Observing multiple stellar populations with FORS2@VLT

Main sequence photometry in outer regions of NGC 6752, NGC 6397, and NGC 6121 (M 4).*

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ABSTRACT

Aims. We present the photometric analysis of the external regions of three Galactic Globular Clusters: NGC 6121, NGC 6397 and NGC 6752. The main goal is the characterization of the multiple stellar populations along the main sequence (MS) and the study of the radial trend of the different populations hosted by the target clusters.

Methods. The data have been collected using FORS2 mounted at the ESO/VLT@UT1 telescope in UBV filters. From these data sets we extracted high-accuracy photometry and constructed color-magnitude diagrams. We exploit appropriate combination of colors and magnitudes which are powerful tools to identify multiple stellar populations, like $B$ versus $U-B$ and $V$ versus $C_{UBRI} = (U-B)-(B-I)$ CMDs.

Results. We confirm previous findings of a split MS in NGC 6752 and NGC 6121. Apart from the extreme case of ω Centauri, this is the first detection of multiple MS from ground-based photometry. For NGC 6752 and NGC 6121 we compare the number ratio of the blue MS to the red MS in the cluster outskirts with the fraction of first and second generation stars measured in the central regions. There is no evidence for significant radial trend. The MS of NGC 6397 is consistent with a simple stellar population. We propose that the lack of multiple sequences is due both to observational errors and to the limited sensitivity of $U, B, V, I$ photometry to multiple stellar populations in metal-poor GCs.

Finally, we compute the helium abundance for the stellar populations hosted by NGC 6121 and NGC 6752, finding a mild ($\Delta Y \sim 0.02$) difference between stars in the two sequences.

1. Introduction

Over the last years, the discovery that the color-magnitude diagrams (CMDs) of many globular clusters (GCs) are made of multiple sequences has provided overwhelming proof that these stellar systems have experienced a complex star-formation history. The evidence that GCs host multiple stellar populations has reawakened the interest on these objects both from the observational and the theoretical point of view.

Multiple sequences have been observed over all the CMD, from the main sequence (MS, e.g. [Piotto et al. 2007]) through the sub-giant branch (SGB, e.g. [Piotto et al. 2012]) and from the SGB to the red-giant branch (RGB, e.g. [Marino et al. 2008]) and even in the white-dwarf cooling sequence ([Bellini et al. 2013a]).

Multiple populations along the RGB have been widely studied in a large number of GCs (e.g. [Yong et al. 2008], [Lee et al. 2008], [Monelli et al. 2013]) by using photometry from both ground-based facilities and from the Hubble Space Telescope (HST). In contrast, with the remarkable exception of ω Centauri ([Sollima et al. 2007], [Bellini et al. 2009b]), the investigation of multiple MSs has been carried out with HST only (e.g. [Bedin et al. 2004], [Piotto et al. 2007], [Milone et al. 2012a] and references therein, [Bellini et al. 2013b]).

In this paper we will exploit the FOcal Reducer and low dispersion Spectrograph 2 (FORS2), mounted at the Very Large Telescope (VLT) of the European Southern Observatory (ESO) to obtain accurate $U, B, V, I$ photometry of MS stars in the outskirts of three nearby GCs, namely NGC 6121 (M 4), NGC 6397, and NGC 6752, and study their stellar populations.

The paper is organized as follows: in Sect.2 we provide an overview on the three GCs studied in this paper. The observations and the data reduction are described in Sect.3. The CMDs are analyzed in Sect.4 where we also show evidence of bimodal MSs for stars in the outskirts of NGC 6121 and NGC 6752 and calculate the fraction of stars in each MS. In Sect.5 we study the radial distribution of stellar populations in NGC 6752 and NGC 6121. In Sect.6 we estimate the helium difference between the two stellar populations of NGC 6121 and NGC 6752. A summary follows in Sect.7.

* Based on observations at the European Southern Observatory using the Very Large Telescope on Cerro Paranal through ESO programme 089.D-0978 (P. I. G. Piotto)
element abundance. NGC 6397 exhibits modest star-to-star variability that the RGB stars of this cluster show a spread in light-elemen-
tations of oxygen and sodium and a mild Na-O anti-correlation (e.g. Norris 1981, Carretta et al. 2007, 2012) in close analogy with what was ob-
served in most Galactic GCs (see e.g. Carretta et al. 2005, Yong et al. 2008, 2003, Carretta et al. 2012, Monelli et al. 2013). In particular, there are three main groups of stars with different Na, O, N, Al, that populate three different RGBs when appropriate indices are used (like the c1 and c2 Stromgren indices or the cUBJ visual index, Yong et al. 2008, 2003, Carretta et al. 2012, Monelli et al. 2013). As shown by Milone et al. 2013 (hereafter Mi13), the CMD of NGC 6752 is made of three distinct sequences that can be followed continuously from the MS to the SGB and from the SGB to the RGB. These sequences correspond to three stellar populations with different light-element and helium abundance.

3. Observations and data reduction

For this work we used 2 × 2 binned images taken with the ESO/FORS2 (2 × 2 k × 4 k MIT CCDs) mounted at the VLT, using the standard resolution collimator. With this configuration, the field of view of FORS2 is reduced to ~ 6.8′ × 6.8′ by the MOS unit in the focal plane and the pixel scale is ~ 0″/25/pixel. The dithered images of NGC 6121, NGC 6397 and NGC 6752 were used (like the F225W, F336W from HST/WFC3) are used. Observations of the double MSs from multi-wavelength HST photometry have been interpreted with two stellar pop-
ulations with different light-element abundance and a modest helium variation of ΔY ~0.01 (di Criscienzo et al. 2010, Milone et al. 2012).

2. Properties of the target GCs

Multiple stellar populations have been widely studied in the three GCs analyzed in this paper. In this section we summarize the observational scenario and provide useful information to interpret our observations.

2.1. NGC 6121

NGC 6121 is the closest GC (d ~ 2.2 kpc) and has intermediate metal abundance ([Fe/H]=−1.16 [Harris 1996, 2010 edition]). The RGB stars of this cluster exhibit a large spread in the abundance distribution of some light-elements such as C, N, O, Na and Al (Gratton et al. 1986, Brown et al. 1990, Drake et al. 1992, Smith & Briley 2005). There is evidence of a CN bimodality distribution and Na-O anticorrelation (e.g. Norris 1981, Ivans et al. 1999). The distribution of sodium and oxygen is also bimodal. Sodium-rich (oxygen-poor) stars define a red sequence along the RGB in the U versus $U−B$ CMD, while Na-poor stars populate a bluer RGB sequence (Marino et al. 2008). Further evidence of multiple sequences along the RGB of NGC 6121 is provided by Lee et al. (2009) and Monelli et al. (2013). NGC 6121 has a bimodal HB, populated both on the blue and red side of the instability strip. The HB morphology of this cluster is closely connected with multiple stellar populations, indeed blue HB stars are all Na-rich and O-poor (hence belong to the second stellar generation) while red-HB stars have the same chemical composition as first-generation ones (Marino et al. 2011).

2.2. NGC 6397

Located at a distance of 2.3 kpc, NGC 6397 is a very metal-poor GC ([Fe/H] = −2.02 [Harris 1996, 2010 edition]). In late 1970s, Bell et al. (1979) have already demonstrated that the RGB stars of this cluster show a spread in light-element abundance. NGC 6397 exhibits modest star-to-star variations of oxygen and sodium and a mild Na-O anti-correlation (e.g. Ramírez & Cohen 2002, Carretta et al. 2005). Similarly to NGC 6121 the distribution of sodium and oxygen is bimodal, and the groups of Na-rich (O-poor) and Na-poor (O-rich) stars populate two distinct RGBs in the Strömgren y versus c1 index diagram (Lind et al. 2011). The MS of NGC 6397 is also bimodal, but the small color separation between the two MSs can be detected only when appropriate filters (like the F225W, F336W from HST/WFC3) are used. Observations of the double MSs from multi-wavelength HST photometry have been interpreted with two stellar populations with different light-element abundance and a modest helium variation of ΔY ~0.01 (di Criscienzo et al. 2010, Milone et al. 2012).

2.3. NGC 6752

NGC 6752 is a nearby metal-poor GC (d = 4.0 kpc, [Fe/H] = −1.54 [Harris 1996, 2010 edition]). More recent works confirm star-to-star light-element variations in NGC 6752 (Grundahl et al. 2002, Yong et al. 2003, 2008, 2013, Carretta et al. 2005, O-Na, Mg-Al, C-N (anti-)correlations for both unevolved (Gratton et al. 2001, Shen et al. 2010, Pancino et al. 2010) and RGB stars (Yong et al. 2005, Carretta et al. 2007, 2012) in close analogy with what was observed in most Galactic GCs (see e.g. Ramírez & Cohen 2002, Carretta et al. 2007, 2009 and references therein). In particular, there are three main groups of stars with different Na, O, N, Al, that populate three different RGBs when appropriate indices are used (like the c1 and c2 Stromgren indices or the cUBJ visual index, Yong et al. 2008, 2003, Carretta et al. 2012, Monelli et al. 2013). As shown by Milone et al. 2013 (hereafter Mi13), the CMD of NGC 6752 is made of three distinct sequences that can be followed continuously from the MS to the SGB and from the SGB to the RGB. These sequences correspond to three stellar populations with different light-element and helium abundance.
This plot shows that there is an important gradient of brightness with distance. This gradient changes with time and with the position of the Sun relative to the pointing of the telescope and could produce a photometric zero point variation across the FORS2 detectors. The illumination gradient in the flat fields could contribute to the observed enlargement of the CMDs.

We obtained star fluxes using local sky values, and therefore it is expected that these systematic effects are negligible. If the gradient in the flat-field images is not properly removed during the pre-reduction procedure, the pixel quantum efficiency correction will be wrong. The consequence is that the luminosity of a star measured in a given location of the CCD will be underestimated (or overestimated) with respect to the luminosity of the same star measured in another location of the CCD.

Using the measured star positions and fluxes, we performed a correction in a similar way to what described by Bellini et al. (2009a). It is a self-consistent auto-calibration of the illumination map and takes advantage of the fact that the images are well dithered.

For each cluster and for each filter, the best image (characterized by lower airmass and best seeing) is defined as reference frame. We computed each star position and magnitude in each individual exposure using an appropriate PSF and to obtain a catalog of stars for each frame. We registered, for each cluster and for each filter, all star positions and magnitudes of each catalog into a common frame (master-frame) using linear transformations. The final result is a list of stars (master list) for each cluster. For each filter and each star measured in NGC 6121, in Fig. 2 we plot the rms of the photometric residual and of the position as a function of the mean magnitude. In the case of NGC 6752 and NGC 6397 the distributions are similar. As required by the referee, we specify here that we used magnitude to express the luminosities of stars in this paper.

We noted that all the CMDs of the three GCs showed unusually spread out sequences (see panel (a) of Fig. 3 for an example of the V versus U − V CMD of NGC 6397). Part of this spread is due to differential reddening, but this is not the only cause. In fact, we found that, selecting stars in different regions of the master list, we obtained shifted MSs. As an example, in panel (d) of Fig. 3 we show the variation of the color Δ(U − V) for NGC 6397. This plot shows that there is an important gradient of Δ(U − V) along the x-axis. We selected in this plot two groups of stars: the stars with x > 1050 and that with x < 1050. We plotted these two sub-samples in the V versus U − V CMDs, respectively in black crosses (x > 1050) and red circles (x < 1050); panel (a) of Fig. 3 shows the result. The two groups form two shifted MSs. This effect is present in all the CMD of the three GCs, even if with different extent levels.

Table 1. Log of observations

| Filter       | Exp. time | Airmass (sec ζ) | Seeing (arcsec) |
|--------------|-----------|-----------------|-----------------|
| **NGC 6121** |           |                 |                 |
| u_HIGH       | 25 × 410 s| 1.004−1.104     | 0′:58−0′:90     |
| b_HIGH       | 25 × 200 s| 1.007−1.113     | 0′:71−1′:20     |
| v_HIGH       | 25 × 52 s | 1.118−1.251     | 0′:70−1′:21     |
| I_BESS       | 25 × 30 s | 1.036−1.150     | 0′:56−1′:03     |
| **NGC 6397** |           |                 |                 |
| u_HIGH       | 25 × 410 s| 1.153−1.452     | 0′:81−1′:09     |
| b_HIGH       | 35 × 200 s| 1.144−1.599     | 0′:73−1′:52     |
| v_HIGH       | 50 × 52 s | 1.142−1.272     | 0′:82−1′:23     |
| I_BESS       | 25 × 30 s | 1.251−1.355     | 0′:70−1′:21     |
| **NGC 6752** |           |                 |                 |
| u_HIGH       | 25 × 410 s| 1.227−1.416     | 0′:67−1′:30     |
| b_HIGH       | 33 × 200 s| 1.227−1.850     | 0′:49−1′:36     |
| v_HIGH       | 25 × 52 s | 1.367−1.483     | 0′:68−0′:86     |
| I_BESS       | 25 × 30 s | 1.293−1.363     | 0′:50−0′:77     |

Freudling et al. (2007) showed that there is an illumination gradient in the FORS2 flats produced by the twilight sky. This gradient changes with time and with the position of the Sun relative to the pointing of the telescope and could produce a photometric zero point variation across the FORS2 detectors.

**Fig. 2.** The photometric (left panels and top-right panel) and position residuals (middle- and bottom-right panels) from the single measurements in the single images of NGC 6121 plotted as a function of the average magnitude. Grey points show all detected stars; black points refer to proper motion selected stars. In the case of NGC 6752 and NGC 6397 the distributions are similar.

**Fig. 3.** Shows the variation of the color CMDs, respectively in black crosses (x > 1050) and red circles (x < 1050); panel (a) of Fig. 3 shows the result. The two groups form two shifted MSs. As an example, in panel (d) of Fig. 3 for an example of the V versus U − V CMD of NGC 6397. Part of this spread is due to differential reddening, but this is not the only cause. In fact, we found that, selecting stars in different regions of the master list, we obtained shifted MSs. As an example, in panel (d) of Fig. 3 we show the variation of the color Δ(U − V) for NGC 6397. This plot shows that there is an important gradient of Δ(U − V) along the x-axis. We selected in this plot two groups of stars: the stars with x > 1050 and that with x < 1050. We plotted these two sub-samples in the V versus U − V CMDs, respectively in black crosses (x > 1050) and red circles (x < 1050); panel (a) of Fig. 3 shows the result. The two groups form two shifted MSs. This effect is present in all the CMD of the three GCs, even if with different extent levels.

We acquired using u_HIGH, b_HIGH, v_HIGH and I_Bessel broad band filters between April 14, 2012 and July 23, 2012. A detailed log of observations is reported in Table 1. Figure 1 shows the combined field of view for each cluster.

For the data reduction we used a modified version of the software described in Anderson et al. (2006). Briefly, for each image we obtained a grid of 18 spatially varying empirical point spread functions (PSFs, an array of 3 × 3 PSFs for each chip of FORS2) using the most isolated, bright and not saturated stars. In this way, to each pixel of the image corresponds a PSF that is a bi-linear interpolation of the closest four PSFs of the grid. This makes it possible to measure star positions and fluxes in each individual exposure using an appropriate PSF and to obtain a catalog of stars for each frame. We registered, for each cluster and for each filter, all star positions and magnitudes of each catalog into a common frame (master-frame) using linear transformations. The final result is a list of stars (master list) for each cluster. For each filter and each star measured in NGC 6121, in Fig. 2 we plot the rms of the photometric residual and of the position as a function of the mean magnitude. In the case of NGC 6752 and NGC 6397 the distributions are similar. As required by the referee, we specify here that we used magnitude to express the luminosities of stars in this paper.

We noted that all the CMDs of the three GCs showed unusually spread out sequences (see panel (a) of Fig. 3 for an example of the V versus U − V CMD of NGC 6397). Part of this spread is due to differential reddening, but this is not the only cause. In fact, we found that, selecting stars in different regions of the master list, we obtained shifted MSs. As an example, in panel (d) of Fig. 3 we show the variation of the color Δ(U − V) for NGC 6397. This plot shows that there is an important gradient of Δ(U − V) along the x-axis. We selected in this plot two groups of stars: the stars with x > 1050 and that with x < 1050. We plotted these two sub-samples in the V versus U − V CMDs, respectively in black crosses (x > 1050) and red circles (x < 1050); panel (a) of Fig. 3 shows the result. The two groups form two shifted MSs. This effect is present in all the CMD of the three GCs, even if with different extent levels.
We divided each FORS2 chip in a spatial grid of 10 × 10 boxes, and, for each box, we computed the average of the residuals from the stars located in that region in each single image. This provides a first spatial correction to our photometry. To obtain the best correction, we iterate until the residual average became smaller than 1 mmag. To guarantee convergence we applied, for each star, half of the correction calculated in each box. Moreover, to obtain the best correction at any location of the camera, we computed a bi-linear interpolation of the closest 4 grid points. At the edges of the detectors the correction is less efficient, because the corresponding grid-points have been moved toward the external borders of the grid to allow the bi-linear interpolation to be computed all across the CCDs. In panel (e) of Fig. 3 we show our final correction grid for the v_HIGH filter.

The final correction grids are different for each filter and for each set of images. In particular, the patterns are different from filter to filter, as well as the size of the zero point variations. This quantity also changes using different data-sets. The maximum amplitudes of our corrections are tabulated in Table 2.

We corrected the spread of the CMD due to differential reddening using the procedure as described by Milone et al. (2012b). Briefly, we defined a fiducial line for the MS of the cluster. Then, for each star, we considered a set of neighbors (usually 30, selected anew for each filter combination) and estimated the median offset relative to the fiducial sequence. These systematic color and magnitude offsets, measured along the reddening line, represent an estimate of the local differential reddening. With this procedure we also mitigated the photometric zero-point residuals left by the illumination correction (especially close to the corners of the field of view). Panel (c) of Fig. 3 shows the CMD after all the corrections are applied.

The photometric calibration of FORS2 data for UBV Johnson and Ic Cousins bands was obtained using the photometric Secondary Standards star catalog by Stetson (2000). We matched our final catalogs to the Stetson standard ones, and derived calibration equations by means of least squares fitting of straight lines using magnitudes and colors.

Table 2. Maximum amplitudes of photometric zero-points corrections.

| Filter   | NGC 6121 | NGC 6397 | NGC 6752 |
|----------|----------|----------|----------|
| u_HIGH   | 0.11     | 0.13     | 0.09     |
| b_HIGH   | 0.04     | 0.05     | 0.03     |
| v_HIGH   | 0.12     | 0.04     | 0.06     |
| I_BESS   | 0.04     | 0.04     | 0.04     |

3.1. Proper motions

Since NGC 6121 (l,b=350°97,15°97) and NGC 6397 (l,b=338°17;−11°96) are projected at low Galactic latitude,
Fig. 4. $V$ versus $B - V$ CMD of stars in the field of view of NGC 6121 (left), NGC 6397 (middle), and NGC 6752 (right). The insets show the vector-point diagram of stellar displacements along the X and Y direction. Black and gray points indicate stars that, according to their proper motions, are considered cluster members and field stars, respectively (see text for details).

Results are shown in Fig. 4. The figure shows the $V$ versus $B - V$ CMDs for NGC 6121, NGC 6397 and NGC 6752. The insets show the vector-point diagrams of the stellar displacements for the same stars shown in the CMDs: the cluster-field separation is evident. Likely cluster members are plotted in black both in the CMDs and in the vector-point diagrams, in gray the rejected stars.

4. The CMDs of the three GCs

Previous studies on multiple stellar populations have demonstrated that the $U - B$ color is very efficient in detecting multiple RGBs (see Marino et al. 2008 and Milone et al. 2010 for the cases of NGC 6121 and NGC 6752), and multiple MSs (see Milone et al. 2012b, Mi13 for the cases of NGC 6397 and NGC 6752). As discussed by Sbordone et al. (2011), CNO abundance variations affect wavelengths shorter than $\sim 400$ nm owing to the rise of molecular absorption bands in cooler atmospheres. The consequences are that the CMDs in $UB$ filters show enlarged sequences, mainly due to variations in the N abundance, with the largest variations affecting the RGB and the lower MS.
Motivated by these results, we started our analysis from the $B$ versus $U-B$ CMDs shown in Fig. [5] the inset of each panel is a zoom in of the upper MS, between $\sim 1.5$ and $\sim 2.5$ magnitudes below the turn off.

A visual inspection at these CMDs reveals that the color broadening of MS stars in both NGC 6121 and NGC 6752 is larger than that of NGC 6397. A small fraction of MS stars in NGC 6121 and NGC 6752 defines an additional sequence on the blue side of the most-populous MS.

To investigate whether the widening of the MSs is due to the presence of multiple populations we identified in the $B$ versus $U-B$ CMD of each cluster two groups of red-MS (rMS) and blue-MS (bMS) stars, as shown in panels (a) of Fig. [5]. We colored the two MSs in red and blue respectively, and these colors are used consistently hereafter. In the case of NGC 6121 and NGC 6752, where there is some hint of a split MS, we identified by eye the fiducial that divide the rMS and bMS. In the case of NGC 6397 we have considered as rMS (or bMS), the stars that are redder (or bluer) than the MS fiducial line. Each inset shows the color distribution of $\Delta(U-B)$ for the two MSs, where $\Delta(U-B)$ is obtained by subtracting the color of the fiducial that divide the two MSs to the color of the rMS and bMS stars. In the cases of NGC 6121 and NGC 6752 the color distributions show a double peak that could be due to the presence of two populations; we fitted them with a sum of Gaussians (in red and blue respectively for the rMS and bMS). We applied a moving box procedure to further verify that the distribution of $\Delta(U-B)$ in the case of NGC 6121 is bimodal. We changed the binsize, ranging from 0.005 to 0.02 (approximately the error in color) with steps of 0.001. Furthermore, from our dataset we determined a kernel-density distribution by assuming a Gaussian kernel with $\sigma = 0.02$ mag. In all cases, we consistently found that the distribution can only be reproduced by two Gaussians.

A multiple sequence in NGC 6752 had already been identified by Mi13 using HST data. Very recently, we had the first F275W, F336W, F438W, WFC3 images of NGC 6121 from the HST GO-13297 UV Large Legacy Program (P.I. Piotto). Even a preliminary reduction of the data shows a clear separation of the MS into two branches in the F438W vs F336W-F438W CMD, fully confirming what we anticipate here in the equivalent, groundbased $U$ vs $U-B$ diagram of Fig. [5].

In the case of NGC 6397, it is possible to fit the distribution with a single Gaussian.

As an additional check for the presence of multiple populations, we investigated whether the widening of the MSs of all the GCs is intrinsic or if it is entirely due to photometric errors. We have compared two CMDs, $B$ versus $U-B$ with $V$ versus $V-I$, obtained using independent datasets. We considered the rMS and bMS defined previously: if the color spread is entirely due to photometric errors, a star which is red (or blue) in the $B$ versus $U-B$ CMD will have the same chance of being either red or blue in the $V$ vs $V-I$. By contrast, the fact that the two sequences identified in the first CMD have systematically different colors in the second one, would be a proof that the color broadening of the MS is intrinsic. In panels (b) of Fig. [5] we plotted the rMS and bMS in $V$ versus $V-I$ CMDs. The fact that the rMS stars of both NGC 6121 and NGC 6752 have, on average, different $V-I$ than bMS stars demonstrates that the color broadening of their MS in the $U$ versus $U-B$ CMDs is intrinsic. This is the first evidence that the MS of NGC 6121 is not consistent with a simple stellar population. In the case of NGC 6397 rMS and bMS stars share almost the same $V-I$ thus suggesting that most of the colors broadening is due to photometric errors.

As last test, we plotted the two MSs in the $V$ versus $c_{U,B,I}$ CMD. The $c_{U,B,I}$ index, which is defined as the color difference $(U-B)-(B-I)$, is a very efficient tool to identify mul-

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig5}
\caption{$B$ versus $(U-B)$ CMD for NGC 6121 (left), NGC 6397 (middle), and NGC 6752 (right). The inset is a zoom around the upper MS. The CMDs only show the cluster members and are corrected by zero point variations and differential reddening.}
\end{figure}
multiple sequences in GCs. Indeed it maximizes the color separation between the stellar populations that is due to both helium and light-element variations (Monelli et al. 2013). Panels (c) of Fig. 6 confirm the previous results: rMS and bMS of NGC 6121 and NGC 6752 are well defined in the V versus cUBI CMDs, but this is less evident for NGC 6397.

As a last prof, we plotted in Fig. 7 the (U − B) versus (V − I) diagrams for each cluster: in red and in blue are plotted the rMS and bMS defined previously. The figure shows that for both NGC 6121 and NGC 6752 the two MSs are well defined, while for NGC 6397 the rMS and bMS stars are mixed.

Figure 8 shows the V versus cUBI diagram for the three GCs studied in this paper. In their analysis of multiple stellar populations in 22 GCs, Monelli et al. (2013) found that all the analyzed clusters show a multimodal or spread RGB in the V versus cUBI diagram, and the cUBI value of each star depends on its light-element abundance. The cUBI-index width of the RGB (W_RGB) correlates with the cluster metallicity, with the more metal rich GCs having also the largest values of W_RGB. In order to compare the MSs of the three GCs studied in this paper, we introduce a quantity, W_MS, which is akin of W_RGB, but is indicative of the cUBI-index broadening of the MS. The procedure...
Fig. 7. Color-color diagrams for NGC 6121 (left panel), NGC 6397 (central panel) and NGC 6752 (right panel). In red (triangles) and blue dots the rMS and bMS as defined in Fig. 6.

Fig. 8. $V$, $c_{U,B,I}$ diagrams for NGC 6121 (left), NGC 6397 (middle) and NGC 6752 (right).

to determine $W_{MS}$ is illustrated in Fig. 9 for NGC 6121 and is the same for the other clusters. We have considered the magnitude of the TOs as magnitude of reference: $V_{MSTO} \sim 16.6$ in the case of NGC 6397, $V_{MSTO} \sim 17.4$ for NGC 6752, and $V_{MSTO} \sim 16.75$ for NGC 6121. Panel (a) of Fig. 9 shows the $V$ versus $c_{U,B,I}$ diagram for NGC 6121 in a range of magnitudes from $V_{MSTO} - 0.5$ to $V_{MSTO} + 5$. In this range of magnitudes, we obtained the fiducial line for the MSs computing the 3.5σ-clipped median of the color in interval of 0.35 mag and interpolated these points with a spline. In our analysis we used only MS stars with $2 < V - V_{MSTO} < 2.5$ where the MS split is visible for both NGC 6121 and NGC 6752. This magnitude interval is delimited by the two dashed lines of Fig. 9. The thick line is the fiducial in the considered magnitude interval. The
verticalized V versus $\Delta c_{U,B,I}$ diagrams is plotted in panel (b) of Fig. 9 while panel (c) shows the histogram distribution of $\Delta c_{U,B,I}$. The MS width, $W_{\text{MS}}$, is defined as the $\Delta c_{U,B,I}$ extension of the histogram and is obtained by rejecting the 5% of the reddest and the bluest stars on the extreme sides. To account for photometric error, we have subtracted from the observed $W_{\text{MS,OBS}}$ the average error in $c_{U,B,I}$ in the same magnitude interval, i.e. $W_{\text{MS}} = \sqrt{W_{\text{MS,OBS}}^2 - \sigma_{c_{U,B,I}}^2}$.

We found that the most metal-rich GC, NGC 6121, exhibits the largest $c_{U,B,I}$ index width for MS stars ($W_{\text{MS}} = 0.169 \pm 0.014$). The spread in $c_{U,B,I}$ is smaller in the case of NGC 6752 ($W_{\text{MS}} = 0.115 \pm 0.006$) and drops down to $W_{\text{MS}} = 0.093 \pm 0.014$ in the most metal-poor GC NGC 6397. To estimate the statistical uncertainty in measuring $W_{\text{MS}}$, we used the bootstrap resampling of the data to generate 10000 samples drawn from the original data sets. We computed the standard deviation from the mean of the simulated $W_{\text{MS}}$ and adopted this as uncertainty of the observed $W_{\text{MS}}$.

These findings make it tempting to speculate that the $c_{U,B,I}$ index width of the MS could be correlated with the cluster metallicity, in close analogy with what observed for RGB stars. An analysis of a large sample of GCs is mandatory to infer any conclusion on the relation between $W_{\text{MS}}$ and [Fe/H].

Mi13 have identified three stellar populations in NGC 6752 that they have named as ‘a’, ‘b’, and ‘c’. Population ‘a’ has a chemical composition similar to field halo stars of the same metallicity, population ‘c’ is enhanced in sodium and nitrogen, depleted in carbon and oxygen and enhanced in helium ($\Delta Y \sim 0.03$), while population ‘b’ has an intermediate chemical composition between ‘a’ and ‘c’ and is slightly enhanced in helium ($\Delta Y \sim 0.01$). However, the MSs of populations ‘b’ and ‘c’ are nearly coincident in the $m_{F336W} - m_{F467M}$ CMD of NGC 6752, obtaining that in the rMS there are the 74% ± 2% of MS stars, and in the bMS the remaining 26% ± 4%.

In the case of $V$ versus $c_{U,B,I}$, we obtained that the rMS and bMS contain respectively 75% ± 3% and 25% ± 5% of MS stars. In panels (d), (e) and (f) of Fig. 10 we applied the same procedure in the $B$ versus $(U - B)$ CMD of the MS fiducial line (see text for details). Panel (b) shows the verticalized MS versus $(U - B)$, the less populous MS identified in this paper should correspond to the population ‘a’ identified by Mi13, while the rMS hosts both population ‘b’ and population ‘c’ stars.

4.1. The fraction of rMS and bMS in NGC 6121 and NGC 6752

In order to measure the fraction of stars in each MS we followed the procedure illustrated in Fig. 10 for NGC 6752, which we already used in several previous papers (e.g. [Piotto et al. 2007, Mi13]).

Panel (a) shows the V versus $c_{U,B,I}$ CMD of the MS stars in the magnitude interval 19.25 < $V$ < 20.55, where the MS split is most evident. We verticalized the selected MS by subtracting the color of the stars to the color of the fiducial line of the rMS, obtaining $\Delta c_{U,B,I}$. The fiducial line is obtained by hand selecting the stars of the rMS, dividing them in bins of magnitude, computing the median colors of the stars within each bin and interpolating these median points with a spline. The verticalized V versus $\Delta c_{U,B,I}$ diagram is plotted in panel (b).

The $\Delta c_{U,B,I}$ color distribution of the stars for three magnitude intervals is shown in panels (c). Each histogram clearly shows two peaks and has been simultaneously fitted with a double Gaussian, whose single components are shown in blue and in red for the bMS and the rMS, respectively.

For each magnitude interval, from the area under the Gaussians we infer the fraction of bMS and rMS stars. The errors
between 0.15 and 0.5. I all cases, the resulting fraction of stars are in agreement with the values we quote above within the errors. The results from the two CMDs imply that in the rMS and bMS there are, respectively, 63% ± 3% and 37% ± 4% of MS stars.

5. The radial distribution of stellar populations in NGC 6752 and NGC 6121

The analysis of the radial distribution of rMS and bMS stars in NGC 6121 and NGC 6752 is an important ingredient to shed light on the formation and the evolution of multiple stellar populations in these GCs. Indeed, theoretical models predict that, when the GC forms, second-generation stars should be more centrally concentrated than first-generation ones, and many GCs could still keep memory of the primordial radial distribution of their stellar populations (e.g. D'Ercole et al. 2008, Bekki 2011, Vesperini et al. 2013).

The radial distribution of stellar populations in NGC 6752 is still controversial. Kravtsov et al. (2011) determined wide-field multi-band photometry of NGC 6752 and studied the distribution of its stellar populations across the field of view. They have concluded that there is a strong difference in the radial distribution between the populations of RGB stars that are bluer (bRGB) and redder (rRGB) in (U − B) color, and obtained similar findings from the study of the SGB. Specifically, at a radial distance close to the half-mass radius (\(r_h = 1.91\) R\(_\odot\) Harris 1996, 2010 edition) the fraction of rRGB stars abruptly decreases. These results are in disagreement with the conclusions by Mi13 who showed that the three stellar populations identified in their papers share almost the same radial distribution. Kravtsov and collaborators analyzed stars with a radial distance from the center of NGC 6752 out to ~ 9.5, while the study by Mi13 is limited to the innermost ~ 6 arcmin. In this paper we extend the analysis to larger radii.

As already mentioned in Sect. 4, we suggest that the bMS of NGC 6752 corresponds to the population ‘a’ identified by Mi13, while the most populous rMS hosts both population ‘b’ and population ‘c’ stars of Mi13. For this reason, in this section, we rename the bMS in MSa and the rMS in MSbc.

In order to investigate the radial distribution of stellar populations within the field of view analyzed in this paper, we divided the catalog of NGC 6752 stars into two groups at different radial distance from the cluster center, each containing almost the same total number of stars.

The inner sample of stars (inner field) lies between 5.89 and 10.62 from the cluster center. The outer group of stars (outer field) is between 10.62 and 17.89 from the center. We estimated the fraction of stars in each group by following the same procedure described in Sect. 4.1.

The results are illustrated in Fig. 12. In the left panels we show the verticalized V versus \(\Delta UV\_B\) and the B versus \(\Delta U - B\) diagrams for stars in the inner field. In this region the MSa contains 27% ± 4% and the MSbc hosts the remaining 73% ± 3% of the total number of MS stars. In the outer field (right panels of Fig. 12) the MSa and the MSbc are made of the 27% ± 5% and 73% ± 3% of MS stars, respectively. We conclude that there is no evidence for a gradient within the field of view studied in this paper.

1 We assume that stars in the fields of NGC6752 and NGC6121 are representative of stellar populations at the studied radial distance; we are not able to investigate any dependency on the angular position using the dataset presented in this work.

To further investigate the radial distribution of stellar populations in NGC 6752 we compare the results obtained in this paper for stars with distance from the cluster center larger than ~ 6 arcmin and the fraction of stars that have been estimated by Mi13 in the internal regions by using the same method.

Since the MSbc contains both populations ‘b’ and population ‘c’ stars, we have added together the fractions of population ‘b’ (f\(_{bMS}\)) and population ‘c’ stars (f\(_{cMS}\)) listed by Milone et al. (2013, see their Table 4) and calculated the fraction of stars in these two populations: f\(_{b+cMS}\) = f\(_{bMS}\) + f\(_{cMS}\). As aforementioned in Sect. 6, we further compare the fractions of population ‘a’ stars by Mi13, with the fractions of MSa stars derived in this paper. The values of f\(_{b+cMS}\) and f\(_{b+cMS}\) are listed in Tab. 3.

Results are shown in Fig. 13 where the top panels show the distribution of the fraction of population ‘a’ (in blue) and the fraction of population ‘b’ + ‘c’ (in red) as a function of the radial distance from the cluster center, while the bottom panels show the radial trend of the ratio between the fraction of population ‘a’ and the fraction of population ‘b’ + ‘c’. In the left panels we show both the above described distributions considering single radial intervals for each set of data, while in the right panels we divided each radial interval in different bins. Our findings suggest that there is no evidence for a radial gradient among population ‘a’ and population ‘b’ + ‘c’ of NGC 6752.

In order to investigate the radial distribution of stellar populations in NGC 6121, we divided the field of view analyzed in this paper into two regions, with radial distance from the cluster center 5.12 < R < 9.63 (inner field) and 9.63 < R < 17.81 (outer field). Each region contains almost the same number of stars. We determined the fraction of rMS and bMS stars by following the same recipe described in detail for NGC 6752. The results are shown in Fig. 14. We found that in the inner field the fraction of bMS is 40% ± 13% and the fraction of rMS is 60% ± 13%. For the outer field we obtain that the bMS and the rMS contains respectively the 36% ± 6% and the 64% ± 4% of the total number of the considered MS. Also for NGC 6121 we found no evidence of population gradients.

6. The helium content of stellar populations in NGC 6121 and NGC 6752.

The ultraviolet pass-band is very efficient to separate multiple sequences due to its sensitivity to difference in C, N, O abundance (Marino et al. 2008, Sbordone et al. 2011b). In contrast, B − I and V − I colors are marginally affected by light-element variations, but are very sensitive to the helium abundance of the stellar populations (e.g. D'Antona et al. 2002, Pirolli et al. 2007).

| R\(_{min}\) | R\(_{max}\) | R\(_{ave}\) | f\(_{POPa}\) | f\(_{POPbc}\) | Seq. |
|---------|---------|---------|---------|----------|-----|
| 0.00    | 1.70    | 0.95    | 0.25 ± 0.02 | 0.75 ± 0.05 | MS   |
| 0.00    | 1.70    | 0.87    | 0.28 ± 0.03 | 0.72 ± 0.04 | RGB  |
| 1.70    | 6.13    | 3.26    | 0.27 ± 0.04 | 0.73 ± 0.06 | RGB  |
| 5.89    | 17.89   | 10.88   | 0.26 ± 0.04 | 0.74 ± 0.02 | MS   |
| 0.00    | 0.53    | 0.31    | 0.24 ± 0.02 | 0.76 ± 0.07 | MS   |
| 0.53    | 0.83    | 0.68    | 0.23 ± 0.02 | 0.75 ± 0.05 | MS   |
| 0.83    | 1.12    | 0.97    | 0.28 ± 0.02 | 0.72 ± 0.07 | MS   |
| 1.12    | 2.33    | 1.44    | 0.28 ± 0.03 | 0.72 ± 0.05 | MS   |
| 1.70    | 3.11    | 2.35    | 0.26 ± 0.05 | 0.74 ± 0.07 | RGB  |
| 3.11    | 6.13    | 4.15    | 0.30 ± 0.05 | 0.70 ± 0.07 | RGB  |
| 5.89    | 10.62   | 8.63    | 0.27 ± 0.04 | 0.73 ± 0.03 | MS   |
| 10.62   | 17.89   | 13.12   | 0.27 ± 0.05 | 0.73 ± 0.03 | MS   |
We assumed a primordial helium abundance for the bMS, $Y = 0.248$, and used for the rMS different helium content, with $Y$ varying from 0.248 to 0.400 in steps of $0.001$. To account for the appropriate chemical composition of the two stellar populations of NGC 6121 we assumed for the bMS and the rMS the abundances of C, N, O, Mg, Al, and Na as measured for first and second-generation RGB stars listed by Marino et al. (2008, see their Table 6).

We used the ATLAS12 program and the SYNTH code (Kurucz 2005; Castelli 2005; Sbordone et al. 2007) to generate synthetic spectra for the adopted chemical compositions, from $\lambda \sim 2,500$ Å to $\lambda \sim 10,000$ Å. Synthetic spectra have been integrated over the transmission curves of the $U, B, V, I$ filters, and, we calculated the color difference $X - I$ for each value of helium of our grid.

The best-fitting model is determined by means of chi-square minimization. Since the $U$ magnitude is strongly affected by the abundance of light elements we used $B - I$ and $V - I$ colors only to estimate $Y$. The helium difference corresponding to the best-fit models are listed in Table 2 for each value of $I_{\text{CUT}}$.

We derived that the rMS is slightly helium enhanced with respect to the bMS (which has $Y = 0.248$), with an average helium abundance of $Y = 0.268 \pm 0.008$ This is the internal error estimated as the rms scatter of the $N = 5$ independent measurements divided by the square root of $N - 1$. Results are shown in Fig. 15 for the case of $I_{\text{CUT}} = 17.7$, where we represented the synthetic colors corresponding to the best-fitting model as red asterisks.
Fig. 11. As in Fig. 10 but for NGC 6121. In the case of $V$ versus $c_{UBI}$ CMD, we obtained that rMS and bMS contain respectively $60 \pm 7\%$ and $40 \pm 8\%$ of MS stars in panel (c1), $61 \pm 6\%$ and $39 \pm 7\%$ of MS stars in panel (c2). In the case of $B$ versus $(U - B)$ CMD we obtained that rMS and bMS contains respectively $67 \pm 7\%$ and $33 \pm 10\%$ of MS stars in panel (f1), $75 \pm 13\%$ and $25 \pm 14\%$ of MS stars in panel (f2).

Fig. 12. Color distribution analysis for the MSs stars of NGC 6752 in two different radial bins, containing almost the same number (855 and 854) of stars. In the inner field (left panels) we obtained that MSa (blue) and MSbc (red) contain respectively $28 \pm 6\%$ and $72 \pm 4\%$ of MS stars in the $V$ versus $c_{UBI}$ CMD, and $27 \pm 6\%$ and $73 \pm 4\%$ of MS stars in the $B$ versus $(U - B)$ CMD. In the outer field (right panels) we obtained that MSa and MSbc contain respectively $26 \pm 7\%$ and $74 \pm 4\%$ of MS stars in the $V$ versus $c_{UBI}$ CMD, and $29 \pm 8\%$ and $71 \pm 6\%$ of MS stars in the $B$ versus $(U - B)$ CMD.
Fig. 13. Top: Radial distribution of the fraction of population ‘a’ (blue) and ‘b’+‘c’ (red) stars with respect the total number of stars. Bottom: radial trend of the ratio between \( f_{\text{pop}} \) and \( f_{\text{spec}} \) stars. On the left we considered single radial interval for each set of data, while in the right panel we divided the radial interval in different bins. The distribution seems to be flat in both the cases.

For completeness we also calculated synthetic colors of two MS stars with the \( I = I_{\text{CUT}} \) and the same chemical composition (same abundance of light elements). We assumed for bMS primordial helium and for rMS the helium abundance of the best-fitting model. Results are represented as blue squares in Fig. 15 and confirm that the abundance of light elements assumed in the model does not affect our conclusion on the helium abundance of the two MSs, which are based on the optical colors. Instead the different CNO content strongly affect the \( U \) band.

In principle, the He content of stellar populations in GCs can also be estimated using He lines in HB star spectra (e.g. the HeI line at \( \lambda = 5875.6 \) Å line, Villanova et al. 2009, 2012, Marino et al. 2014). However, spectroscopic measurement of He in GC stars has many limitations. First of all, He can only be measured for stars in a very limited temperature interval (8500 < \( T \) < 11500 K). In fact, stars with \( T \leq 8500 \) K are not sufficiently hot to form He lines, while stars bluer than the Grun-dahl jump (Grundahl et al. 1999, \( T \geq 11.500 \) K) are affected by He sedimentation and metal levitation which alter the original surface abundance. The HB of NGC 6121 is populated both on the red and the blue side of the RR Lyrae instability strip. Spectroscopic investigation by Marino et al. (2011) reveals that the blue HB is made of second population Na-rich and O-poor stars, while red HB stars belong to the first population. In NGC 6121, the HB segment with 8500 < \( T < 11500 \) K corresponds to the blue HB, and therefore it only provides partial information only. In this cluster (as in many others) it is not possible to spectroscopically measure the He content of the first population.

Villanova et al. (2012) have used the HeI line at \( \lambda = 5875.6 \) to estimate the helium content of six blue-HB stars in the blue HB of NGC 6121. All of them are second-population stars. They derived a mean value of \( Y = 0.29 \pm 0.01 \) (random) \( \pm 0.01 \) (systematic) and conclude that second-population stars would be enhanced in helium by \( \sim 0.04-0.05 \) dex. This estimate of the He content has been made by assuming LTE approximation. However, the HeI line at \( \lambda = 5875.6 \) is affected by NLTE effect, which can cause an error in the \( Y \) estimate as large as \( \Delta Y = 0.10 \) (see Marino et al. 2014 for the case of NGC 2808). Appropriate NLTE analysis is required to infer reliable He abundances from spectroscopy of HB stars in NGC 6121. In contrast, the He difference between red- and blue-MS stars in NGC 6121 comes from the colors of the fiducial lines, which have small color uncertainties.

### Table 4. Parameters used to simulate Synthetic Spectra of rMS and bMS stars and estimation of helium difference between the two population for different \( I_{\text{CUT}} \) in the case of NGC 6121

| \( I_{\text{CUT}} \) | \( T_{\text{EFF,MS}} \) | \( \log g_{\text{MS}} \) | \( \log g_{\text{AMS}} \) | \( \Delta Y \) |
|-----------------|-----------------|-----------------|-----------------|---------|
| 17.3            | 5542            | 4.58            | 4.57            | 0.014   |
| 17.5            | 5397            | 4.60            | 4.60            | 0.021   |
| 17.7            | 5247            | 4.63            | 4.63            | 0.022   |
| 17.9            | 5095            | 4.65            | 4.65            | 0.024   |
| 18.1            | 4944            | 4.66            | 4.66            | 0.021   |
| average         |                 | 4.62            | 0.020, \( \sigma \) = 0.008 |

6.2. NGC 6752

We followed the same procedure to estimate the average helium difference between MSa and MSbc stars. We measured the color difference between the two fiducial lines of MSa and MSbc in the \( I \) versus \((X - I)\) CMDs (Fig. 16), where \( X = U, B, V, \) at reference magnitudes \( I_{\text{CUT}} = 18.55, 18.75, 18.95, 19.15 \) and 19.35. The color difference \( \Delta(X - I) \) at \( I_{\text{CUT}} = 18.95 \) is plotted in the bottom panel of Fig. 16 as a function of the central wavelength of the \( X \) filter.
bMS contain respectively 62 ± 0.025 in steps of 0.006. As for NGC 6121, since the $U$ magnitude is a difference ($\Delta V = 0.006$). We assumed for the MSa the same C, N, O, Mg, Al and Na abundances of the population ‘a’ of Mi13; for the chemical composition of the MSbc we considered the average of the abundances of the population ‘b’ and ‘c’ listed by Mi13.

As mentioned above, we obtained synthetic spectra for the adopted chemical compositions, integrated them over the transmission curves of the $U$, $B$, $V$, $J$ filters, and computed the helium difference using the best-fitting model.

We obtained that the MSbc is helium enhanced with respect to the MSa of $\Delta Y = 0.025 \pm 0.006$. As for NGC 6121, since the $U$ magnitude is affected by the abundance of light elements, we used $B - I$ and $V - I$ colors only to estimate $Y$. Note that the abundance of light elements assumed in the model does not affect our conclusion on the helium abundance of the two MSs, as already proved in the case of NGC 6121.

### Table 5. Parameters used to simulate Synthetic Spectra of MSa and MSbc stars and estimation of helium difference between the two populations for different $t_{\text{cut}}$ in the case of NGC 6752

| $t_{\text{cut}}$ | $T_{\text{eff,MSa}}$ | $T_{\text{eff,MSbc}}$ | log g MSa | log g MSbc | $\Delta Y$ |
|-----------------|----------------------|------------------------|-----------|-----------|-----------|
| 18.35           | 5410                 | 5456                   | 4.65      | 4.65      | 0.021     |
| 18.75           | 5524                 | 5506                   | 4.67      | 4.67      | 0.023     |
| 18.95           | 5100                 | 5150                   | 4.69      | 4.69      | 0.025     |
| 19.15           | 4946                 | 4998                   | 4.70      | 4.70      | 0.025     |
| 19.35           | 4798                 | 4851                   | 4.72      | 4.72      | 0.026     |
| average         |                      |                        |           |           | 0.024, $\sigma = 0.006$ |

6.3. Relation between HB morphology and Helium abundance

In their work [Milone et al. (2014b)] have sought correlations between HB morphology indicators and physical and morphological GC parameters. Among these parameters there is also the maximum helium difference between stellar populations hosted by GCs.

They introduced two different parameters to describe the HB morphology: $L_1$, that is the color difference between the RGB and the coolest border the HB, and $L_2$, that is the color extension of the HB (for more details, see Fig. 1 ofMilone et al. 2014b).

They divided the sample of 74 GCs in three groups: in the first group, G1, there are GCs with [Fe/H]$\geq -1.0$; the second group, G2, includes GCs with [Fe/H] $< -1.0$ and $L_2 \leq 0.4$; the third group, G3 contains GCs with $L_2 > 0.4$.

They found a tight correlation between $L_1$ and the maximum internal helium difference ($\Delta Y$, measured on the MS) for the group G2+G3 (see Fig. 8 of their paper).

In our work we add two more points to their data-set, the Helium difference between the two populations of NGC 6752 and NGC 6121, as computed in this work. In the case of NGC 6752, the added point constitutes a lower limit because the Helium difference between Pop$_{a}$ and Pop$_{bc}$, $\Delta Y$(Pop$_{a}$-Pop$_{bc}$), is the average value between $\Delta Y$(Pop$_{a}$-Pop$_{b}$) and $\Delta Y$(Pop$_{a}$-Pop$_{c}$).

The result is in Fig. 17 in black there are the points of Milone et al. (2014b) and in grey the points added in this work. In analogy to the work of Milone et al. (2014b), the crosses refer to the Gi GCs, triangles to G2 group and dots to G3 clusters. Our data points confirm the tight correlation between $L_2$ and $\Delta Y$. We found a Spearman’s rank correlation coefficient $r_{G2+G3} = 0.93$ (to be compared to $r_{G2+G3} = 0.89 \pm 0.17$ found by Milone et al. 2014b), with $\sigma_{r_{G2+G3}} = 0.08$ (the uncertainty in $r$ is estimated by means of bootstrapping statistic, as in Milone et al. 2014b).
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Fig. 15. Top panels: MS fiducial in 3 $X - I$ CMDs ($X = U, B, V$) of NGC 6121. The horizontal lines represent the magnitudes $I_{\text{CUT}}$ for which the color distance between the two MSs is calculated. For each $I_{\text{CUT}}$ the error in $\Delta(X - I)$ is shown. Bottom panel: $X - I$ color distance between rMS and bMS at $I_{\text{CUT}} = 17.7$ as a function of the central wavelength of the $X$ filter. Observations are represented with gray dots. Red asterisks are the best-fitting model, while blue squares are the results obtained calculating synthetic colors of two MS stars with the same light-element chemical composition, but different He content. The blue squares demonstrate that the abundance of light elements assumed in the model does not affect the results on the He abundance of the two MSs in the optical colors but strongly affect the $U$ band.

Fig. 16. As in Fig. 15 but for NGC 6752. In the top panels, the fiducial blue is that of the MSa and the red fiducial is for MSbc.

Fig. 17. The HB morphological parameter $L_2$ as a function of the logarithm of the maximum helium difference among stellar populations in GCs. The black line is the best-fitting straight line for G2+G3 GCs. In black there are the data of Milone et al. (2014b), in grey the data of this work.

This result is a further proof that the helium-enhanced stellar populations are likely related to the HB extension, as predicted by theory.

7. Summary

The photometric analysis of ESO/FORS2 data of the external regions of the three nearby Galactic GCs NGC 6121 (M 4), NGC 6752 and NGC 6397 has confirmed that the first two GCs host multiple stellar populations. Indeed, the $B$ versus $U - B$ and $V$ versus $c_{U,B,I}$ CMDs of NGC 6752 and NGC 6121 show a split of the MS in two components. Excluding the unique case of $\omega$ Cen, this is the first time that a split of the MS is observed using ground-based facilities.

The multiple stellar populations of NGC 6397 was investigated by Milone et al. (2012a) using HST data. They found two stellar populations characterized by a modest helium variation $\Delta Y \sim 0.01$. Unfortunately, in this work, it was not possible to analyze these populations, because of the size of our photometric errors is comparable to the small color separation between the MSs.

Using HST data, Mi13 have already demonstrated that NGC 6752 host three stellar populations. They computed the radial trend of the ratio between the number of stars of different populations out a radial distance from the center of 613. Because of larger photometric errors, we have resolved only two MSs. Comparing them with the work of Mi13, we found that the less populous MS corresponds to their population ‘a’, while the most populous MS hosts both their populations ‘b’ and ‘c’. In average we found that the MSa contains about 26% of the total number of stars and the MSbc host about 74% of the MS stars. The most straightforward interpretation is that the MSa is formed by stars of the first generation with chemical abundances similar to that of the Galactic halo field stars with the same metallicity; the MSbc hosts stars of second generation, formed out of material processed through first-generations stars. This population is characterized by stars enhanced in helium, with $\Delta Y \sim 0.025$. Our measurement of the helium enhancement is in agreement with the average $\Delta Y$ of the populations ‘b’ ($\Delta Y \sim 0.01$) and
c’ (AY ≈ 0.03) obtained by Mil13. We extended the study of the radial trend of the populations of NGC 6752 to more external regions, confirming the results of Mil13, of a flat distribution. Therefore we cannot confirm the results by Kravtsov et al. (2011) and Kravtsov et al. (2014); they found that the two populations show a strong gradient at a radial distance close to the half-mass radius.

In a recent work on NGC 6121, Milone et al. (2014b) investigate the bottom of the MS of this cluster using HST near-infrared photometry. They found that the MS splits into two sequences below the MS knee. In particular they identified two MSs: a MSI that contains ~ 38% of stars and MSII formed by the remaining 62%. They show that the split of the MS is mainly due to the effect of H₂O molecules, present in the atmospheres of M-dwarfs, on their near-infrared color, and that it is possible to associate the MSI to a first generation of stars and the MSII to a second one. Marino et al. (2009), analyzing spectra of RGB stars, found that ~ 64% of stars are Na-rich and O-poor and the remaining ~ 36% have chemical abundances similar to those of Halo-field stars with the same metallicity. All these results are in agreement with what we have obtained in this work: the MS of NGC 6121 splits in the B versus (U – B) and V versus (U,B,V) CMDs. We found two MSs: a less populous MS that contains ~ 37% of MS stars and which constitutes the first generation of stars and a more populous second generation MS that contains ~ 63% of stars. Villanova et al. (2012), using spectroscopic measurements of blue HB (bHB) stars, obtained that the difference in helium abundance between these stars and the red HB (rHB) stars is AY = 0.02±0.03. A spectroscopic analysis of Marino et al. (2011) revealed that the rHB stars have solar-scaled [Na,Fe], while bHB stars are Na enhanced. In contrast to the results of Villanova et al. (2012), a lower constraint to the level of He enhancement is set by Valcarce et al. (2014), founding a maximum ΔY = 0.01 between bHB and rHB stars. Analyzing how the two MS of NGC 6121 behave in different CMDs, we computed the helium abundance difference between them. Our result is ΔY ≈ 0.020 ± 0.005, in agreement with that obtained by Villanova et al. (2012). Also in the case of NGC 6121, we did not find evidence of changes in the fraction of bMS/rMS stars in the radial range between 1.2 < R < 4.1 rₚ.

Milone et al. (2014b) found a correlation between the HB morphological parameter L₃ and the maximum helium difference among stellar populations in GCs. Using the helium abundances computed in this work for NGC 6121 and NGC 6752, we confirm this correlation and the theoretical indications that helium enhanced stellar populations are responsible of the HB extension.

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