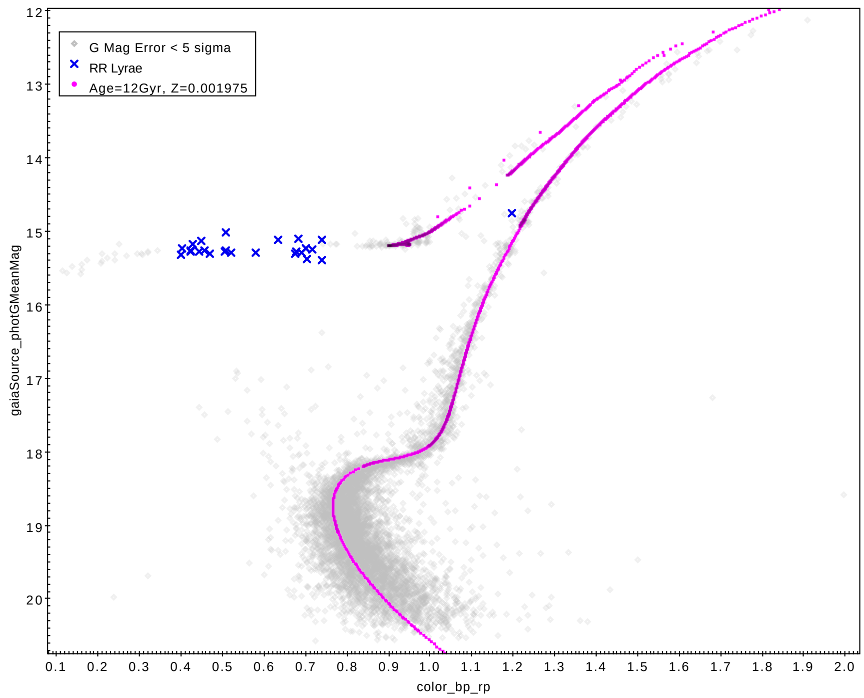

FIG. 7. Best fit for cluster corrected with $E(B-V) = 0.090$: BaSTI isochrone with age 12 Gyr, metallicity $Z = 0.001975$ and abundance ratio $[Fe/H] = -1.20$

We did this by using χ^2 as our error function:

$$\chi^2 = \sum_i \left(p_i^{obs} - p_i^{theo}\right)^2, \tag{6}$$

where p_i^{obs} are the observed data points of the CMD and p_i^{theo} are the theoretical points of the isochrone.

Following a Bayesian approach, [19] derive a detailed method for evaluating how well an isochrone fits data. They also present a way of finding the minimum distance between the CMD and the isochrone. We applied the simpler version of this problem by following the method described in [3]. Here, instead of using the minimal distance, the data is binned horizontally or vertically, and the error function is computed with the horizontal or vertical distance between the data and the isochrone. We binned the data in G magnitude into 75 separate intervals. Each bin has a width of 0.1 magnitudes and about 20 stars. In each of the bins, the χ^2 was calculated horizontally, with the colour of every isochrone point and the colour mean of the Gaia data in the corresponding bin.

We obtained a χ^2 of 2.9×10^{-4} when the isochrone was treated with $E(B-V) = 0.090$, and a χ^2 of 3.7×10^{-4} when it was treated with $E(B-V) = 0.056$. The fit of the former is slightly better. However, both fits are still valid and of high quality as both have a low χ^2 (< 0.1).

V. DISCUSSION

A. Age and Metallicity Estimates

Our estimates show this cluster is old (12 Gyr) and has low metallicity Z. This value is $\sim 10^{-1}$ times the metallicity of the Sun, and is close to the metallicity of the Galaxy's halo, where the cluster is located.

Furthermore, the presence of isolated branches confirms that the cluster is composed by a SSP. However, there are some recent studies that show the metallicity of GCs are not as constant as previously thought [13].

B. CMD Dependency on Age

The age of a cluster will determine the turn-off point, where the stars leave the MS. A younger cluster will have a more pronounced turn-off point, and its MS will reach a higher magnitude.

C. CMD Dependency on Metallicity

The metallicity of a cluster also has a relevant impact on the CMD. A less metal rich cluster will have a steeper red giant branch. In addition, its turn-off point will be shifted more to the right.

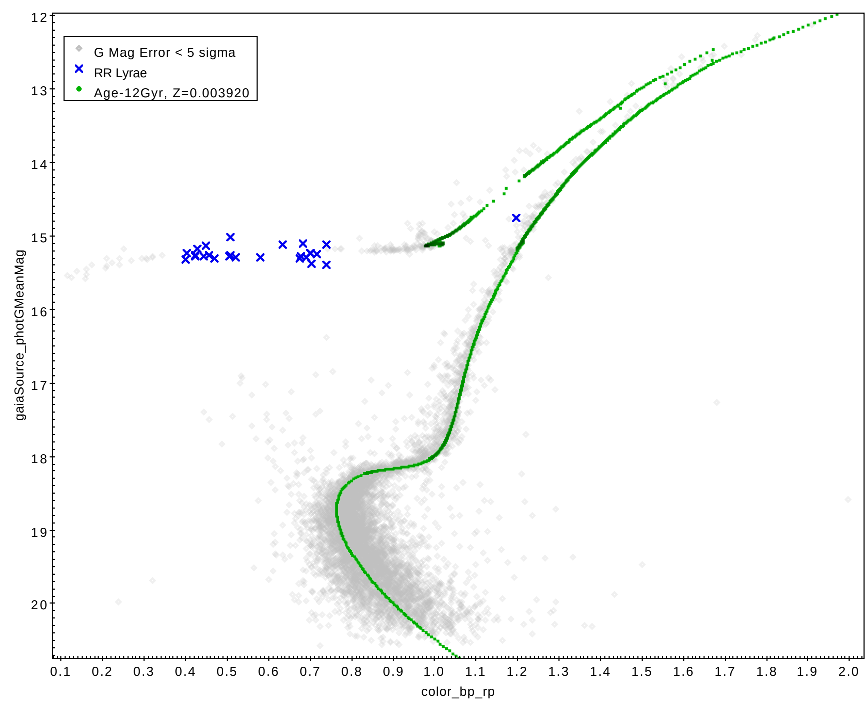

FIG. 8. Best fit for cluster corrected with $E(B-V) = 0.056$: BaSTI isochrone with age 12 Gyr, metallicity $Z = 0.00392$ and abundance ratio $[Fe/H] = -0.90$

D. Reddening and Metallicity Degeneracy

Metallicity and reddening present degeneracy, so we have two results with the same age but different metallicity when we correct by different reddening values. This does not mean that our results are not correct, indeed we have two good results within the error values.

E. RR Lyrae Stars in the Cluster

As mentioned in section III B, during filtering by magnitude error, we noticed a population of stars with high errors at ~ 15.2 magnitudes in G. We then proceeded to check if they belonged to the same branch. As expected, in the CMD (see Figure 6), these stars are located in the Zero Age Horizontal Branch (ZAHB), specifically RR Lyrae. We theorise that the high errors are due to their variable nature in a timescale shorter than Gaia's. There is also an outlier lying along the RGB, close to the helium flash.

VI. SUMMARY

In this report, we have estimated the age and metallicity of the GC NGC 6362, located in the inner Galactic halo, by isochrone fitting. We used Gaia DR3 data [8] and theoretical isochrones from BaSTI [18].

By adjusting the isochrones for extinction with two excess values, we have obtained two sets of results. Firstly, when adjusting with color excess $E(B-V) = 0.090$ [11], we obtained an estimated age of 12 Gyr and a metallicity Z of 0.001975. Secondly, for $E(B-V) = 0.056$, the obtained age was equal to the first case, and the metallicity Z was equal to 0.003920. Our estimates indicate this is an old cluster with low metallicity. Its CMD presents clear and separate branches, showing its stars are part of a SSP.

We have computed a χ^2 analysis to evaluate the goodness-of-fit of the isochrones to the CMD of the cluster. We obtained a χ^2 of 2.9×10^{-4} and 3.7×10^{-4} when using color excess $E(B-V) = 0.090$ and $E(B-V) = 0.056$ respectively. Thus, the first case is slightly better, but both fits are accurate as both have $\chi^2 < 0.1$.

Metallicity and reddening present degeneracy, so we have two results with the same age but different metallicity when we use different reddening values, producing two sets of good results.

Furthermore, we have found stars that possibly are RR Lyrae. These have high error but clearly land on the ZAHB of the CMD. We believe their high uncertainties are produced by their variability, as it has a shorter timescale than Gaia observing times. There is also an outlier close to the helium flash in the RGB.

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