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# The quite complex "Simple Stellar Populations" of globular clusters

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**Abstract.** There is compelling observational evidence that globular clusters (GCs) are quite complex objects. A growing body of photometric results indicate that the evolutionary sequences are not simply isochrones in the observational plane -as believed until a few years ago- from the main sequence, to the subgiant, giant, and horizontal branches. The strongest indication of complexity comes however from the chemistry, from internal dispersion in iron abundance in a few cases, and in light elements (C, N, O, Na, Mg, Al, etc.) in *all* GCs. This universality means that the complexity is *intrinsic* to the GCs and is most probably related to their formation mechanisms. The extent of the variations in light elements abundances is dependent on the GC mass, but mass is not the only modulating factor; metallicity, age, and possibly orbit can play a role. Finally, one of the many consequences of this new way of looking at GCs is that their stars may show different He contents.

**Keywords.** Stars: abundances, Population II – Galaxy: globular clusters

## 1. It's not so simple

Globular Clusters (GCs) have long been considered the best approximations of a *Simple Stellar Population* (Renzini & Buzzoni 1986), and this may still be valid for some purposes. However, they are not truly simple. We know that GCs contain a fraction of binaries (e.g., Meylan & Heggie 1987). But now we also know that their stars are not strictly coeval; for old clusters, like the Galactic globulars, the age differences are so small to be hardly detectable, but the same is not true for the Magellanic Clouds ones. And we also know that the initial chemical composition of the stars we presently observe was not the same.

There is a growing body of observational evidence of the complexity of GCs, both from photometry (with multiple, or split, or wide sequences) and from spectroscopy (with large differences in light elements and even, in a few cases, with spreads in metallicity).

Of course, $\omega$ Cen is the first example that comes to mind, even if for its characteristics (or better, because of its characteristics) it has often been labelled as the nucleus of an ancient dwarf spheroidal galaxy. However, $\omega$ Cen is only the tip of the iceberg and there are many other interesting cases, like M54, which lies in the nucleus of the Sagittarius dwarf galaxy (Ibata *et al.* 1994, Bellazzini *et al.* 2008a), and which resembles $\omega$ Cen in several aspects. But also more "normal", lower mass clusters show peculiarities, like NGC 2808 which, among many other oddities, presents three well separated main sequences (Bedin *et al.* 2004, Sollima *et al.* 2007). I will come back to these three objects later.

Among other evident examples we find for instance M22 (NGC 6656) which had long been suspected to have a dispersion in metallicity (from photometry, e.g. Hesser *et al.* 1977 or spectroscopy, e.g. Brown & Wallerstein 1992, but see also Ivans *et al.* 2004)

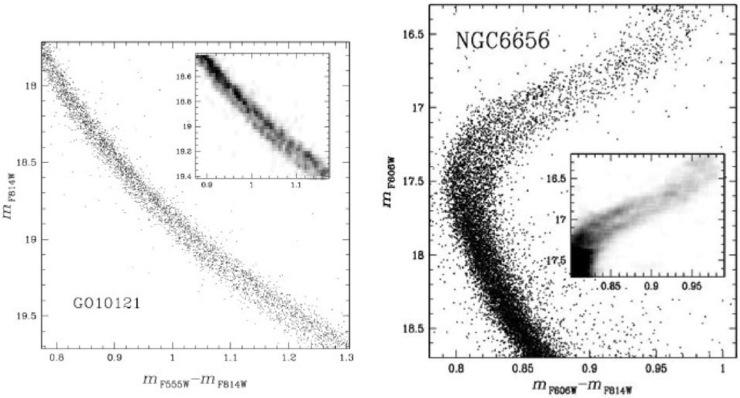

**Figure 1.** Examples of split main sequences or subgiant branches recently found in Galactic GCs using the high precision photometry of ACS@HST: NGC 6752 (Milone *et al.* 2009), and M22 (courtesy of A. Milone).

and that also displays a split in the SGB and RGB (see Fig. 1), or NGC 1851 with its split SGB (Milone *et al.* 2008) and RGB (Han *et al.* 2009), and its anomalous chemical abundances (e.g. Yong *et al.* 2009).

Interestingly, thanks to the exquisite precision of the ACS camera on HST (whose photometry can reach the depth and precision to detect even small colour and magnitude differences), more clusters were found to show wide or even split evolutionary sequences, from the main sequence and up to the SGB and RGB. The newest entries are 47 Tuc, where Anderson *et al.* (2009) find both a split SGB and a wide faint main sequence, and NGC 6752, unsuspected until now, which shows a split main sequence (Milone *et al.* 2009); for both, see Fig. 1. It seems that more and more GCs are beginning to unveil their complex photometric sequences; for a more extended discussion, see the earlier reviews by Piotto (2008, 2009).

Even if the evidence from photometry is the easiest to see, even for non-specialists, the strongest proof that GCs harbour at least two stellar generations comes from spectroscopy. Not only we may see stars with the same evolutionary status but with very different chemical composition in GCs, at least for some light elements, but also this situation is not limited to a few "freaks", as $\omega$ Cen or M22† were considered for a long time. The chemical signatures we used to call "anomalies" are widespread and show up in *all* clusters studied. Bimodality -and anticorrelation- in CN and CH strengths, or anticorrelations between other light elements, like Na and O, or Mg and Al, have long been observed in evolved stars, where they could be explained, although with some difficulties, considering extra-mixing episodes (see e.g. the reviews by Smith 1987 and Kraft 1994 where the extra-mixing *vs* the primordial-enrichment hypotheses are discussed).

However, these same so-called chemical anomalies were later found also in non evolved, main sequence stars (e.g., Cannon *et al.* 1998 found a bimodality in CN, CH in 47 Tuc, and other authors in many other GCs, see the review by Gratton *et al.* 2004).

Once established that the Na-O anticorrelation was present also in unevolved stars (Gratton *et al.* 2001 found it for the first time in NGC 6752 and NGC 6397, followed

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† Recently, the claim of a dispersion in metallicity in M22 has gained substance, and two papers appeared. One is based on a sample of 17 stars studied with high resolution spectra (Marino *et al.* 2009), and indicates differences both in metallicity and heavy elements. The second paper, by Da Costa *et al.* (2009), presents a larger sample, but metallicity is derived from the Calcium triplet. Both show a bimodality in metallicity.

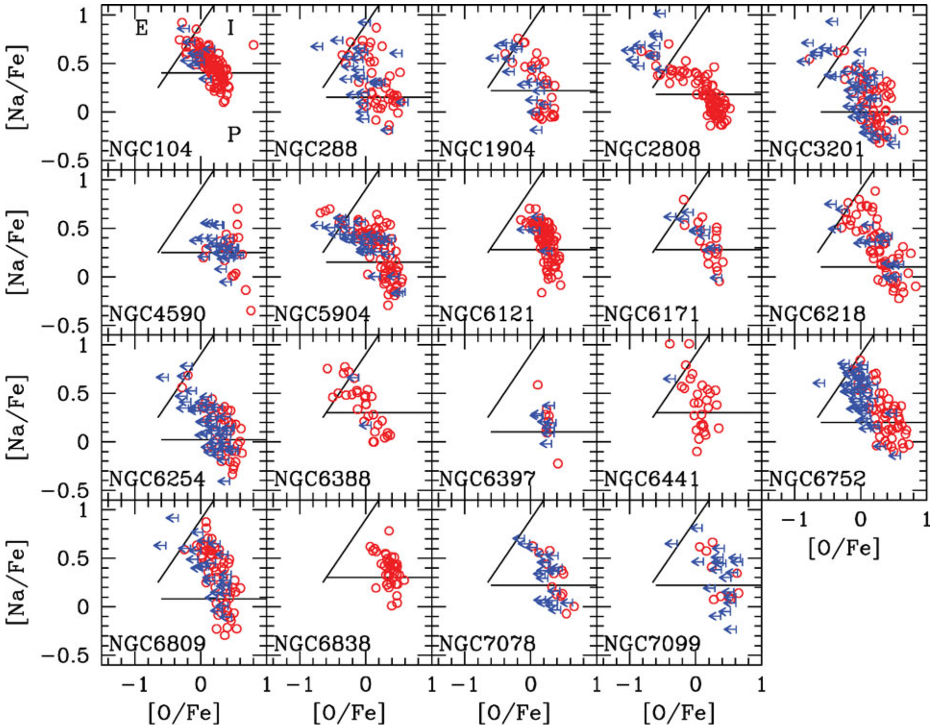

**Figure 2.** Na-O anticorrelations in 19 GCs observed with FLAMES@VLT, with separation among Primordial, Intermediate, and Extreme populations (see Carretta *et al.* 2009a for details).

by Ramirez & Cohen 2002 in M71, and by Carretta *et al.* 2004 in 47 Tuc), it became clear that another explanation was required. These chemical signatures are the result of H-burning at high temperature (ON, NeNa, MgAl cycles: see Denisenkov & Denisenkova 1989, Langer et al. 1993); the resulting chemical patterns cannot be produced in low mass, main sequence stars like those we are presently seeing in GCs. So the typical chemical signature of high N, Na, Al, and low C, O, Mg *must have originated in a previous generation of more massive stars, that polluted the gas from which part of the GC stars formed later.*

Perhaps the most famous pair of elements showing such variations, anti-correlated with each other, are O and Na. This Na-O anticorrelation was first found among cluster giants, mainly by the Lick-Texas group, by Kraft, Sneden, and many collaborators. They studied two-three tens of targets per cluster, observing stars one by one; for a review of their work, see Kraft (1994) and Gratton *et al.* (2004). The availability of efficient spectrographs at 8-10m telescopes, and their multi-object capabilities have permitted to extend this kind of study both to faint, unevolved stars and to much larger samples. About three years ago, there were about 200 giants studied in literature, and about 50 unevolved stars, as shown in Carretta *et al.* (2006) in their presentation of the Na-O anticorrelation in about 100 stars in NGC 2808, studied with FLAMES@VLT.

The work by Carretta and collaborators (e.g. Carretta *et al.* 2009a) has further demonstrated the universality of the Na-O anticorrelation; all GCs studied show it, as evident in the 19 GCs displayed in Fig. 2. However, this anticorrelation is not the same in all clusters; the shape and the extension vary from cluster-to-cluster. On the basis of the Na and O abundances, Carretta and collaborators separated the cluster stars in first-generation and second-generation ones. The first are the ones with Na and O similar to field stars of the same metallicity, the second show varying degrees of O depletion and Na enhancement. Na and O are not the only light elements involved. Also Mg, Al (and even Si and F, Yong *et al.* 2005, Smith *et al.* 2005) are altered. In particular, Al is a powerful probe of the nature of first-generation polluters, due to the very high temperatures required for its production.The modification from the primordial value varies a lot from cluster to cluster (Carretta *et al.* 2009b: in some clusters Al changes a lot, in other much less or not at all). This is an indication that different polluters were at work. The chemical changes come all from H-burning, but at very different temperatures, and this indicates that polluters† of different mass were at work in different GCs.

## 2. The iceberg tip

A few clusters show the characteristics described above in a extreme way and have been the footholds, if one may say so, to convince even the distracted astronomer that something did not fit the notion of GCs being simple, old, boring systems.

### 2.1. *ω Centauri*

When talking of the complexity of GCs, the first example that comes to mind is of course $\omega$ Cen. It had long been suspected that it could host stars of different metallicity, given the width of the sequences (e.g., Cannon & Stobie 1973, Alcaino & Liller 1987) and also demonstrated by pioneering spectroscopic work (see Butler *et al.* 1978, Cohen 1981). Given the huge amount of papers dedicated to $\omega$ Cen, I can only touch upon a tiny fraction of the works on this cluster, concentrating on the very recent results, which show not only dispersion in colour or metallicity, but actual discrete separation in different sub-samples of the total cluster population. Initially the clear indication of multiple populations came from the RGB (Lee *et al.* 1999, Pancino *et al.* 2000, Ferraro *et al.* 2004), see Fig. 3. Several metallicities, and perhaps different ages were deduced for the different RGB sequences, in particular for the very metal-rich “anomalous RGB”, see for instance the high resolution spectroscopic study of 40 giants by Norris & Da Costa (1995), the work on Ca abundances of about 500 giants observed at low spectroscopic resolution by Norris et al (1996), the Strömgren photometry by Hilker & Richtler (2000), the high resolution analysis of 6 stars on the “anomalous” RGB by Pancino *et al.* (2002), the near-IR spectroscopy of about 20 giants by Origlia *et al.* (2003), the study of main sequence stars by Stanford *et al.* (2007), the large survey at intermediate spectroscopic resolution by Johnson *et al.* (2009).

However, the differences go deeper, and with data obtained with HST, it was possible to detect also separate main sequences (Bedin *et al.* 2004, see Fig. 3), to which I will come back later.

### 2.2. *NGC 2808*

Even more “normal”, less massive clusters show striking features. NGC 2808, among many other marked peculiarities, presents three well separated main sequences (Piotto *et al.* 2005). It also has a very complex Horizontal Branch (HB), with three main groups of stars, that cannot be explained under standard assumptions. Both these features seem to require He enhancement in part of its stars (see next Section), which would also naturally agree very well with the observed Na-O anticorrelation (the third most extended one,

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† While no definitive consensus has been reached on the actual nature of the polluters, the most promising candidates are fast rotating massive stars (e.g. Decressin *et al.* 2007), and asymptotic giant branch stars (e.g., Ventura *et al.* 2001). Since they are discussed in other contributions, I will not say more on the subject.

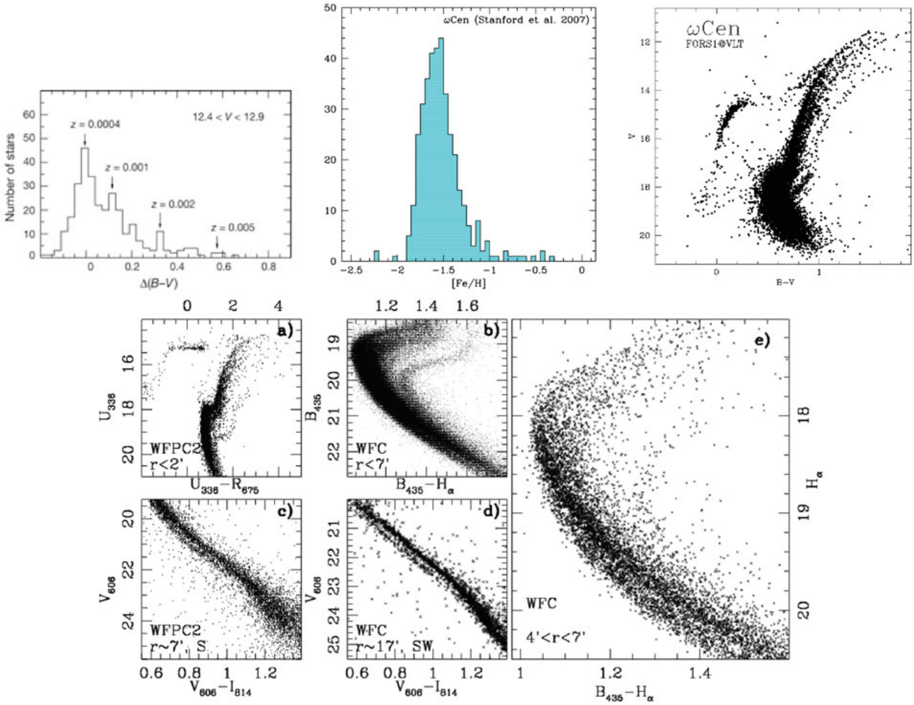

**Figure 3.** Evidence of multiple populations in $\omega$ Cen: Upper left panel: distribution in colour of RGB stars from Lee *et al.* (1999). Central upper panel: distribution in [Fe/H] of main sequence stars, adapted from Stanford *et al.* (2007). Upper right panel: distinct RGBs, from Ferraro *et al.* (2004). Lower panel: collection of CMDs showing the various populations, both for evolved and main sequence stars, from Bedin *et al.* (2004).

after $\omega$ Cen and M54), since Na-rich and O-poor stars should also be He-rich (the main outcome of H-burning is, of course, He). Fig. 4 shows the three main sequences, a plausible interpretation of its HB (D'Antona *et al.* 2005), and the Na-O anticorrelation (Carretta *et al.* 2006).

## 2.3. *M54*

M54 is the second most massive cluster of the Galaxy, and lies at the center of the disrupting Sgr dwarf galaxy. It has been suspected to have a dispersion in metallicity since the observations by Sarajedini & Layden (1995), whose CMD shows a wide RGB, compatible with a dispersion of 0.16 dex in [Fe/H], see Fig. 5. This has been recently confirmed by low resolution spectroscopy of a very large sample of M54 and Sgr stars (Bellazzini *et al.* 2008a, see Fig. 5). The very recent results obtained by Carretta *et al.* (2010) using FLAMES spectra of about 80 RGB stars further confirm this: M54 has a dispersion in metallicity of the order of about 0.2 dex, well above the errors (see Fig. 5). Furthermore, it has a very extendend Na-O anticorrelation, more extended for the metal-rich than for the metal-poor stars. Carretta *et al.* (2010) also noticed that the same happens in $\omega$ Cen. M54 deserves more study, but it's clear that it resembles $\omega$ Cen; maybe, as it has been suggested (Bellazzini *et al.* 2008a, Carretta *et al.* 2010), we see it now as $\omega$ Cen was a long time ago, before the dwarf galaxy around it dispersed.

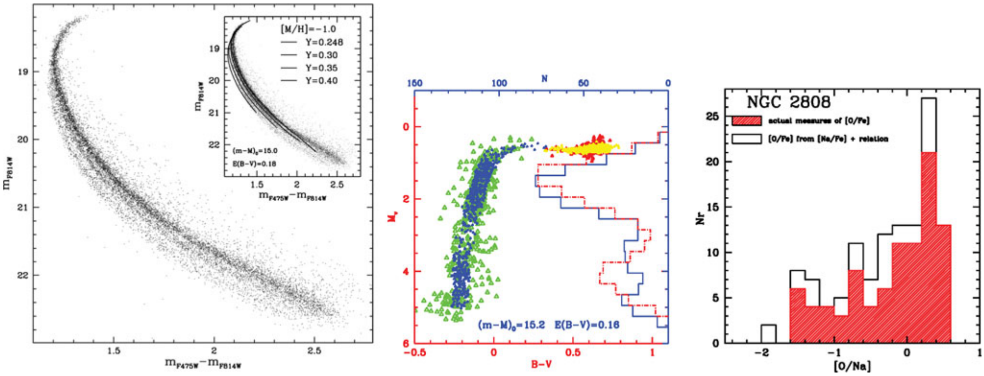

**Figure 4.** Evidence of multiple populations in NGC 2808. Left panel: the three separate main sequences found by Piotto *et al.* (2007). Central panel: the complex HB, and the interpretation assuming three different He contents, made by D'Antona *et al.* (2005). Right panel: the distribution of Na and O abundances, with three peaks, as found in Carretta *et al.* (2006).

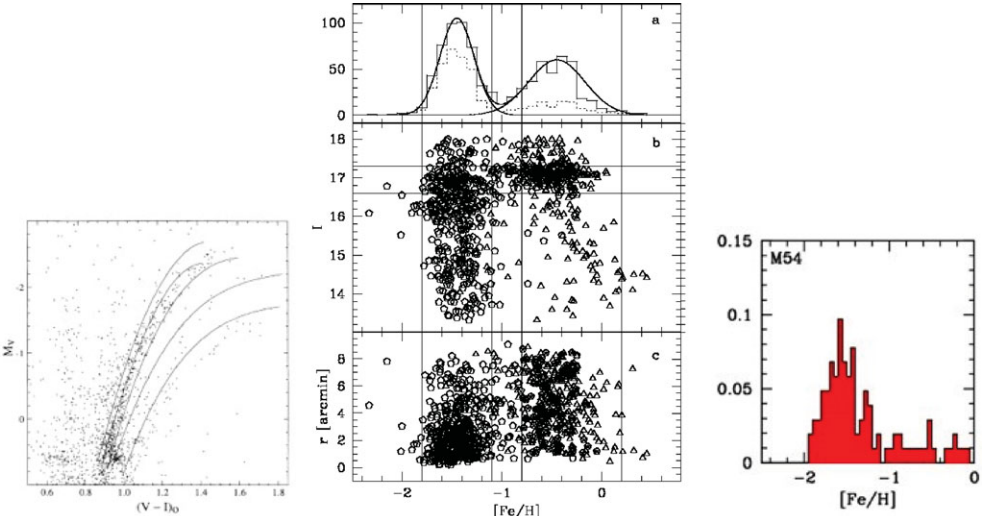

**Figure 5.** Dispersion in metallicity in M54. Left panel: Sarajedini & Layden (1995) found a colour dispersion in the RGB. Central panel: Separation of M54 from the Sgr population in Bellazzini *et al.* (2008a), based on Calcium triplet observations of several hundreds of stars; notice that both M54 and Sgr show a noticeable dispersion in [Fe/H]. Right panel: results obtained by Carretta *et al.* (2010) from 76 star in M54 (peaked at [Fe/H]∼ −1.6) and 25 stars in Sgr (extending in [Fe/H] from about −1 to solar) observed with FLAMES@VLT.

## 3. Are there different He abundances in GCs ?

The main problem for establishing if He is variable in GCs it that it is difficult to see the effect of small variations in the CMDs, apart from the HB, which is a sort of "amplifier". HBs suffer from the notorious "second-parameter" problem: metallicity is of course the first parameter explaining their structure, age is most probably the second, but their combination cannot explain all HBs, in particular at the bluer, hotter extremes.

A solution is to bring also He into the problem, since an higher He content means brighter and bluer HBs. As shown in Fig. 4, D'Antona *et al.* (2005) were able to reproduce the observed distribution of HB stars in NGC 2808 assuming three different He contents (from a "primordial" value of Y = 0.25 for the red HB, to Y = 0.40 for the extreme blue

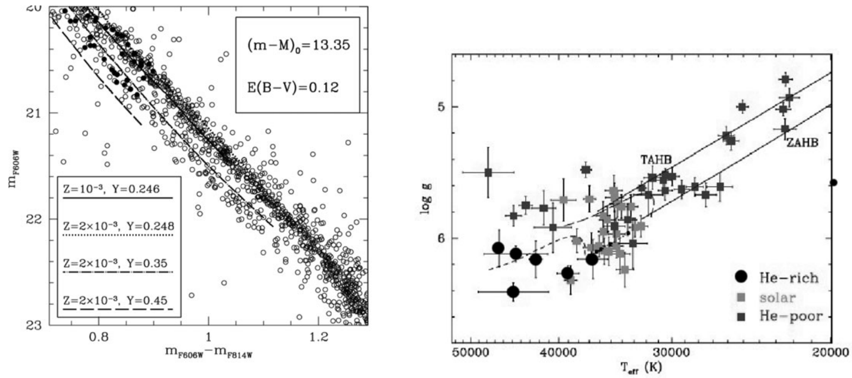

**Figure 6.** He abundances in $\omega$ Cen. Left panel: the two main sequences in Piotto *et al.* (2005), with star observed with FLAMES indicated by filled red and blue circles. The isochrones shown have been computed for $Z = 1\times10^{-3}$, $Y = 0.25$ and $Z = 2\times10^{-3}$, $Y = 0.35$. Right panel (adapted from Moehler *et al.* (2007)): blue and extreme HB stars for which Moehler *et al.* obtained low resolution spectra and for which determined temperatures, gravities, and He abundances; part of the extreme HB stars are He-enhanced.

HB). A similar exercise has been done by Busso *et al.* (2007) and D'Antona & Caloi (2008) for NGC 6388, producing similar results. This is a strong indication that GC stars are not so homogeneous in He as we thought: in the same cluster we may have stars with "normal" He and stars with different levels of He-enhancement, even if perhaps this doesn't happen in all clusters, or at least not at this high level.

It could be very interesting to directly measure He abundances in GC stars; however, this is possible only on the HB, and with many limitations. There is a small range in temperature (9500-11500 K) where He lines can be observed (even if they are tiny, at a few percent of the continuum level) and He abundances are not altered by dilution and mixing. Recently, Villanova *et al.* (2009) have obtained high resolution, high S/N of a few HB stars in NGC 6752, but their results are not decisive: they could measure He only in four stars, all of them Na-poor, O-rich (hence expected to be He-"normal", that is what they found), while they could not do so for the only Na-rich, O-poor star (expected to be He-enhanced). On the other hand, He has been found to be enhanced in some very blue HB stars in NGC 2808 and $\omega$ Cen (see Moehler *et al.* 2007 and Fig. 3), even if the cause of He-enhancement could also be mixing following a late He-flash (Castellani & Castellani 2003) for these extreme HB stars.

In the present volume there is also a discussion (see Bragaglia *et al.* 2010 for a lengthier presentation) on how to determine differences in He abundances from RGB stars using colours, metallicities, and magnitude of the RGB bump.

Finally, maybe the strongest case for He-enhancement of part of GC stars comes from two massive objects. The first one is again $\omega$ Cen, with its two separate main sequences (see Fig. 3). Piotto *et al.* (2005) obtained spectra of moderate resolution for 17 stars on the blue and 17 stars on the red sequences; surprisingly, the blue sequence turned out to be more metal-rich by about 0.3 dex. This could be explained only if we assume that the blue sequence is also much more He-rich than the red one (Y∼0.35-0.38 *vs* 0.25) as seen from isochrone fit. Of course we have to remember that the different metallicities are actually measured, while the He-enhancement is only inferred.

The split main sequence is even more spectacular in NGC 2808 (Fig. 4), and again the three sequences can be well fit assuming the same age but three different He levels (i.e., Y∼ 0.25, 0.30, and 0.38, see Piotto *et al.* 2007).

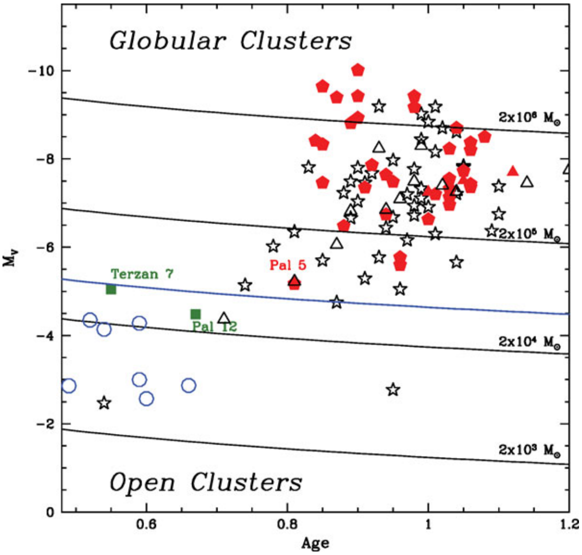

**Figure 7.** Relative Age parameter vs absolute magnitude $M_V$ for globular and old open clusters. Red filled pentagons and triangles are GCs where Na-O anticorrelation has been observed, in the Milky Way or the LMC respectively; green squares are clusters which do not show (yet?) evidence for O-Na anticorrelation (Terzan 7 and Pal 12, both in the Sgr dwarf galaxy). Open stars and triangles mark clusters for which not enough data is available. Finally, open circles are old open clusters (data from Lata *et al.* 2002). Superimposed are lines of constant mass (light solid lines, see Bellazzini *et al.* 2008b). The heavy blue solid line (at a mass of $4 \times 10^4$ $M_\odot$) is the proposed separation between globular and open clusters. This figure is taken from Carretta *et al.*, submitted

## 4. Summary and perspectives

We have seen that there is photometric evidence of multiple populations in many GCs. This generally happens among the most massive ones in our Galaxy, but not exclusively (see the cases of NGC 6752, M4). Mass is an important factor. It has been shown that many properties correlate with cluster mass, for instance, the maximum temperature reached on the HB (Recio-Blanco *et al.* 2006)

However, mass is not all the story. We have seen that all GCs display the Na-O anticorrelation, but if we quantify its extension (using e.g., the Interquartile range, see Carretta 2006) and plot it against total cluster mass, or integrated magnitude, we see that, preferentially, only high-mass clusters have an extended anticorrelation. This is, however, only a necessary condition; a notable counterexample is the massive GC 47 Tuc, which has a short anticorrelation. Some other factor, maybe metallicity, or age, or cluster orbit have to be involved.

Finally, I recall that the Na-O (and similar) anticorrelations seem to represent an intrinsic property of GCs: each time Na and O have been measured, they anti-correlate, while this does not happen in open clusters (see Fig. 7) or for field stars. So maybe we have an operative definition of the separation between globular and open clusters: GCs are those aggregates massive enough to sustain self-pollution, hence able to host at least two stellar generations and to develop a Na-O anticorrelation. This has of course to be related to the mechanism of cluster formation.

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