

MULTIPLE STELLAR POPULATIONS IN GALACTIC GLOBULAR CLUSTERS: OBSERVATIONAL EVIDENCE

A.P. Milone¹, G. Piotto², L.R. Bedin³, A. Bellini⁴, A.F. Marino⁵ and Y. Momany⁶

Abstract. An increasing number of both photometric and spectroscopic observations over the last years have shown the existence of distinct sub-populations in many Galactic globular clusters and shattered the paradigm of globulars hosting single, simple stellar populations. These multiple populations manifest themselves in a split of different evolutionary sequences in the cluster color-magnitude diagrams and in star-to-star abundance variations. In this paper we will summarize the observational scenario.

Keywords: stars: abundances, stars: atmospheres, stars: population II, galaxy: globular clusters

1 Introduction

In recent years an increasing amount of photometric and spectroscopic observational evidence have shattered the paradigm of globulars as the prototype of single, simple stellar populations (see Piotto 2009 for a recent review). Spectroscopic studies have demonstrated that most globular clusters (GC) have no detectable spread in their iron content and also *s*-process elements do not exhibit large star-to-star variations in the majority of globulars (e.g. Carretta et al. 2009a and references therein). On the contrary, every time we have at our disposal a large sample of stars for a given GC, star-to-star variations in the light elements C, N, O, Na, and Al have been clearly detected (e.g. Carretta et al. 2009b, Pancino et al. 2010 and references therein). These variations are related to correlations and anticorrelations, which indicate the occurrence of high temperature hydrogen-burning processes (including CNO, NeNa, MgAl cycles) and cannot occur in presently observed low mass GC stars.

Today it is widely accepted that the observed light-elements variations provide strong support to the presence of multiple stellar populations in GCs with the second generations formed from the material polluted by a first generation of stars. On the contrary the debate on the nature of possible polluters is still open (e.g. D'Antona et al. 2004, Decressin et al. 2007).

While abundance variations are well known since the early sixties, it was only the recent spectacular discovery of multiple sequences in the color-magnitude diagram (CMD) of several GCs that provides an un-controversial prove of the presence of multiple stellar populations in GCs and brought new interest and excitement in GCs research (e.g. Piotto et al. 2007). Photometric clues, often easy to detect simply by the inspection of high-accuracy CMDs, arise in form of multiple main sequences (MS, Bedin et al. 2004, Piotto et al. 2007, Milone et al. 2010), split sub-giant branch (SGB, Milone et al. 2008, Anderson et al. 2009, Piotto 2009), and multiple red-giant branch (RGB, Marino et al. 2008, Yong et al. 2008, Lee et al. 2009).

Many population properties, like the chemical composition, the spatial distribution, the fraction of stars in each population and their location in the CMD apparently differ from cluster to cluster. Multiple stellar populations have been detected for the first time in the Milky Way satellite ω Centauri in form of either multiple MSs (e.g. Anderson 1997, Bedin et al. 2004, Bellini et al. 2010), multiple SGBs (e.g. Sollima et al.

¹ Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 3, Padova, I-35122, Italy

² Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 3, Padova, I-35122, Italy

³ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

⁴ Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 3, Padova, I-35122, Italy

⁵ Max Plank Institute for Astrophysics, Postfach 1317, 85741, Garching, Germany

⁶ European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago, Chile

2005), multiple RGBs (Lee et al. 1999, Pancino et al. 2000) and large star-to-star variation in iron and *s*-elements (e.g. Johnson et al. 2010, Marino et al. 2010). Due to its large mass this GCs have been always considered as a peculiar stellar system and often associated to the remnant of a dwarf galaxy.

The ‘extreme’ case of ω Centauri is not analyzed in this work where we focus on ‘normal’ GCs. The following sections are an attempt to define some groups of ‘normal’ clusters that share similar properties.

2 Light-elements correlations and spread RGB. The case of NGC 6121.

The Na-O anticorrelation has been observed in all the Galactic GCs studied to date and indicates the presence of multiple stellar populations in GCs. These chemical inhomogeneities revealed themselves a spread or bimodal distribution of stars along the RGB when sensitive colors are used.

In this context the nearby GC NGC 6121 (M4) is one of the most studied cases (e.g. Ivans et al. 1999, Marino et al. 2008). An high resolution spectroscopic study conducted on a sample of more than a hundred RGB stars in this GC, has recently demonstrated that two different stellar populations are present (Marino et al. 2008). These two populations have been identified by means of a strong dichotomy in the sodium abundance, that is related to a bimodality in the CN band strengths. The presence of two different groups of stars is visible also on the Na-O anticorrelation: a bulk of stars with Na and O resembling the halo field content, and likely associated to the first stellar generation, can be easily distinguished from stars enhanced in Na and with lower O abundance, associated with the second generation. The two populations of Na-poor/O-rich/CN-weak and Na-rich/O-poor/CN-strong stars populate two different regions along the RGB, when plotted in a U vs. $(U - B)$ CMD. The Na-rich group defines a narrower sequence on the red side of the main RGB locus, while the Na-poor one populates a bluer, more spread portion of the RGB. The RGB spread is visible from the base of the RGB to its tip, and it is due to the dichotomy in the CN bands, given that the U filter is highly affected by CN molecular bands.

3 Multimodal MSs. The cases of NGC 2808 and NGC 6752

In few cases the MS morphology strongly supports the presence of stellar generations with different helium content. The most striking evidence comes from the color magnitude diagram (CMD) of NGC 2808 which exhibits two additional MSs that run blueward of the main MS ridge line and have been associated to subsequent episodes of star formation (Piotto et al. 2007).

Apart from the triple MS, NGC 2808 shows observational evidence indicating the presence of multiple stellar populations also in other region of the CMD. Its horizontal branch (HB) is greatly extended blueward and is well populated on both sides of the instability strip. The distribution of stars along the HB is multimodal (Sosin et al. 1997, Bedin et al. 2000) with three significant gaps, one of these gaps being at the color of the RR Lyrae instability strip. In fact, even though the HB is well populated both to the blue and to the red of the instability strip, very few RR Lyrae stars have been identified in NGC 2808. The other two gaps are on the blue extension of the HB and delimit three distinct segments.

Even the RGB is not consistent with a single stellar population. The CMDs shown by Yong et al. (2007) and Lee et al. (2009) revealed a large color spread among RGB stars that cannot be attributed to photometric errors only. Furthermore, an analysis of medium-high-resolution spectra of 122 RGB stars have revealed an extended Na-O anticorrelation in NGC 2808 (Carretta et al. 2006) with the presence of three distinct groups: O-normal (peak at $[O/Fe] +0.28$), O-poor (peak at $[O/Fe] -0.21$) and super-O-poor (peak at $[O/Fe] -0.73$) stars.

On the basis of their relative numbers, Piotto et al. (2007) associated the three MSs with the three HB segments defined by Bedin et al. (2000), and the three groups of stars with different O content found by Carretta et al. (2006). Since cluster stars have around the same iron content (Carretta et al. 2007, 2010), a multimodal distribution of He abundances seems to be the only way to take into account for both the complex HB and the multiple MS (D’Antona et al. 2005) and is consistent with the observed abundance pattern. In this case the population associated to the red MS (rMS) have nearly primordial helium, while stars of the middle (mMS) and blue MS (bMS) are formed from the ejecta produced by an earlier stellar generation through the complete CNO and MgAl cycle and are He-enhanced ($Y \sim 0.33$ and $Y \sim 0.38$, respectively). This scenario is nicely confirmed by the recent work of Bragaglia et al. (2010) who measured chemical abundances of one star on the rMS and one on the bMS and found that the latter shows an enhancement of N, Na, and Al and a depletion of C and Mg as expected for material polluted by first-generation massive stars.

A split or a broad MS is not a peculiarity of NGC 2808 but is present also in other GCs like 47 Tucanae and NGC 6752 (Anderson et al. 2009, Milone et al. 2010). In these cases the color spread has been tentatively attributed to small variations in He ($\Delta Y \sim 0.02-0.03$). As an example in Fig. 1 we show the Hess diagram for MS stars of NGC 2808 and NGC 6752 from Hubble space telescope *HST* ACS/WFC and WFC3/UVIS cameras.

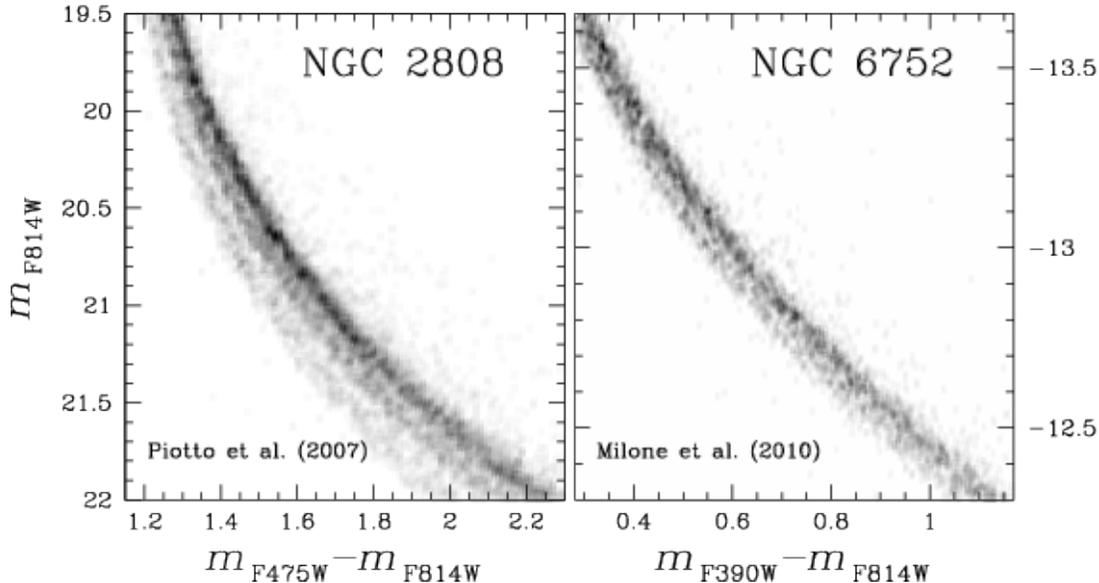


Fig. 1. Hess diagram of NGC 2808 and NGC 6752 zoomed around the MS region.

4 SGB split clusters: NGC 1851 and NGC 6656

High-accuracy photometry obtained with the WFPC2, the WFC/ACS and the WFC3/UVIS cameras on board of the *HST* has revealed that in several clusters there is a broad, split, or multimodal SGB as shown in Fig. 2 for NGC 1851, NGC 6388, NGC 104, NGC 6656, NGC 5286, and NGC 6715 (Milone et al. 2008, Anderson et al. 2009, Piotto et al. 2009, Moretti et al. 2008).

NGC 1851 and NGC 6656 are the most studied clusters of this group and will be analyzed in more detail in the following. We find that the SGB of both NGC 1851 and NGC 6656 is clearly split into two branches with the bright SGB component containing about the 60% of the total number of SGB stars and the remaining 40% of stars belonging to the faint SGB (Milone et al. 2008, Piotto 2009, Marino et al. 2009).

These results have brought new interest on these GCs and a lot of effort have been made to understand their star formation history. Theoretic studies demonstrate that the double SGB can be explained in terms of two stellar groups, only slightly differing in age, with the younger one having an increased C+N+O abundance (Cassisi et al. 2008, Ventura et al. 2009). Indeed, significant star-to-star variations in the overall CNO abundance have been detected among NGC 6656 RGB stars by Marino et al. (2010) and in two out four NGC 1851 giants by Yong et al. (2009). As an alternative possibility, we note that the double SGB is consistent with two stellar populations with constant CNO but differing in age by ~ 1 Gyr (Milone et al. 2008).

A peculiar property of the cluster pair NGC 1851-NGC 6656 is the large scatter in the abundance of those *n*-capture elements that are associated to *s*-process (Marino et al. 2009, 2010, Hesser et al. 1982, Yong et al. 2008). In both clusters *n*-capture elements are clearly segregated around two distinct values of barium and yttrium in sharp contrast with what found in most GCs, where the abundance of these elements does not exhibit significant star-to-star variations. As an example, Fig. 3a shows the iron abundance as a function of [Y/Fe] for NGC 6656.

These recent results nicely match with previous photometric analysis by Ritcher et al. (1999) and Calamida et al. (2007) who found that NGC 6656 and NGC 1851 exhibit a bimodal distribution in the m_1 index among RGB stars. A similar RGB bimodality has been observed in the *hk* index by Lee et al. (2009) and in the *U* vs. (*U-I*) and *U* vs. (*U-V*) CMD by Han et al. (2009) and Momany et al. (2004). In these cases the RGB components are clearly associated to the two SGBs.

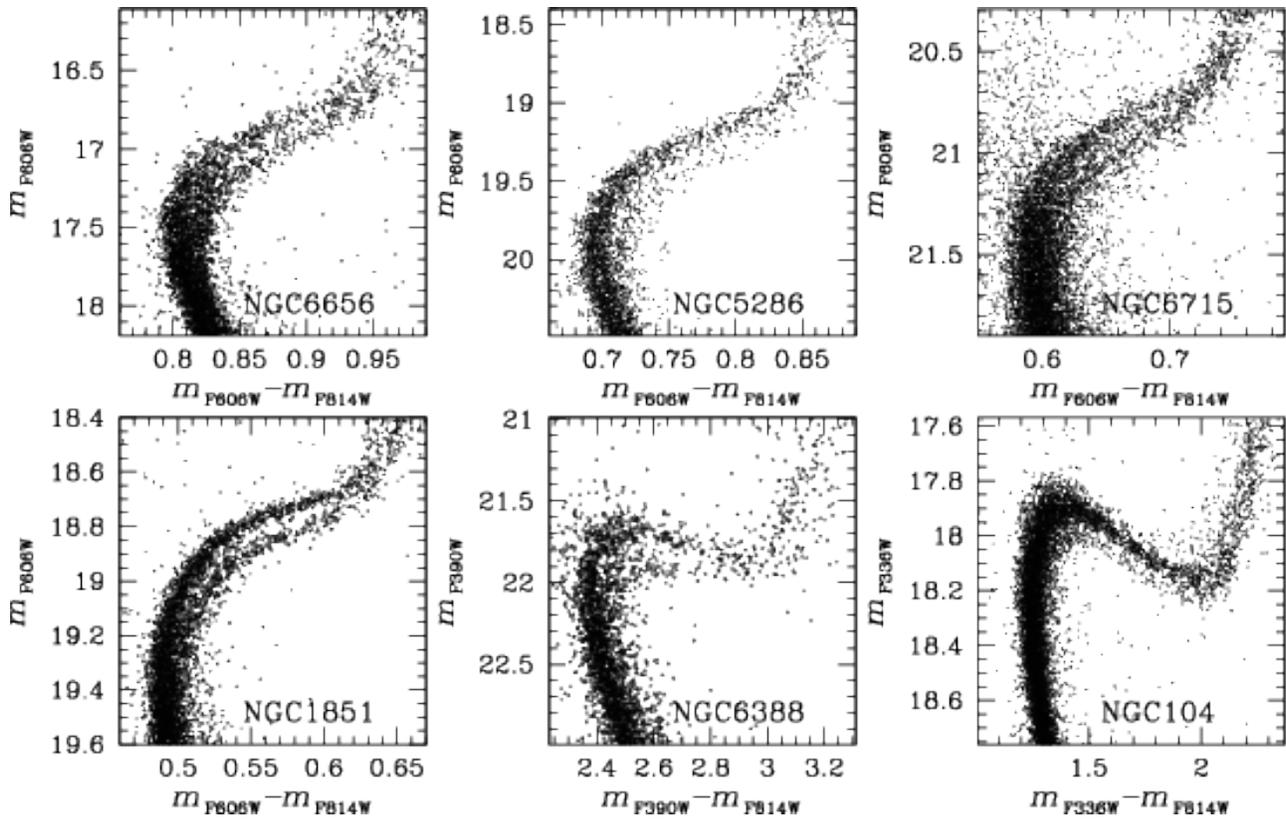


Fig. 2. Collection of CMDs from *HST* ACS/WFC and WFC3/UVIS data for six GCs with spread or split SGB. (Piotto et. 2010, Milone et al. 2008, 2010 Anderson et al. 2009).

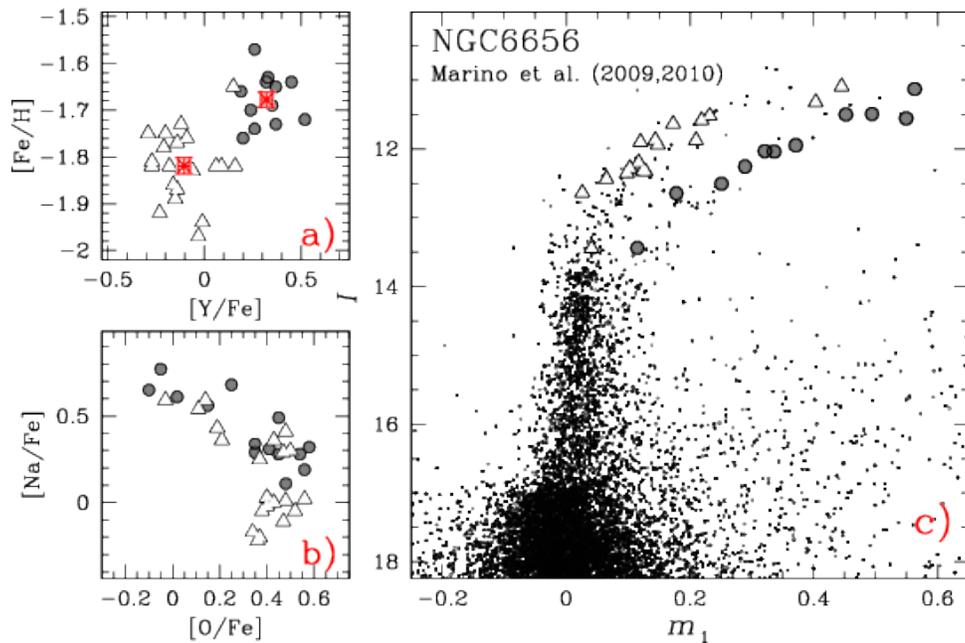


Fig. 3. *Panel a)*: $[\text{Fe}/\text{H}]$ as a function of $[\text{Y}/\text{Fe}]$ for RGB stars in NGC 6656. The two groups of *s*-rich and *s*-poor stars are plotted as gray circles and white triangles, respectively. The Na-O anticorrelation for the same stars of NGC 6656 is shown in *Panel b)* while in *Panel c)* we marked them in the I versus m_1 diagram.

In the light of these results we matched spectroscopic data of NGC 6656 from Marino et al. (2009, 2010) with the Strömgren photometry by Richter et al. (1999). Results are shown in Fig. 3c where we plotted the m_1 versus I diagram for NGC 6656 corrected for differential reddening and found that s -rich and s -poor stars define two distinct RGBs. As the m_1 index is strongly dependent by the CN bands strength, we expect this bimodality as due to the overabundance in both C and N measured by Marino et al. (2010) in s -rich stars.

A fundamental piece of the puzzle comes from the [Fe/H] measurements. While the presence of a possible iron dispersion among stars in NGC 1851 is still controversial (Yong et al. 2008, Carretta et al. 2010, Villanova et al. 2010), when we compare the iron abundance for NGC 6656 with the s -elements abundance, we find a strong correlation, with s -rich stars having a systematically higher [Fe/H] of $\delta[\text{Fe}/\text{H}] = 0.14 \pm 0.03$ (Marino et al. 2009) as shown in Fig. 3a. This result demonstrates that, at odds with ‘normal’ monometallic GCs the different stellar populations of NGC 6656 have significant differences in their iron content and that core-collapse supernovae played a prominent role in the star formation history of this cluster.

An intriguing property of this pair of clusters is that both the s -rich and the s -poor group of stars have its own Na-O anticorrelation as shown in Fig 3b for NGC 6656. For the latter a C-N anticorrelation has also been detected in both the s -groups by Marino et al. (2010). Variations in light elements have been considered as the signature of multiple stellar populations, therefore this result may indicate that NGC 1851 and NGC 6656 have experienced a very complex star formation history with the presence of two stellar groups with discrete s -elements abundance, each containing multiple generation of stars with different sodium and oxygen content.

5 Conclusions

For several decades GCs have been considered as the best approximation of simple stellar populations consisting of coeval and chemically homogeneous stars. This picture have been mainly challenged by two two observational facts.

Since the seventies we know that GCs exhibit a peculiar pattern in their chemical abundances with large star-to-star variations in the abundances of C, N, Na, O, Mg, and Al. These variations are primordial since they are observed in stars at all the evolutionary phases and are peculiar to GC stars. Field stars only changes in C and N abundance expected from typical evolution of low-mass stars.

In addition, since the early sixties we know that the HB of some GCs are quite peculiar. The distribution of stars along the RGB can be multimodal with the presence of one or more gaps and in some cases the HB can be extended toward very high temperatures. It is well known metallicity is the first parameter governing the HB morphology there are some GCs with almost the same iron content but different HB morphology demonstrating the metallicity alone is not enough to reproduce the observational scenario. This problem, known as the *second-parameter* problem, still lacks of a comprehensive understanding.

The recent discoveries of multiple stellar populations in GCs have shattered once and for all the long-held paradigm of GCs as simple stellar populations and brought new interest on these stellar systems.

It is very tempting to relate the second parameter HB problem to the complex abundance pattern of GCs as well as to the multiple sequences observed in the CMD of some clusters. As already mentioned the observed variations of light elements indicate the presence of material processed through hot H-burning processes and should be also He-enriched. While small variations in helium content should have a small impact on colors and magnitudes for MS stars a large impact is expected on the colors of HB stars since He-rich stars should be also less massive.

In summary the discovery of multiple stellar populations started a new era on globular cluster research. While the observational scenario is still puzzling and there is a rather incoherent picture of the multipopulation phenomenon, for the first time we might have the key to solve a number of problems, like the abundance anomalies and possibly the second parameter problem, as well as the newly discovered multiple sequences in the CMD.

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