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Multiple stellar populations in Galactic GCs: observational evidence

Giampaolo Piotto

Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio, 3, I-35122 Padova, Italia, e-mail: giampaolo.piotto@unipd.it

Abstract. An increasing number of photometric observations of multiple stellar populations in Galactic globular clusters is seriously challenging the paradigm of GCs hosting single, simple stellar populations. These multiple populations manifest themselves in a split of some evolutionary sequences of the cluster color-magnitude diagrams. In this paper we will summarize the observational scenario.

Key words. Stars: Population II – Galaxy: globular clusters

1. Introduction

Globular clusters (GC) have generally been though consisting of coeval and chemically homogeneous stars. Color-magnitude diagrams (CMD) of GCs like NGC 6397 (King et al. 1998, Richer et al. 2007) fully support this paradigm of GCs hosting simple stellar populations. However, there is a growing body of observational facts which challenge this traditional view. Since the eighties we know that GCs show a peculiar pattern in their chemical abundances (Gratton el al. 2004 for a review). While they are generally homogeneous insofar Fe-peak elements are considered, they often exhibit large anticorrelations between the abundances of C and N, Na and O, Mg and Al. These anticorrelations are attributed to the presence at the stellar surfaces of a fraction of the GC stars of material which have undergone H burning at temperatures of a few ten millions K (Prantzos et al. 2007). This pattern is peculiar to GC stars. Field stars only show changes in C and N abundances expected from typical evolution of low mass stars (Gratton et al. 2000, Sweigart & Mengel 1979, Charbonnel 1994). This abundance pattern is primordial, since it is observed in stars at all evolutionary phases (Gratton et al. 2001). Finally, the whole stars are interested (Cohen et al. 2002).

In addition, since the sixties we know that the horizontal branches (HB) of some GCs can be rather peculiar. In some GCs the HB can be extended to very hot temperatures, implying the loss of most of the stellar envelope (see compilation by Recio-Blanco et al. 2006). The distribution of the stars along the HB can be clumpy, with the presence of one or more gaps (Ferraro et al. 1998, Piotto et al. 1999). This problem, usually known as the *the second parameter* problem, still lacks of a comprehensive understanding: many mechanisms, and many parameters have been proposed to explain the HB peculiarities, but none apparently is able to explain the entire observational scenario. It is well possible that a combination of parameters is responsible for the HB morphology (Fusi Pecci et al. 1993). Surely, the

Send offprint requests to: G. Piotto

total cluster mass seems to have a relevant role (Recio-Blanco et al. 2006).

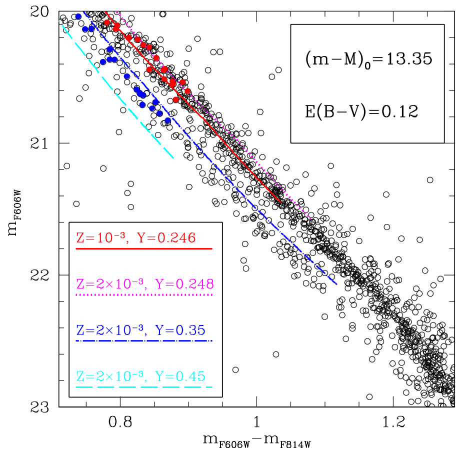

Fig. 1. The double MS of ω Centauri. The bluest MS is more metal rich, and it can be reproduced by models only assuming a very high He content 0.35<Y<0.40 (from Piotto et al. 2005).

It is tempting to relate the second parameter problem to the complex abundance pattern of GCs. Since high Na and low O abundances are signatures of material processed through hot H-burning, they should be accompanied by high He-contents (D'Antona & Caloi 2004). In most cases, small He excesses up to dY$\sim$0.04 (that is Y$\sim$0.28, assuming the original He content was the Big Bang one) are expected. While this should have small impact on colors and magnitudes of stars up to the tip of the RGB, a large impact is expected on the colors of the HB stars, since He-rich stars should be less massive. E.g., in the case of GCs of intermediate metallicity ([Fe/H] -1.5), the progeny of He-rich, Na-rich, O-poor RGB stars should reside on the blue part of the HB, while that of the "normal" He-poor, Na-poor, O-rich stars should be within the instability strip or redder than it. However, within a single GC a correlation is expected between the distribution of masses (i.e. colors) of the HB-stars and of Na and O abundances.

In summary, a number of apparently independent observational facts seems to suggest that, at least in some GCs, there are stars which have formed from material which must have been processed by a previous generation of stars. The questions is: do we have some direct, observational evidence of the presence of multiple populations in GCs? Very recent discoveries, made possible by high accuracy photometry on deep HST images, allowed us to positively answer to this question. In this paper, we will summarize these new observational facts, and briefly discuss their link to the complex abundance pattern and to the anomalous HBs.

2. Direct Observational Evidence of Multiple Populations in GCs

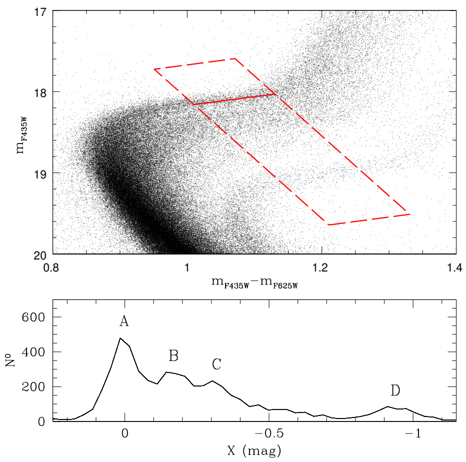

Fig. 2. The multiple SGB in Omega Centauri. There are at least 4 distinct SGBs, plus a small fraction of stars spreaded between SGB-C and SGB-D (from Villanova et al. 2007)

The first, direct observational evidence of the presence of more than one stellar population in a GCs was published by Bedin et al. (2004). Bedin et al. found that, for a few magnitudes below the turn-off (TO), the main sequence (MS) of ω Centauri splits in two (Fig. 1). Indeed, the suspect of a MS split in ω Cen was already raised by Jay Anderson in his PhD thesis, but the result was based on only one external WFPC2 field, and this finding was so un-

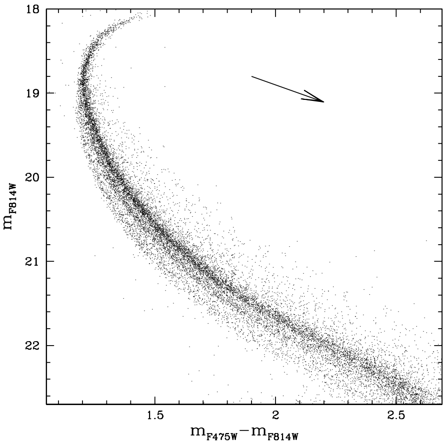

Fig. 3. The spectacular triple MS of NGC 2808. Note the narrowness of the turnoff. The arrow indicates the reddening line.

expected that he decided to wait for more data and more accurate photometry to be sure of its reality. Indeed, Bedin et al. (2004) confirmed the MS split in Jay Anderson field and in an additional ACS field located 17 arcmin from the cluster center. Now, we know that the multiple MS is present all over the cluster, though the ratio of blue to red MS stars diminishes going from the cluster core to its envelope (Sollima et al. 2007, Bellini et al. 2008, in preparation).

The more shocking discovery on the multiple populations in ω Cen, however, came from a follow-up spectroscopic analysis that showed that the blue MS has twice the metal abundance of the dominant red branch of the MS (Piotto et al. 2005). The only isochrones that would fit this combination of color and metallicity (cf. Fig. 1) are extremely enriched in helium ($Y \sim 0.38$) relative to the dominant old-population component, which presumably has primordial helium.

Indeed, the scenario in ω Cen is even more complex. As it is already evident in the CMD of Bedin et al. (2004), this object has at least three MSs, which spread into a highly multiple sub-giant branch (SGB) with at least four distinct components (Fig. 2) characterized by different metallicities and ages (Sollima et al. 2005, Villanova et al. 2007; the latter has a detailed discussion.) A fifth, more dispersed component is spread between the SGB-C and SGB-D of Fig. 2.

These results reinforced the suspicion that the multiple MS of ω Cen could just be an additional peculiarity of an already anomalous object, which might not even be a GC, but a remnant of a dwarf galaxy instead. In order to shed more light on the possible presence of multiple MSs in Galactic GCs, we undertook an observational campaign with *HST*, properly devised to search multiple sequences at the level of the upper-MS, turn-off (TO), and SGB. The new data allowed us to show that the multiple evolutionary sequence phenomenon is not a peculiarity of ω Centauri only.

As shown in Fig. 3, also the CMD of NGC 2808 is splitted into three MSs (Piotto et al. 2007). Because of the negligible dispersion in Fe peak elements (Carretta et al 2006), Piotto et al. (2007) proposed the presence of three groups of stars in NGC 2808, with three different He contents, in order to explain the triple MS of Fig. 3. These groups may be associated to the three groups with different Oxygen content discovered by Carretta et al. (2006). These results are also consistent with the presence of a multiple HB, as discussed in D'Antona and Coloi (2004) and D'Antona et al. (2006). Finally, we note that the narrowness of the TO region displayed by Fig. 3 suggests that the 3 stellar populations of NGC 2808 must have a small age dispersion, much less than 1 Gyr.

At the meeting, someone raised the suspect that the multiple sequences in NGC 2808 may be an artifact of differential reddening. Indeed, it is well known since Walker (1999) that NGC 2808 suffers a small amount of differential reddening. Bedin et al. (2000) calculated a differential reddening of the order of 0.02 magnitudes in E(B-V) from the cluster center to ~400 arcsec from the center. The split of the sequences in Fig. 3 is more than an order of magnitude larger than this value. In any case, being aware of the presence of differential reddening, we corrected for it. The CMD of NGC 2808 published in Piotto et al. (2007) and reproduced in Fig. 3 has been corrected for differential reddening, adopting the

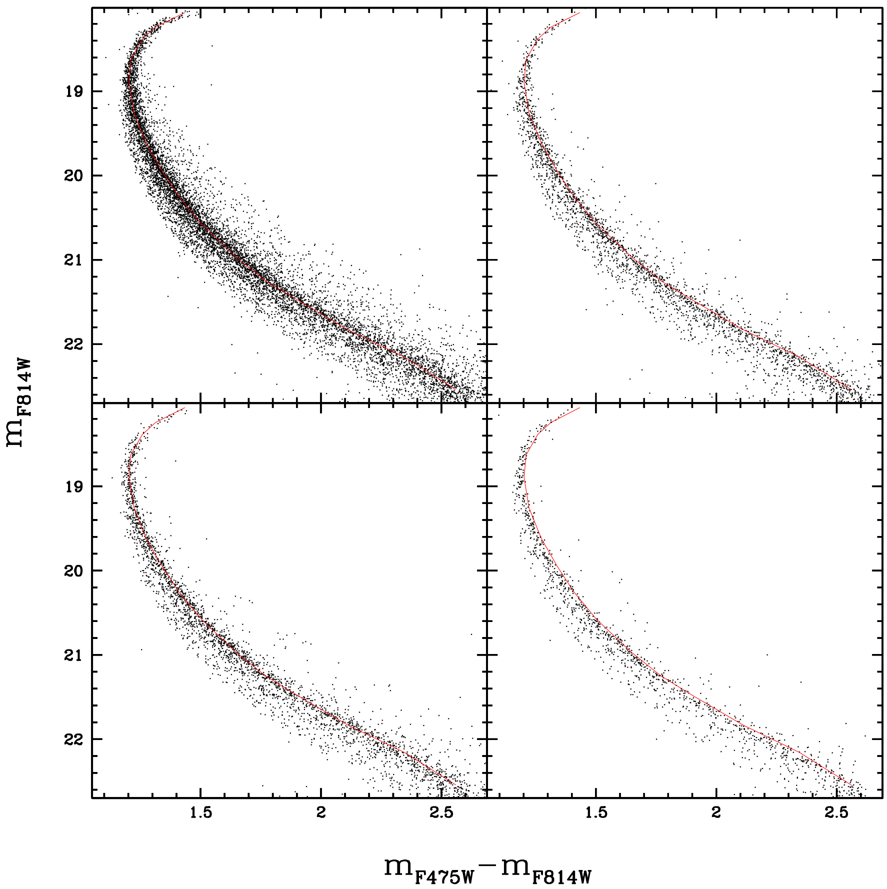

Fig. 4. Original, not corrected for differential reddening CMD of NGC 2808 in the four quadrants of the ACS field. The triple MS is well visible, and with exactly the same shape in all quadrants. The small offsets of the fiducial line of the reddest MS indicates the level of differential reddening within the ACS field.

procedure described in Sarajedini et al. (2007), which allows also to correct for small, residual spatial variation of the photometric zero point which affects the ACS data (see Sarajedini et al. 2007 for more details). There are additional arguments against the differential reddening argument. First of all, the TO-SGB regions of the CMD are very narrow (this is the region of the CMD which should be mostly affected by differential reddening, as shown by the reddening line plotted in Fig. 3). The three MSs of Fig. 3 tend to diverge from the TO to fainter magnitudes, while differential reddening would simply cause a shift of the sequences parallel to the reddening line. Finally, differential reddening tends to randomly broaden the CMD sequences, not to create coherent features, which, we note, are exactly the same everywhere within the ACS field, as shown in Fig. 4.

Also NGC 1851 must have at least two, distinct stellar populations. In this case the observational evidence comes from the split of the SGB in the CMD (Fig. 5) of this cluster (Milone et al. 2007). Would the magnitude difference between the two SGBs be due only to an age difference, the two star formation episodes should have been separated by at least 1 Gyr. However, as shown by Cassisi et al. (2007), the presence in NGC 1851 of two stellar populations, one with a normal α-enhanced chemical composition, and one characterized by a strong CNONa anticorrelation pattern could reproduce the observed CMD split. In this case, the age spread between the two populations could be much smaller, possibly consistent with the small age spread implied by the narrow TO of NGC 2808. In other terms, the SGB split would be mainly a consequence of the metallicity difference, and only negligibly affected by (a small) age dispersion. Cassisi et al. (2007) hypothesis is supported by the presence of a group of CN-strong and a group of CN-weak stars discovered by Hesser et al. 1982, and by a recent work by Yong and Grundahl (2007) who find a NaO anticorrelation among NGC 1851 giants.

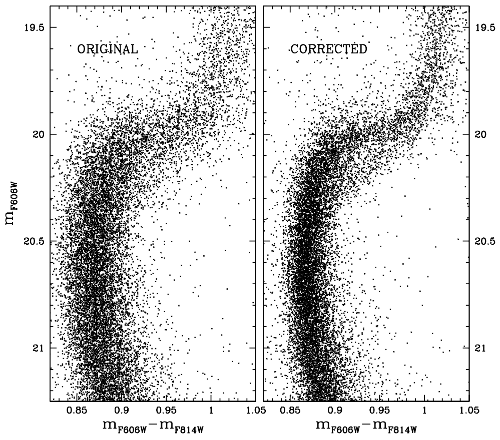

Fig. 6. After the correction for differential reddening, also NGC 6388 shows a double SGB (Piotto et al. 2008, in preparation).

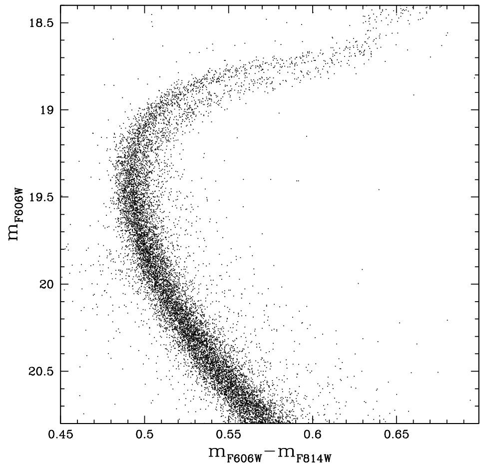

Fig. 5. The double SGB in NGC 1851. The two SGBs are separated by about 0.12 magnitudes in F606W (from Milone et al. 2007)

NGC 1851 is considered a sort of prototype of bimodal HB clusters. Milone et al. (2007) note that the fraction of fainter/brighter SGB stars is remarkably similar to the fraction of bluer/redder HB stars. Therefore, it is tempting to associate the brighter SGB stars to the CN-normal, s-process element normal stars and to the red HB, while the fainter SGB should be populated by CN-strong, s-process element-enhanced stars which should evolve into the blue HB. In this scenario, the faint SGB stars should be slightly younger (by a few 10^7 to a few 10^8 years) and should come from processed material which might also be moderately He enriched, a fact that would help explaining why they evolve into the blue HB. By studying the cluster MS, Milone et al. (2007) exclude an He enrichment larger than ΔY=0.03), as expected also by the models of Cassisi et al. (2007). Nevertheless, this small He enrichment, coupled with an enhanced mass loss, would be sufficient to move stars from the red to the blue side of the RR Lyrae instability strip. Direct spectroscopic measurements of the SGB and HB stars in NGC 1851 are badly needed.

There is at least another cluster which undoubtedly shows a split in the SGB: NGC 6388 (Piotto et al. 2008, in preparation). Figure 6 shows that, even after correction for differential reddening, the SGB of NGC 6388 closely resembles the SGB of NGC 1851. NGC 6388, as well as its twin cluster NGC 6441, are two extremely peculiar objects. Since Rich et al. (1997), we know that, despite their high metal content, higher than in 47 Tucanae, they have a bimodal HB, which extends to extremely hot temperatures (Busso et al. 2007), totally un-expected for this metal rich cluster. NGC 6388 stars also display a NaO anticorrelation (Carretta et al. 2007). Unfortunately, available data do not allow us to study the MS of this cluster, searching for a MS split. Hopefully, new data coming from the HST program GO11233 should help to constrain the MS width, and therefore the He dispersion. In this context, it is worth noting that Caloi and D'Antona (2007), in order to reproduce the HB of NGC 6441, propose the presence of three populations, with three different He contents, one with an extreme He enhancement of Y=0.40. Such a strong enhancement should be visible in a MS split, as in the case of ω Cen and NGC 2808. A strong He enhancement and a consequent MS split may also apply to NGC 6388, because of the many similarities with NGC 6441.

One more cluster, M54, shows a complex CMD (see, e.g., Siegel et al. 2007). This cluster has been shown, however, in too many papers to cite here, to be a part of the Sagittarius dwarf galaxy that is in process of merging into the Milky Way, and very possibly the nucleus of that galaxy. Actually, it is still matter of debate which parts of the CMD of M54 represent the cluster population and which ones are due to the Sagittarius stars. M54 may have a complex stellar populations as ω Cen, though this fact will be much harder to demonstrate.

Finally, we note that the multiple population phenomenon in star clusters may not be confined only to Galactic GCs. Mackey & Broby Nielsen (2007) suggest the presence of two populations with an age difference of ~300 Myr in the 2 Gyr old cluster NGC 1846 of the Large Magellanic Cloud (LMC). In this case, the presence of the two populations is inferred by the presence of two TOs in the CMD. These two populations may either be the consequence of a tidal capture of two clusters or NGC 1846 may be showing something analogous to the multiple populations identified in the Galactic GCs. NGC 1846 might not be an exception among LMC clusters. Vallenari et al. (1994) already suggested the possibility of the presence of two stellar populations in the LMC cluster NGC 1850. A quick analysis of the CMDs of about 50 clusters from ACS/HST images shows that about 10% of them might show evidence of multiple generations (Milone et al. 2008, in preparation).

3. Discussion

So far, we have identified four Galactic globular clusters for which we have a direct evidence of multiple stellar populations, and they are all quite different:

1) In ω Centauri ($\sim 4 \times 10^6\ M_\odot$), the different populations manifest themselves both in a MS split (interpreted as a split in He and metallicity abundances) and in a SGB split (interpreted in terms of He, metallicity, and age variations > 1 Gyr), which implies at least four different stellar groups within the same cluster, which formed in a time interval greater than 1 Gyr. Omega Centauri has also a very extended HB (EHB), which extends far beyond 30.000K.

2) In NGC 2808 ($\sim 1.6 \times 10^6\ M_\odot$), the multiple generation of stars is inferred from the presence of three MSs (also in this case interpreted in terms of three groups of stars, with different He content), possibly linked to three stellar groups with different oxygen abundances, and possibly to the multiple HB. The age difference between the 3 groups is significantly smaller than 1 Gyr. Also NGC 2808 has an EHB, extended as much as the HB of ω Cen. It shows an extended NaO anticorrelation.

3) In the case of NGC 1851 ($\sim 1.0 \times 10^6\ M_\odot$), we have evidence of two stellar groups from the SGB split. It is difficult to establish the age difference between the two stellar populations without a detailed chemical abundance analysis. However, available observational evidence seems to imply that the SGB split may be due to a difference in CN, Na, O, and s-process elements, while the age difference could be small (e.g. as small as in the case of NGC 2808). On the other hand, if the SGB split would be due only to age, the two star formation episodes should have happened with a time separation of ~ 1 Gyr. From the analysis of the cluster CMD, there seems to be no MS split, which would imply a small He spread, if

any ($\Delta Y < 0.03$). The cluster has no EHB, but it shows a bimodal HB. It shows a NaO anticorrelation.

4) In NGC 6388 ($\sim 1.6 \times 10^6\ M_\odot$) we have evidence of two stellar groups from a SGB split. With the available observational data it is not possible to establish whether there is a split in the MS of this GC. NGC 6388 has an EHB, possibly as extended as in the cases of NGC 2808 and ω Cen. It shows an extended NaO anticorrelation.

Another massive ($\sim\ 2.0 \times 10^6\ M_\odot$) GC, M54, is suspected to host multiple populations, though the analysis is strongly hampered by the contamination of the Sagittarius galaxy. Also M54 has an EHB, similar to the HB of NGC 2808 and ω Cen (Rosenberg et al. 2004).

At least one LMC intermediate age cluster shows a population split at the level of the TO: NGC 1846. This is a massive clusters, among the most massive LMC clusters according to Chrysovergis et al. (1999), though probably not as massive as the above Galactic GCs (a more accurate mass estimate for this cluster is needed). Other LMC clusters are suspected to shows a similar TO splitting.

Many GCs are clearly not simple, single-stellar-population objects. The emerging evidence is that the star-formation history can vary strongly from GC to GC, and that, GCs are able to produce very unusual objects, as no such He-rich MS stars have ever been found elsewhere. At the moment, we can note that the three GCs in which multiple generations of stars have been clearly identified (Omega Cen, NGC 2808, and NGC 1851), and the two other GCs expected to contain more than one stellar generation (NGC 6388 and NGC 6441: Fig 6, Caloi & D'Antona 2007, Busso et al. 2007) are among the ten most massive GCs in our Galaxy. This evidence suggests that cluster mass might have a role in the star-formation history of GCs.

Reconstruction of this star-formation history requires a a better understanding of the chemical enrichment mechanisms, but the site of hot H-burning remains unclear. There are two requisites: (i) temperature should be high enough; and (ii) the stars where the burning occurs should be able to give back the processed material to the intracluster matter at a velocity low enough that it can be kept within the GC itself (a few tens of km/s). Candidates include: (i) Massive ($M > 10 M_\odot$) rotating stars (Decressin et al. 2007); (ii) the most massive among the intermediate mass stars undergoing hot bottom burning during their AGB phase (Ventura et al. 2001). The two mechanisms act on different timescales (10^7 and 10^8 yr, respectively), and both solutions have their pros and cons. The massive star scenario should avoid mixture of O-poor, Na-rich material with that rich in heavy elements from SNe, while it is not clear how the chemically processed material could be retained by the proto-cluster in spite of the fast winds and SN explosions always associated to massive stars. Producing the right pattern of abundances from massive AGB stars seems to require considerable fine tuning. In addition, both scenarios require that either the IMF of GCs was very heavily weighted toward massive stars, or that some GCs should have lost a major fraction of their original population (Bekki and Norris 2006), and then may even be the remnants of tidally disrupted dwarf galaxies, as suggested by the complexity in the CMD of ω Cen and M54.

Also in view of these problems, it will be important to understand the role of the capture of field stars by massive forming globular clusters, as suggested by Kroupa (1998), see also Fellhauer et al. 2006).

The observational scenario is becoming more complex, but, the new results might have indicated the right track for a comprehensive understanding of the formation and early evolution of GCs. We are perhaps for the first time close to compose what has been for decades and still is a broken puzzle, which includes the cluster star chemical anomalies, the HB peculiarities, and, now, the multiple evolutionary sequences.

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