The Hubble Space Telescope UV Legacy Survey of Galactic Globular Clusters

XXII. Relative ages of multiple populations in five Globular Clusters.

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ABSTRACT

Aims. We present a new technique to estimate the relative ages of multiple stellar populations hosted by five globular clusters: NGC104 (47Tuc), NGC6121 (M4), NGC6352, NGC6362 and NGC6723.

Methods. We used the catalogs of the database “HST UV Globular cluster Survey (HUGS)” to create color-magnitude and two-color diagrams of the Globular Clusters. We identified the multiple populations within each globular cluster, and we divided them into two main stellar populations: POPa or first generation (1G) and POPb, composed of all the successive generations of stars. The new technique allows us to obtain an accurate estimate of the relative ages between POPa and POPb.

Results. The multiple populations of NGC104 and NGC6121 are coeval within 220 Myr and 214 Myr, while those of NGC6352, NGC6362 and NGC6723 are coeval within 336 Myr, 474 Myr and 634 Myr, respectively. These results were obtained combining all the sources of uncertainties.

Key words. Techniques: photometric – Stars: Population II – (Galaxy:) globular clusters: general

1. INTRODUCTION

The concept that Galactic Globular Clusters (GCs) host multiple stellar populations is supported by an overwhelming amount of observational facts, and accepted by the astronomical community. However, the origin and the timescales for the formation and the evolution of multiple populations (MPs) are still under debate and study. The most accredited scenarios support that MPs phenomenon in GCs is due to multiple events of star formation. These formation scenarios consider the existence of a first generation (1G) characterized by stars having chemical properties similar to that of the interstellar medium out of which they formed, and a second generation (2G), formed from the material processed by 1G stars. Among the proposed alternatives to explain 2G stars, the intermediate mass Asymptotic giant branch (AGB) scenario (D’Antona et al. 2002) predicts that 2G stars were born from the AGB ejecta within 100 Myr (D’Ercole et al. 2012). On the other hand, de Mink et al. (2009) proposed that 2G population was born from processed low-velocity material ejected by massive stars with masses between 1.2-1.7 $M_\odot$, to explain the presence of double MS. The age is another fundamental factor, since the lower age limit of a star cluster to show MPs is 2 Gyr (Martocchia et al. 2017). The MPs in the young star cluster NGC1978 in the Magellanic Clouds are coeval within 1±20 Myr (Martocchia et al. 2018). Similarly, Saracino et al. (2019) found that the star cluster NGC2121 hosts coeval MPs within 6±12 Myr. These results reveal that young GCs put tighter constraints than older ones on the MPs formation timescale.

In the last years, the investigation of MPs was expanded to GCs outside the Milky Way (MW). The fact that not only our Galaxy hosts MPs allows us to compare GCs formed in systems with different star formation histories, providing clues on MPs phenomenon. Moreover, it turns out that the environment is not one primary requirement of MPs formation. Nardiello et al. (2019) analyzed the stellar populations within the GC Mayall II (G1), located in the halo of the nearby Andromeda galaxy. Several works focused on the discovery that intermediate age (1-2 Gyr) clusters in the Magellanic Clouds show extended main sequence turn off and splitted main sequence (MS) (Saracino et al. 2019, Gilligan et al. 2019, Martocchia et al. 2019). Bastian & de Mink (2009) proposed the rotational velocity of stars with masses between 1.2-1.7 $M_\odot$ to explain the presence of double MS. The age is another fundamental factor, since the lower age limit of a star cluster to show MPs is 2 Gyr (Martocchia et al. 2017). The MPs in the young star cluster NGC1978 in the Magellanic Clouds are coeval within 1±20 Myr (Martocchia et al. 2018). Similarly, Saracino et al. (2020) found that the star cluster NGC2121 hosts coeval MPs within 6±12 Myr. These results reveal that young GCs put tighter constraints than older ones on the MPs formation timescale.

The Treasury program “The Hubble Space Telescope (HST) UV Legacy Survey of Galactic Globular Clusters” (GO-
13297, P. Piotto, Piotto et al. (2015) provided us with an unprecedented UV dataset of more than 50 GCs. The aim of the project was the photometric characterization of the MPs in GCs by combining the new UV data with optical HST data from the program “ACS Survey of GCs” (GO-10775, P. Sarajedini, Sarajedini et al. 2006). Based on this dataset, Nardiello et al. (2015) developed a new procedure for evaluating the relative age of MPs within NGC6352, assuming the different populations in the cluster have the same metallicity. Recently, Oliveira et al. (2020) employed a new code to provide a statistical fitting of isochrones to observed CMDs and to derive age differences between 1G and 2G in Bulge GCs.

In this work, we present a new technique developed to estimate the relative age of MPs, using their main sequence turn off (MSTO) as indicator of age. The GCs we considered in this work are five: NGC104 (47Tuc), NGC6121 (M4), NGC6352, NGC6362 and NGC6723. A proper identification of 1G stars and those of subsequent generations is a fundamental point for the application of our method. For this reason, we selected these objects because they show well-separated multiple sequences in their UV CMDs. The last three GCs of our sample were previously analyzed by Nardiello et al. (2015) and Oliveira et al. (2020), providing a direct evaluation of the method reliability.

The paper is organized as follows. Data reduction and analysis are briefly described in Section 2. In section 3, we show the procedure adopted to characterize MPs within the GCs. In section 4, the new method is explained. The results and comparison with literature are discussed in section 5. Summary and conclusions follow in Section 6.

2. OBSERVATION AND DATA REDUCTION

In this work we used the catalogs obtained in the project “HST UV Globular cluster Survey” (HUGS) Nardiello et al. (2018a). For a detailed description of the data reduction pipeline used to obtain these catalogs, we refer the reader to Bellini et al. (2017) and Nardiello et al. (2018b). The catalogs contain the positions of the stars, the magnitude in five filters (F275W, F336W, F438W, F606W, and F814W), and quality parameters such as the photometric errors in a filter X (σX), the quality-of-fit (QFIT), and the shape of the source (SHARP).

To analyze the MPs within GCs, we selected well measured stars on the basis of these parameters, as done by Nardiello et al. (2018b). Briefly, we divided the sample of stars in a given filter X into bins of 0.5 magnitudes, and we calculated the 3σ-clipping median values in each bin. We interpolated these median values using a spline, and we rejected all the stars that are 3σ above (in the case of σX ) or below (in the case of QFIT) the median parameters. Stars with -0.2<SHARP<0.2 were considered as well measured. All stars that satisfy the three conditions were selected and used during the analysis data.

We used the procedure described in Milone et al. (2012a) to correct the magnitudes for differential reddening. In the case of NGC104, NGC6362 and NGC6723, the results obtained from this procedure do not lead either to a significant correction or to a considerable improvement of the CMDs. For this reason, we decided to continue the analysis without taking into consideration the differential reddening correction for these objects.

3. MULTIPLE STELLAR POPULATIONS WITHIN GLOBULAR CLUSTERS

Since optical filters are less sensitive to light elements variations, such as C, N and O, they allow us to identify MPs in CMDs only when metallicity and/or C+N+O content changes among the cluster stars (NGC1851, Milone et al. 2012b; M22, Milone et al. 2013). Each cluster analyzed in this work hosts stars having all the same metallicities and C+N+O content, and in this manuscript we refer to multiple populations as the phenomenon due to the variation of light elements (C,N,O) among the cluster stars. In this context, the UV HST filters F275W, F336W and F438W are efficient for the identification of MPs in GCs, because they are sensitive to the variations of the molecular bands of OH, NH, CH and CN. Taking advantage of this possibility, we selected stars on the MS, sub-giant branch (SGB) and red-giant branch (RGB) and rejected those that are not on these three evolutionary phases, in three steps. The GC NGC6362 is taken as an example in Fig. 1. First, we selected the stars in the F814W CMD (top panels). We draw by hand two fiducial lines: one on the blue and one on the red side of each evolutionary phase. We rejected the stars lying on the left-hand side and on the right-hand side of the blue and red fiducial lines, respectively (grey points). The stars lying between the two fiducial lines and in a specific F814W range were selected (black points).

Fig. 1. Procedure adopted to select MS (left-hand panels), SGB (middle panels) and RGB stars (right-hand panels) in the F814W CMD of NGC6362. The top panels show the median values in each bin. We interpolated these median values using a spline, and we rejected those that are not on these three evolutionary phases. The hand drawn fiducial lines of each evolutionary phase are reported in blue and red. Grey and black points represent rejected and selected stars, respectively. The F814W magnitude ranges where MS, SGB and RGB stars were selected are shown by horizontal dashed lines in the top panels.
In the $m_{\text{F814W}}$ versus $m_{\text{F336W}}$ CMD, considering the previously selected stars (middle panels), we followed the same procedure in the final step, we selected in the $m_{\text{F814W}}$ CMD diagram is represented by the histogram. Fitting a bimodal gaussian profile, we identified the $\Delta m_{\text{F275W}, \text{F336W}, \text{F438W}}$ value useful to separate the stars into the MPs which they belong to. The stars on the left and right hand-side of the cyan vertical line were classified as MSa and MSb, respectively. The two-color diagram $m_{\text{F336W}} - m_{\text{F438W}}$ versus $m_{\text{F275W}} - m_{\text{F336W}}$ of MS stars of each GC are shown in Figures 3 and 4. We built the same diagrams for SGB and RGB stars of each GC. Since in the two-color diagrams of SGB and RGB stars two sequences are always clearly visible, in this case we divided the MPs drawing by hand a continuous line. We identified stars below and above the line as stars belonging to POPa (green) and stars belonging to POPb (magenta), respectively. The samples of stars that belong to POPa and POPb of each GC analyzed in this work are formed by the combination of MS, SGB and RGB selected stars.

**4. RELATIVE AGE OF MPs WITHIN THE SELECTED GCs.**

The analysis of relative ages of MPs allows us to improve our knowledge about the formation and evolution of the different populations hosted by GCs.

In this work we propose a new technique to estimate the relative age of the two main populations, POPa and POPb, hosted by five GCs: NGC104 (47 Tuc), NGC6121 (M4), NGC6352, NGC6362, NGC6723. The previous section, we have taken advantage of the UV filters to identify the two main populations hosted by our sample of GCs. In order to obtain the relative age between POPa and POPb we considered them as simple stellar populations, and we used the optical $m_{\text{F814W}}$ versus $m_{\text{F606W}} - m_{\text{F814W}}$ CMD because (in first approximation) these filters are not affected by light element variations.

We estimated the relative age of the two populations comparing the observed MSTO color with theoretical models. The technique is inspired by the horizontal method introduced by [Rosenberg et al. 1999](#). This method considers a point on the RGB and the shape of this evolutionary phase mainly depends on the metallicity of the population. In “normal” GCs the different MPs have the same metal content within the errors, consequently, the point defined on the RGB will be almost the same. In order to avoid the introduction of more photometric errors associated with the RGB color in the computation of relative ages, we used a method that does not take into account this point. The innovation of our method resides on the MSTO colors difference, imposing strong constraints on metallicity and Helium content. In this way, we achieve a differential measure of age that is independent from distance and reddening.

**4.1. Theoretical models**

The procedure adopted to obtain the theoretical models is shown in Figure 5, where NGC6362 is taken as an example.
**Fig. 3.** The $m_{F336W} - m_{F438W}$ versus $m_{F275W} - m_{F336W}$ two-color diagram of MS (bottom panels), SGB (middle panels) and RGB (top panels) stars of POPa (green) and POPb (magenta) belonging to NGC104 (left-hand panels), NGC6121 (center panels), NGC6352 (right-hand panels).

**Table 1.** $\text{[Fe/H]}$ (Carretta et al. 2009 for NGC104, NGC2808, NGC6121, NGC6723; Nardiello et al. 2015 for NGC6352; Massari et al. 2017 for NGC6362), $\text{[α/Fe]}$, mean difference in helium $\Delta Y$ between POPa and POPb (Milone et al. 2018) and absolute age of POPa, Age(POPa), (Dotter et al. 2010), considered to obtain the theoretical model of each GC.

| Cluster   | $\text{[Fe/H]}$ | $\text{[α/Fe]}$ | $\Delta Y$  | Age(POPa) [Gyr] |
|-----------|-----------------|-----------------|--------------|----------------|
| NGC104    | -0.76 ± 0.02    | 0.4             | 0.011 ± 0.005 | 12.8 ± 0.5     |
| NGC6121   | -1.18 ± 0.02    | 0.4             | 0.009 ± 0.006 | 12.5 ± 0.5     |
| NGC6352   | -0.67 ± 0.02    | 0.4             | 0.019 ± 0.014 | 13.0 ± 0.5     |
| NGC6362   | -1.07 ± 0.05    | 0.4             | 0.003 ± 0.011 | 12.5 ± 0.5     |
| NGC6723   | -1.10 ± 0.07    | 0.4             | 0.005 ± 0.006 | 12.8 ± 0.5     |

**Table 2.** Value of color and magnitude of MSTO and observed $\delta_{c,T}$ obtained for POPa and POPb within GCs.

| Cluster   | MSTO(POPa) $m_{F606W} - m_{F814W}$ | MSTO(POPb) $m_{F606W} - m_{F814W}$ | $\delta_{c,T}$ |
|-----------|------------------------------------|------------------------------------|----------------|
| NGC104    | 0.5368±0.0004 17.024±0.004        | 0.5359±0.0002 16.994±0.002        | 0.0009±0.0005  |
| NGC6121   | 0.904±0.001    15.67±0.01         | 0.9039±0.0008 15.904±0.008        | 0.0005±0.0015  |
| NGC6352   | 0.768±0.001    17.765±0.009       | 0.763±0.001   17.925±0.009        | 0.005±0.001    |
| NGC6362   | 0.540±0.001    18.200±0.008       | 0.530±0.001   18.175±0.009        | 0.001±0.001    |
| NGC6723   | 0.5564±0.0005  18.273±0.005       | 0.5555±0.0004 18.309±0.004        | 0.0010±0.0007  |

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For POPa, we considered a set of isochrones from the Dartmouth Stellar Evolution Database\(^2\) (DSED, Dotter et al. 2008) characterized by \([\text{Fe/H}] = -1.07\), \([\alpha/\text{Fe}] = 0.4\), primordial helium \(Y_p = 0.2496\) and ages that run from 10 000 to 15 000 Myr, in step of 100 Myr. The groups of 2G stars in GCs are helium enriched. Milone et al. (2018) determined the average and the maximum helium difference between 2G and 1G stars in a sample of 57 GCs, including our targets. They estimated a mean \(\Delta Y = 0.003\) for NGC6362 and we assumed this value as helium difference between POPa and POPb of this cluster. In order to obtain a set of isochrones with helium content expected for POPb, we interpolated the set of isochrones of POPa and a set with same value of \([\text{Fe/H}], [\alpha/\text{Fe}]\) and range in age, but with \(Y = 0.33\). Panel (a) of Figure 5 shows three isochrones calculated for an age of 12.5 Gyr, \([\text{Fe/H}] = -1.07, [\alpha/\text{Fe}] = 0.4\), different helium content: the green model (POPa) has primordial helium \(Y_p = 0.2496\), while the red (for POPb) and blue ones have \(Y = 0.2496\) and \(Y = 0.33\), respectively. We interpolated with a spline each isochrone of both the sets for POPa and POPb with a vector having absolute F814W magnitude \(0 \leq M_{F814W} \leq 6\), whose points are evenly spaced by 0.001 mag. For each isochrone of each population, we identify the MS turn-off (MSTO) as the bluer point of the MS. In order to obtain a theoretical model appropriate for NGC6362, we considered for POPa the isochrone having \([\text{Fe/H}] = -1.07, [\alpha/\text{Fe}] = 0.4, Y_p = 0.2496\) and absolute age 12.5 Gyr (Dotter et al. 2010), and for POPb the isochrones with the same value of \([\text{Fe/H}]\) and \([\alpha / \text{Fe}]\), but \(Y = 0.2526\) and all ages. We derived the difference in color between the MSTOs, \(\delta c_{TO}\), as the difference between the MSTO color of POPa and POPb. In panel (b) of Fig. 5 we show two cases to clarify this passage. The green isochrone represents POPa and corresponds to \([\text{Fe/H}] = -1.07, [\alpha/\text{Fe}] = 0.4, Y_p = 0.2496\) and an absolute age of 12.5 Gyr. POPb is represented by the purple and cyan isochrones, which are calculated by assuming the same value of \([\text{Fe/H}]\) and \([\alpha / \text{Fe}]\), but \(Y = 0.2526\) and ages 11 Gyr and 10 Gyr, respectively. The corresponding MSTOs of each isochrone are reported as a dot, colored as their isochrone. The corresponding difference in color, \(\delta c_{TO}\), are shown as purple and cyan lines. We calculated \(\Delta \text{Age}\) subtracting from the MSTO age of POPa, i.e the absolute age of 12.5 Gyr, the MSTO age of all the isochrones of POPb. The theoretical model \(\delta c_{TO} \text{vs } \Delta \text{Age}\) is reported in panel (c) of Fig. 5. The purple and cyan points represent the cases explained in panel (b). In order to obtain a more robust model we interpolated these points with a second-

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\(^{2}\)http://stellar.dartmouth.edu/models/
Fig. 5. Procedure adopted to obtain the reference theoretical models for NGC6362. Panel (a) shows three isochrones of 12.5 Gyr, for [Fe/H]=-1.07, [$\alpha$/Fe]=0.4 and different helium content. The red isochrone with Y=0.2526 (helium-enriched by $\Delta Y=0.003$) is obtained interpolating the isochrone with primordial helium, $Y_p=0.2496$ (green), with the Y=0.33 helium-enriched one (blue). Panel (b) shows how the difference in color among the MSTOs, from which the $\delta_{c TO}$ is calculated. The green isochrone is the same as in panel (a) and represents POPa. The purple and cyan isochrones have the same chemical content as the red isochrone of panel (a), but with age of 11 Gyr and 10 Gyr, respectively. The corresponding $\delta_{c TO}$ of each case is a horizontal line. The theoretical model $\delta_{c TO}$ vs $\Delta$Age for NGC6362 is shown in panel (c). The purple and cyan points are the theoretical model values as obtained from the cases of panel (b).

order polynomial, where the order was chosen to minimize the $\chi^2$ between the polynomial and the observed profile. In this way, we obtained the black theoretical model. Performing the same procedure and considering the values of [Fe/H] (Carretta et al. 2009 for NGC104, NGC6121, NGC6723; Nardiello et al. 2015 for NGC6352; Massari et al. 2017 for NGC6362), [$\alpha$/Fe], $\Delta Y$ (Milone et al. 2018) and absolute age (Dotter et al. 2010) reported in Table 1, we achieved the theoretical models of the other GCs. A different choice of $\alpha$-enrichment strongly influence the models trend on the RGB, while the position of the MSTO changes insignificantly. Since the sum of light elements is constant, we can assume the same [$\alpha$/Fe] value for POPa and POPb, making the relative MSTO position even more invariant.

It is worth noting that the theoretical models are built assuming a fixed absolute age for POPa based on the Dotter et al. (2010) estimation, which uncertainties are of 0.5 Gyr. In Appendix A, we evaluate how the theoretical model is affected by this error, and we prove that it does not influence the final relative age result.

4.2. The relative age

To obtain the relative age between POPa and POPb within the five GCs we compared the theoretical models and the observed $\delta_{c TO}$ values, as shown in Figures 6 and 7. The GC NGC6362 in the middle panel of Figure 7 is taken as an example to explain this step. We measured the color and the magnitude of the MSTOs of POPa and POPb, making the relative MSTO position even more invariant.
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Fig. 6. Application of our technique to estimate the relative ages of MPs in NGC104 and NGC6121. In the observed $m_{F814W}$ versus $m_{F606W} - m_{F814W}$ CMDs POPa (green), POPb (magenta) and their respective MSTOs are plotted. The inserts (a) show a zoomed of the MSTO region. The blue and red fiducial lines are representative of POPa and POPb, respectively. The theoretical models in the insert (b) were obtained assuming the parameters list on the top of the figure.

Fig. 7. The MSTO colors and $F814W$ magnitudes and the observed $\delta c_{TO}$ obtained for the five GCs considered in this work are reported in Table 2. In order to estimate the relative age between POPa and POPb in NGC6362, in the insert of Figure 7, we show the observed $\delta c_{TO}$ on the theoretical model. We concluded that the two main populations of NGC6362 have a difference in age $\Delta Age=73^{\pm}92$ Myr. The uncertainty associated to this estimation of relative age was obtained interpolating the $\delta c_{TO}$ errors with the theoretical model, and it is only due to internal errors.

In addition to these internal errors, we analyzed how the
Fig. 7. As in Figure 6 for the GCs NGC6352, NGC6362 and NGC6723.

helium uncertainty $\sigma_{\Delta Y} = \pm 0.011$ (Milone et al. 2018) and the metallicity one $\sigma_{[Fe/H]} = \pm 0.05$ (Massari et al. 2017) affect the measure of $\Delta$Age. We produced two additional sets of isochrones for POPb characterized by the same $[Fe/H]=-1.07$ and $[\alpha/Fe]=0.4$ of POPa, but with two different helium enhancements: $\Delta Y=0.003+0.011=0.014$ and $\Delta Y=0.003-0.011=-0.008$. We extracted the theoretical models, adopting these two helium enhanced isochrones for POPb and the same isochrone as used above for POPa. Following the procedure previously outlined and comparing the observed $\delta c_{TO}$ with these models we found that an uncertainty of $\pm 0.011$ dex in $\Delta Y$ leads to an uncertainty on $\Delta$Age of $\sigma_{\Delta$Age$(\Delta Y)} = \pm 126$ Myr. Similarly, we calculated the impact of $[Fe/H]$ variations on the estimate of $\Delta$Age. In this case, we used for POPb two sets of isochrones with $[\alpha/Fe]=0.4$, enhanced in helium by $\Delta Y=0.003$ but different metallicity: $[Fe/H]=-1.07 + 0.05 = -1.02$ and $[Fe/H]=-1.07 - 0.05 = -1.12$. We found that an error of $\sigma_{[Fe/H]}=\pm 0.05$ produce an uncertainty $\sigma_{\Delta$Age$([Fe/H])} = 448$ Myr.

Combining all the sources of uncertainties we can establish an upper limit for the uncertainty of the relative age between the two main populations within the cluster. We found that POPa and POPb of NGC6362 are coeval within $\sim 474$ Myr.

We performed the same procedure for the other GCs using the values reported in Table 1. The final results are summarized in Table 3.

5. DISCUSSION

The mechanisms that have brought to the formation of MPs in GCs are still subject of debate. Despite the increasing interest in this topic in the last couple of decades, further and deeper analyses are needed. This work aims to introduce a new technique that can contribute to put light on this astronomical issue. Indeed, a good relative age estimate of MPs leads to clues regarding the formation and the evolution of these last.

In literature, most of the works on the relative age of MPs concern GCs with a large variation of metallicity between different populations. According to Marino et al. (2012), M22 hosts MPs coeval within $\sim 300$ Myr. Studying the globular cluster NGC2419, Lee et al. (2013) showed that this object hosts two stellar populations characterized by a large difference in metallicity and helium abundance. They found
that the most metal-rich population is younger than 2 Gyr. The relative ages of the MPs in NGC 2808 were analyzed by Roh et al. (2011); they found that, if 2G stars are helium and metal enhanced by ΔY = 0.03 and ΔY = 0.16, respectively, compared to 1G stars, then the 2G population is ~1.5 Gyr younger than the 1G population.

Using HST data, Souza et al. (2020) estimated an age difference of 550 ± 410 Myr between the first and the third generations in NGC 6752. The uncertainty of their result decreases to 400 Myr when the helium enhancement is considered.

We compare the results in literature with what we obtained in this work, in cases where the same source of uncertainties were taken into account.

Nardiello et al. (2015) applied isochrone fitting over synthetic CMDs with χ^2 calculations to evaluate the relative age of MPs within NGC 6352. Assuming [Fe/H] = -0.67, [α/Fe] = +0.4 and ΔY = 0.029, they derived an age difference of 10 ± 110 Myr. Considering the same value of metallicity and α-enhancement and ΔY = 0.019, we estimate ΔAge = 273 ± 150 Myr for NGC 6352. Adopting a difference in [Fe/H] and [α/Fe] of 0.02 dex, Nardiello et al. (2015) found that the two populations are coeval within ~300 Myr. This result is perfectly in agreement with our value of σΔAge = 336 Myr, when all the uncertainties are considered.

Recently, Oliveira et al. (2020) used statistical isochrone fitting to estimate the relative age of MPs within eight GCs: NGC 6304, NGC 6352, NGC 6624, NGC 6637, NGC 6652, NGC 6717 and NGC 6723. They found that the individual MPs are coeval within 500 Myr. Moreover, they derived a weighted mean age difference of 41 ± 170 Myr adopting canonical He abundances, which reduces to 17 ± 170 when He-enhancement is taken into account.

Considering [Fe/H] = -0.59, [α/Fe] = +0.2 and ΔY = 0.027, they derived an age difference of 500 ± 480 Myr for NGC 6352. This estimation is comparable to our of 273 ± 150 Myr.

Assuming 2G He-enriched by ΔY = 0.004, Oliveira et al. (2020) found that the relative age of MPs in NGC 6362 is -200 ± 410 Myr. Using ΔY = 0.003, we estimated ΔAge = 73 ± 92 Myr. Despite our mean differential age estimation is slightly higher, it agrees within 1σ with the value obtained by Oliveira et al. (2020).

Finally, we found ΔAge = 25 ± 65 Myr for the MPs in NGC 6723, which is in agreement with the difference in age -100 ± 510 Myr obtained by Oliveira et al. (2020).

In Figure 8, this work and literature results for GCs in common are compared. We conclude that our new technique leads to consistent results with those in literature and with, on average, smaller error bars.

### Table 3. MPs relative ages and their uncertainties.

| CLUSTER | ΔAge (Myr) | σΔAge (Internal) (Myr) | σΔAge (ΔY) (Myr) | σΔAge ([Fe/H]) (Myr) | σΔAge (Δα/ΔFe) (Myr) |
|---------|------------|------------------------|------------------|---------------------|-----------------------|
| NGC 104 | -70        | 49                     | 74               | 202                 | +220                  |
| NGC 6121 | -77       | 130                    | 68               | 157                 | +214                  |
| NGC 6352 | 273      | 150                    | 206              | 220                 | +336                  |
| NGC 6362 | 73        | 92                     | 126              | 448                 | +474                  |
| NGC 6723 | 25        | 65                     | 72               | 627                 | +634                  |

6. CONCLUSIONS

We developed a new technique to estimate the relative ages of the MPs hosted by GCs. In this work, we applied the method to five clusters: NGC 104, NGC 6121, NGC 6352, NGC 6362, NGC 6723. We used the astro-photometric catalogs released by Nardiello et al. (2018a) and we selected the well measured stars on the basis of their photometric parameters. A statistical test was used to divide the MPs along the MS of the GCs. We built the mF336W - mF438W versus mF275W - mF336W two-color diagram of SGB and RGB stars in order to divide the stars in the different evolutionary phases into the populations which they belong to. We defined POPa as the 1G stars and POPb as all the successive generations of stars, and we considered them as simple stellar populations to estimate their relative age.

Considering the values of [Fe/H], [α/Fe], Y reported in Tab. 4, we built the δcTO versus ΔAge theoretical model for each GCs. We defined δcTO as the difference in color...
between the MSTO color of a fixed isochrone age for POPa and the MSTO of all ages isochrones for POPb and the ΔAge as the difference between a fixed age of POPa and all the ages of POPb. The observed δCTO was calculated in the mF814W versus mF606W − mF814W CMD, and we obtained the relative age between the two main populations. The conclusions drawn from our new technique are:

- An uncertainty of ±0.5 Gyr (Dotter et al. [2010]) on the absolute age of POPa does not affect the final value of the relative ages (see Appendix A);
- Combining all the sources of uncertainties (photometry, metallicity and He-enrichment) we estimated an upper limit on the relative ages. We found that the MPs of NGC 104 and NGC 6121 are coeval within 220 Myr and 214 Myr, while those of NGC 6352, NGC 6362 and NGC 6723 are coeval within 336 Myr, 474 Myr and 634 Myr.
- Within the limits of the errors on relative ages indicated above, the different populations in the single clusters are coeval.

The results obtained with our technique are consistent with those in literature. We can affirm that the new method is a good tool to estimate relative ages of MPs within GCs. Finally, our results turn out new observational evidence to put constrains on the formation of MPs in GCs. Several theoretical scenarios were proposed to explain this astronomical topic, even if none of them is able to explain all the observational facts obtained in the last years (Renzini et al. 2015). The most accredited scenarios involve Intermediate Massive AGB stars (D'Antona et al. 2002, D'Ercole et al. 2012), Fast Rotating Massive Stars (Decressin et al. 2007a, 2007b), Massive Interacting Binaries (de Mink et al. 2009, Bastian et al. 2013), or Supermassive stars (Denissenkov & Hartwick 2014, Denissenkov et al. 2015). According to these scenarios the time scales for the formation of the other populations run from few million years to some hundred Myr. Unfortunately, with the results obtained in this work we can not discriminate which scenario is the most appropriate to describe the formation of MPs. Anyway joining our results with the relative ages measured in previous works, we can put a strong constraint: the formation of MPs happens on the same time scale for all the normal GCs.

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Appendix A: Theoretical model

The relative age values are given comparing the observed $\delta c_{TO}$ and the theoretical models. The theoretical models are based on an assumption on the absolute age of POPa. In this work, we adopted the ages obtained by Dotter et al. (2010), with an average uncertainty of $\pm0.5$ Gyr. This appendix aims to investigate how the error on the POPa age affects the theoretical model and, consequently, the relative age estimate.

With this purpose, we take the GC NGC6362 as example. In this cluster, we assumed for POPa an isochrone characterized by $[\text{Fe/H}]=-1.07$ (Massari et al. 2017), $[\alpha/\text{Fe}]=+0.4$, primordial helium Y=0.2496 and age 12.5 Gyr (Dotter et al. 2010). On the other hand, the set of isochrones for POPb has same $[\text{Fe/H}]$ and $[\alpha/\text{Fe}]$, He-enrichment $\Delta Y=0.003$ (Milone et al. 2018) and ages that run from 10 000 Myr to 15 000 Myr, in step of 100 Myr. As described in section 4.1 and Figure 5, we derived the theoretical model for this GC, as shown in Figure A.1 with the color magenta. Reporting the observed $\delta c_{TO}$ on this profile, we obtained a relative age of $73 \pm 92$ Myr. The same Figure displays the theoretical models obtained considering an age of 12 Gyr (cyan) and 13 Gyr (green) for POPa. As shown in the insert, there is a negligible difference among the three models in the region where the observed $\delta c_{TO}$ lies. Indeed, the relative ages found considering the cyan and green models are $94 \pm 87$ Myr and $78 \pm 97$ Myr, respectively. We conclude that an uncertainty of $\pm0.5$ Gyr on the absolute age of POPa does not affect the final relative age result.

Furthermore, we performed a deeper analysis to evaluate how the choice of POPa age affects the theoretical model. We applied the method for NGC6362 considering POPa ages of 10.5 Gyr (blue) and 14.5 Gyr (orange), as shown in Figure A.2. From these cases, we estimated relative ages of $62 \pm 75$ Myr and $107 \pm 118$ Myr, respectively. Despite the inclination variation of the theoretical model, the final results are consistent within error bars. We can affirm that a different choice of POPa age within $\pm2$ Gyr, which is the typical range of GC ages, does not affect the relative age value estimated with our technique.

Fig. A.1. Application of the new technique to estimate the relative age of MPs within NGC6362. The theoretical models were obtained considering POPa ages of 12 Gyr (cyan), 12.5 Gyr (magenta) and 13 Gyr (green). A better comparison between the three models is shown in the insert.

Fig. A.2. Application of the new technique to estimate the relative age of MPs within NGC6362. The theoretical models were obtained considering POPa ages of 10.5 Gyr (blue), 12.5 Gyr (magenta) and 14.5 Gyr (orange).