Spectroscopic evidence of Multiple Stellar Populations in Globular Clusters

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ABSTRACT

Galactic globular clusters are not simple stellar populations. And nothing is simple in their study, basically because we try to reconstruct chains of events that occurred at redshift $z > 2 - 3$ by observing these objects at $z = 0$, after a Hubble time. Fortunately, spectroscopy offers a magnifying lens: differences of tens or hundreds of Myrs between stellar generations are translated into differences in abundances up to a full dex. I will review the complex pattern emerging by the combined efforts of different groups, focusing on the chemical signatures of multiple populations in globular clusters.

KEYWORDS: Stars: abundances – atmospheres – Population II – Galaxy: globular clusters

1 Introduction

This is a mixed audience, with different expertises, so I will give a general overview, focussing on observations, but why spectroscopy? There are two main reasons: one, it is the first and most direct evidence, following from the very same definition of simple stellar populations: coeval stars with the same initial chemical composition. Therefore, if we see abundance variations at the same evolutionary phase, then we see multiple stellar populations. Photometry is, literally, a filtered indicator, showing multiple populations when selected bandpasses, sensitive to CNO elements, are used. However, no heavy elements (Na, Mg, Al) are detected using wide and intermediate band filters. Of course, there are also benefits (large samples, radial distributions, helium estimates, etc, see e.g. Milone et al. 2012, Larsen et al. 2014), but they will be discussed elsewhere.

The second reason is that we observe now in globular clusters (GCs) sub-solar stellar masses, whose main sequence lifetime is comparable to a Hubble time. So globular clusters are very old, born at high redshift and it is challenging to understand how they formed by looking at the $z = 0$ end-products. But fortunately spectroscopy works like a magnifying lens. After the first burst, second generation stars may form after only a few million or a few ten of million years, but even these tiny age differences translate into huge variations in the content of a few elements, up to 1 full dex, providing an excellent time resolution: we can easily distinguish primordial stars with only supernovae nucleosynthesis from younger generations with clear traces of self-enrichment.

In this talk I will present an overview on what we see and where, in a globular cluster and among clusters; what is the mechanism and what are the links with global cluster properties.

2 What we see

By comparing the ranges of element abundances in field and cluster stars, it is well known that very large variations (at the same metallicity) are restricted to the dense environment of globular clusters and only concern light elements. How do these elements vary?

As an example one can use NGC 2808, one of the best studied clusters, with many studies on the involved elements in several evolutionary phases: Carretta et al. (2003: RGB), Moehler et al. (2004: blue hook), Carretta et al. (2004: RGB), Carretta (2006: RGB), Pace et al. (2006: BHB), Bragaglia et al. (2010a: TO), Pasquini et al. (2011: RGB), Gratton et al. (2011: HB), Marino et al. (2014: HB), Carretta (2014: RGB),

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Figure 1: Trends of abundance ratios for light elements in RGB stars of NGC 2808. O, Na, Si, Mg are from Carretta (2015), Al and N abundances from Carretta et al. (in prep.).
Mucciarelli et al. (2015: RGB), D’Orazi et al. (2015: RGB), Carretta (2015: RGB). By using the same sample for all plots, the typical relations among abundance ratios of light elements in NGC 2808 are shown in Figures 1 and 2. These trends involve Na, O (the famous anticorrelation discovered by the Lick-Texas group, see Kraft 1994), Mg, N, Si, Al and, finally, the heaviest elements included: K and Sc.

All these elements are not in scatter plots, but some of them decrease and simultaneously some increase from the level established by supernovae, in second generation stars, so that the chemical signature we see are well defined (anti)correlations among these light elements.

Do we know a common process able to explain all the observed patterns? Yes: the origin of these signature was identified in proton capture reactions in hydrogen burning at high temperature, where several synthesis chains are simultaneously active (Denisenkov & Denisenkova 1989, Langer et al. 1993). However, the required temperatures are high (> $40 \times 10^6$ K for the ON and NeNa cycles, and even higher for the MgAl cycle, $T > 70 \times 10^6$ K), not reached in the interior of the presently observed GC low mass stars. The implication is that this nuclear burning occurred in stars more massive than those evolving today, and this is the reason why since Gratton et al. (2001) discovered the Na-O and Mg-Al anticorrelations among unevolved GC stars (Figure 3), these (anti)correlations are simply an alias for multiple stellar populations.

The temperature stratification may provide in principle useful constraints on the masses of the involved producers: Prantzos et al. (2007) were able to pinpoint a temperature range where all the observations in NGC 6752 were simultaneously satisfied by proton-capture reactions. Several classes of possible polluters fit in this range (massive AGB and super-AGB stars, Ventura et al. 2001; fast rotating massive stars, Decressin et al. 2007; massive binaries, de Mink et al. 2009; supermassive stars, Denissenkov and Hartwick 2014), but the common scenario for feedback-regulated secondary star formation is that second generation (SG) stars are formed by nuclear ejecta processed in the most massive first generation (FG) stars, diluted with different amounts of unprocessed gas, generating the observed anticorrelations.

Dilution with gas of primordial composition is badly required for several reasons (i) the star formation is not 100% efficient (e.g. Lada & Lada 2003), so a fraction of gas is left over; (ii) the chemical feedback from a star is no more than a few percent of its mass, not enough to form all the SG assuming a normal IMF (e.g. de
Mink et al. 2009); (iii) dilution is mandatory to obtain a Na-O anticorrelation from AGB stars, where Na and O are correlated (e.g. D’Ercole et al. 2008, 2010, 2011); and finally (iv) we see in second generation stars traces of the fragile lithium which is destroyed at lower temperatures than those involved in hot H-burning (although it can be also produced in AGB stars, see D’Antona et al. 2012).

2.1 A genetic link between stellar generations?

There seems to be a recent fashion to deny a direct genetic link between first and second generation stars (e.g., the group by Bastian and collaborators, or Schiavon et al. 2016). In other words, what we see would not be nucleosynthesis, due to problems still existing in the theoretical scenarios (yields, interplay between helium and the proton-capture elements, population ratios, to quote a few). To clarify this issue, let us take the observer’s route.

- We know that in GC stars carbon and nitrogen abundances are anticorrelated, but as C decreases the sum C+N increases (see Figure 4, left panel). Thus, either O is also involved (being transformed into N), or we are seeing variable amounts of nitrogen. However, the sum C+N+O is found to be pretty constant in most globular cluster stars (Figure 4, right panel; see also results from APOGEE, Meszaros et al. 2015). Hence, the complete CNO cycle is accounted for.

- The stars with enhanced sodium and depleted oxygen are also rich in aluminum (see Figure 1): the Na-Al correlation links the NeNa and MgAl cycles and moreover the sum Mg+Al does not vary (e.g. Meszaros et al. 2015). Hence, the NeNa and MgAl cycles are accounted for.

- In metal-poor and massive clusters we see silicon anticorrelated with magnesium and/or alternatively correlated with aluminum: results by Carretta et al. (2009) are shown in Figure 5, confirming those for NGC 6752 by Yong et al. (2005), and confirmed by the findings of Meszaros et al. (2015). Hence, the leakage of Mg on silicon (Karakas et al. 2003), bypassing production of Al, is accounted for in these clusters.

- In particular cases also star to star variations in heavier elements like K, Sc are observed (see Figure 2),
and this is explained when proton-captures on argon, at very high temperature, produces these elements, bypassing Al production (e.g. Ventura et al. 2012).

In summary, whatever is the proton-capture reaction involved, either destroying or producing a given specise, we may observe the ashes of the nuclear burning in second generation stars. Therefore, the Occam’s razor tells us that all the observed pattern must be nucleosynthesis: until a better alternative is proposed and motivated, simultaneously explaining all the relations among light-elements, we conclude that we are seeing the signature of hot H-burning in stars more massive than those observed today.

3 Where do we see the spectroscopic evidence in GCs?

By using the main chemical signature, the Na-O anticorrelation, we can ask in what evolutionary phase multiple populations are observed in GCs. In a word, everywhere:

- on the main sequence (MS, see Figure 6, left panel), where the anticorrelation is similar in extent to that observed along the RGB (apart from offsets due to the analyses), despite very different stellar structure (negligible convective envelopes in MS) and H-burning process (p-p in core burning on the MS and CNO-shell burning along the RGB).

- of course on the red giant branch, where large statistics allows to quantify efficiently multiple populations as in our extensive and homogeneous FLAMES survey (Figure 7: Bragaglia et al. 2015; Carretta 2013, 2014, 2015; Carretta et al. 2006, 2007a,b,c, 2009a,b,c, 2010a,b,c,d,e, 2011, 2012a,b,c, 2013a,b, 2014a,b,c, 2015; Gratton et al. 2006, 2007) and in more heterogeneous studies (e.g. Johnson and Pilachowski 2012, Lind et al. 2009, Marino et al. 2008, Yong et al. 2005, see Figure 8), with some useful northern addition from APOGEE (Meszaros et al. 2015).
Figure 5: Si-Mg anticorrelations and Si-Al correlations for massive and/or metal-poor GCs from Carretta et al. (2009b).

Figure 6: Na-O anticorrelation in 47 Tuc for main sequence/turnoff stars from Dobrovolskas et al. (2014) and for RGB stars from Cordero et al. (2014) and Carretta et al. (2009), central and right panels, respectively.
Figure 7: Na-O anticorrelation in 25 GCs from our homogeneous FLAMES survey (see text for references).

Figure 8: Na-O anticorrelation in RGB stars of NGC 6752 (Yong et al. 2005, left panel) and M 13 (Johnson and Pilachowski 2012, right panel).
on the horizontal branch (HB), where the extension of the Na-O anticorrelation is similar to that measured on the RGB (Figure 9). However, Na-poor stars are segregated on the red HB and Na-rich stars on the blue HB (Figure 10, see also Gratton et al. 2011, 2013, 2014, 2015, Marino et al. 2011, Villanova et al. 2009, 2012) because of different helium from nuclear processing, resulting in slightly lower masses on the RGB (see e.g. D’Antona et al. 2002). In fact, we know from both spectroscopy and photometry that second generation Na-rich stars are also enhanced in helium from direct measurements (e.g. Pasquini et al. 2011, Villanova et al. 2012) or from a brighter bump on the luminosity function of the RGB (Bragaglia et al. 2010b), as predicted by Salaris et al (2006) for He-enhanced populations.

- the Na-O anticorrelation is also observed on the asymptotic giant branch (AGB), even if some studies seem to differ (see Fig. 10). Some recent works (Campbell et al. 2013, Johnson et al. 2015a, Lapenna et al. 2015, 2016, MacLean et al. 2016, Wang et al. 2016) find few or no second generation stars on the AGB in some clusters (but see Garcia-Hernandez et al. 2015 for a different view).

In Figure 10 I use the sodium excess with respect to the homogenised sample of field stars from Carretta (2013) to show that most RGB stars belong to the second generation (left panel, cluster stars from our FLAMES survey). I also show AGB stars from some clusters (right panel) and apparently they are more first generation. By taking only field stars within $2\sigma$ from the average at any metal abundance (Fig. 11), we can shift all samples of AGB stars in GCs on the same scale, regardless of details in the original analyses. It is evident that some clusters show a large number of second generation AGB stars, others only a few (Figure 11, left panel). The correlation between the number ratio in AGB and the minimum mass on the HB (Gratton et al. 2010a, reproduced in Figure 11, right panel) tells us that the lack is not an in situ process, but depends on stars failing to reach the AGB phase (see Greggio and Renzini 1990), likely due, again, to their enhanced He abundance.

The issue of multiple stellar populations in the AGB phase is however still open. For example, if we take the AGB failure rate defined by MacLean et al. (2016) from the fraction of SG stars in AGB and RGB, the few SG AGB stars in NGC 6752 are explained only with unlikely enhanced mass loss on the HB (see Campbell et al. 2013, Cassisi et al. 2014). On the other hand, the rate in NGC 2808 contrasts with the expectation that a relevant fraction of HB stars should miss entirely AGB due to low mass and enhanced Helium (e.g. D’Antona et al. 2005), resulting into different distributions in RGB and AGB, that are not observed (Wang et al. 2016).

Several factors contribute to make the situation unclear for AGB stars: observations are done using only AGB samples or through a comparison of both AGB and RGB; different species are used to tag SG stars (Na only, Na and O, Al only, CN only) and, as we will see below, different elements are not always coupled (e.g. Smith et al. 2013); NLTE effects are more relevant in AGB stars; and so on.

On the theoretical side, it is not clear if different scenarios are able to fully explain the observations. The difference for NGC 2808 and 6752 is explained because of the dependence of the maximum Na dispersion in
Figure 10: $[\text{Na/H}]$ ratio as a function of metallicity for Galactic field stars in the solar neighborhood from Carretta (2013; empty grey triangles), with superimposed RGB stars in 25 GCs of our FLAMES survey (left panel). In the right panel, the same with superimposed AGB stars from several studies (see text for references).

Figure 11: As in the previous figure, but taking only Galactic field stars from Carretta (2013) within $\pm 2\sigma$ from the average Na at any metallicity. AGB stars from several studies are shifted to match the minimum Na (left panel). In the right panel, the number ratio of AGB to RGB stars is plotted as a function of the minimum mass on the HB from Gratton et al. (2010a).
AGB on age or metallicity in the FRMS scenario (Charbonnel and Chantereau 2016). However, by interpolating in the age-metallicity plane, for each reasonable combination age-metal abundance one derives approximatively the same maximum Na dispersion in AGB. In the massive AGB scenario, on the other hand, to different ranges in Na must correspond similar values of He, which is provided by the second dredge-up. Something seems to be still missing, in order to explain the observations in this phase.

However, as a first summary, we can state some firm points. The chemical signatures observed in at least two stellar generations in GCs are well matched by hot H-burning nucleosynthesis that perfectly reproduces all the observed (anti)correlations, provided that a mandatory amount of pristine gas is available to dilute nuclearly processed ejecta. The so formed different stellar generations follow rather well the stellar evolution requirements, with SG stars nicely segregated according to their He content, on the HB and probably also on the AGB.

4 In what stellar systems do we see evidence of multiple populations?

By using again mainly the Na-O anticorrelation, we may ask what are the stellar systems where we see the multiple populations phenomenon? In almost every halo, bulge and disk Milky Way globular cluster, over two order of magnitude in total mass, from the tiny Pal 5 in dissolution (Smith et al. 2002) up to ω Centauri (Johnson and Pilachowski 2010, Marino et al. 2011c), a likely remnant of a dwarf galaxy (Figure 12).

In clusters (suspected to be) of extragalactic origin, like M 54, NGC 1851, NGC 1904, NGC 2808, M 68 (see
Figure 13: Na-O anticorrelation in stars of extragalactic GCs: 4 old GCs in LMC (Johnson et al. 2006: blue circles), 3 GCs in the Fornax dSph (Letarte et al. 2006, red circles), and 3 old GCs in LMC (Mucciarelli et al. 2009, black crosses).

Bellazzini et al. 2008, Forbes and Bridges 2010), all with the Na-O anticorrelation studied in our FLAMES survey, and in true, old extragalactic clusters belonging to the Large Magellanic Cloud or to the Fornax dwarf spheroidal galaxy (Figure 13; from Johnson et al. 2006, Letarte et al. 2006, Mucciarelli et al. 2009). Note that no evidence of self-enrichment was found in the intermediate age LMC clusters by Mucciarelli et al. (2008).

In so called iron complex clusters, where the Na-O anticorrelation is found in each metallicity component (Figure 14): from those associated to nuclei of present or former dwarf galaxies, M 54 (Carretta et al. 2010a,e) and ω Centauri (e.g. Norris and Da Costa 1995, Johnson and Pilachowski 2010, Marino et al. 2011c) to the normal clusters with small or moderate dispersion in iron and heavy elements like NGC 1851 (Carretta et al. 2011) or M 22 (Marino et al. 2011a). This is a currently increasing sample (see M 2, Yong et al. 2014; NGC 5286, Marino et al. 2015; NGC 5824, Roederer et al. 2016; M 19, Johnson et al. 2015b).

Dwarf galaxies show by definition a metallicity dispersion, but the anticorrelation is only found in their globular clusters, not in the field (e.g. Carretta et al. 2010c). Of course the progenitors of M 54 and ω Centauri were much more close to the central regions of the Milky Way than present-day dSphs.

The Na-O anticorrelation is found in clusters both likely accreted or formed in situ in the Milky Way, found to lie along two different age-metallicity relations (see VandenBerg et al. 2013, Leaman et al. 2013). In other words this anticorrelation, the main chemical signature of multiple stellar populations, is widespread among clusters and very likely related to their origin since these self-enrichment events occurred in the first 1% of their lifetime and was proposed (Carretta et al. 2010b) to be considered as the main signature of a genuine globular cluster.

One of the best example/application can be borrowed from Doug Geisler. If one looks at an image of Pal 5 it is easy to think of it as an open cluster or an association, whereas the image of NGC 6791 shows a beautiful globular form. However, according to the presence of abundance variations, Pal 5 has multiple populations and it is a proper globular cluster, NGC 6791 is not (Bragaglia et al. 2014, Cunha et al. 2015), and it is only a strange old, metal-rich open cluster (but see Geisler et al. 2012 for a different view on this object). As a safety check, open clusters follow the pattern of field stars and show no sodium excesses anticorrelated to oxygen.
depletions (Figure 15, see De Silva et al. 2009, MacLean et al. 2015, Bragaglia et al. 2014).

5 What is the relation with global cluster properties?

Finally, what is the relation between the multiple stellar populations in GCs and the global cluster properties? With good statistics we can quantify the extent of multiple populations using the interquartile range of the oxygen-sodium ratio, IQR[O/Na], as suggested by Carretta (2006). We found that the total mass is the driving parameter: in Figure 16 (upper panel), we see that a very significant correlation exists between the extension of the anticorrelation and the total mass of the clusters. We used as a proxy for the mass the total cluster absolute magnitude, so that this is the present-day mass, including the initial mass and the memory of all the internal and external processes of dynamical evolution.

Moreover, the link with the main product of H-burning, helium, predicts that helium enhanced stars populate bluer and hotter locations on the HB (e.g. D’Antona et al. 2002, Catelan 2009, Gratton et al. 2010b), since He-enhanced stars have slightly smaller evolving masses, and in fact we found that multiple populations are related to the HB morphology. As predicted, clusters with more extreme anticorrelations have bluer and hotter HBs (Carretta et al. 2007d, Carretta 2015 and references therein), as shown in Figure 16 (lower panel).

Since the minimum sodium in GCs nicely follows the pattern of field stars, from spectroscopy we can select with accuracy the primordial component in each cluster and so also the remaining fraction of second generation stars. In Figure 17 (upper panel), the P component includes all stars along the Na-O anticorrelation with Na abundances $[\text{Na/Fe}] < [\text{Na/Fe}]_{\text{min}} + 4\sigma$.

In present day clusters second generation stars are the majority (Figure 17, lower panel), apart from a few cases like M 53 (Boberg et al. 2016) or NGC 6723 (Gratton et al. 2015). However, SG stars are formed by only a fraction (the most massive stars) of the FG, and this is known as the so called mass budget problem, usually solved by assuming that the precursors of the GCs were much more massive than present-day GCs (Bekki et al. 2007, and many others), losing about 90% of their FG stars and becoming good candidates for main contributors to the halo (see e.g. Carretta 2016).

A selective mass loss is both predicted by different scenarios and dynamical simulations (e.g. D’Ercole et al. 2008, Decressin et al. 2007, Vesperini et al. 2013) and supported by the observation that second generation stars are usually more concentrated (see e.g. Lardo et al. 2011, Milone et al. 2012, Carretta 2015), although there are some counterexamples (e.g. Larsen et al. 2015).

These basic assumptions must confront with two major challenges.

One is the so-called external mass budget problem because evidence is accumulating that in dwarf galaxies GCs cannot have been more massive than 4-5 times, initially, as they account for about 25% of the galaxy mass in metal poor stars (Larsen et al. 2012, 2014b, Tudorica et al. 2015).

Furthermore, simulations of mass loss from gas expulsion predict a strong anticorrelation between the fraction of SG stars and the cluster mass, that is not observed (Khalaj and Baumgardt 2015), and no variation of the fraction of SG as a function of cluster mass or galactocentric distance or metallicity is observed (Kruijssen 2015, Bastian and Lardo 2015), at odds with what expected by mechanisms of mass loss.

Just a caveat: it is risky to mix estimates of the population ratios from spectroscopy, photometry and simulations, as in the last study, because of the decoupling between CN and heavier elements already noted by Graeme Smith and collaborators (see Smith et al. 2013, Smith 2015).

Photometry on one hand and spectroscopy on the other hand are not seeing exactly the same things, because most photometric indexes are essentially sensitive only to CN, NH or CH features. As a consequence of the temperature involved in the H-burning reactions, they sample different range of temperatures, and therefore of polluter masses, than spectroscopy with the observations of the outcome of the NeNa and MgAl cycles.

Usually a division based on CN derives a 50-50 population ratio (e.g. Figure 18, upper left panel for M 5). However, adopting our criterium (Carretta et al. 2009a) based on Na you find that some SG stars are instead counted as FG by CN properties or photometry, even if in these stars Na is as high as in SG stars. Moreover,
Figure 14: Na-O anticorrelation in GCs with metallicity dispersion. First row: M 54 (Carretta et al. (2010a,c)); second row: ω Cen (Norris and Da Costa 1995); third row NGC 1851 (Carretta et al. 2011), fourth row: M 22 (Marino et al. 2011).
Figure 15: [Na/Fe] and [O/Fe] ratios in Galactic field stars as a function of metallicity. Red circles indicate the average O and Na content in GCs from Carretta et al. (2009b) and blue squares are the same for open cluster from De Silva et al. (2009).
Figure 16: interquartile range of the [O/Na] ratio as a function of the total absolute magnitude of GCs (upper panel) and of the maximum temperature along the HB from Recio-Blanco et al. (2006, lower panel). Spearman and Pearson coefficients for the linear regression are indicated.
Figure 17: Division of RGB stars in NGC 5904 into the primordial P component of FG and into the intermediate I and extreme E component of SG according to their O, Na abundances (upper panel). In the lower panel the fractions of P,I,E stars in GCs of our FLAMES survey (Carretta et al. 2009a; red points) and for M 53 (Boberg et al. 2016) and NGC 6723 (Gratton et al. 2015), in blue, are plotted.
Figure 18: Upper left panel: $\lambda$3883 CN residual $\Delta S(3839)$ with respect to the baseline of CN-weak stars (Smith et al. 2013) as a function of [Na/Fe] ratios (Carretta et al. 2009a) in M 5. The horizontal line is the population division based on CN/photometry, whereas the vertical one indicates the ratios FG/SG following the spectroscopic criterion by Carretta et al. (2009a). Upper right panel: the same for M 13 from Smith and Briley (2006) for CN and Johnson and Pilachowski (2012) for Na. In the lower panel, the same for M 4 from Smith and Briley (2005) for CN and Marino et al. (2008) for Na.
Figure 19: [Al/Fe] ratios as a function of [Mg/Fe] ratios in NGC 2808 (Carretta 2014, left panel) with superimposed two dilution models. No single dilution model is able to fit all the three components. Right panel: five groups with distinct chemical composition on the RGB of NGC 2808 from Carretta (2015).

this discrepancy seems to vary from cluster to cluster (see the cases for M 13 and M 4, upper right and lower panels, respectively, in Figure 18).

Finally, it appears to be difficult to account for all the combined spectroscopic and photometric evidence within a single scenario (e.g. Bastian et al. 2015). In particular, the discrete components seen by spectroscopic observations in some clusters (NGC 6752, Carretta et al. 2012a; NGC 2808, Carretta 2014 2015, see Figure 19) suggest that a dilution model with only one class of polluters could not be enough for all components.

So, in conclusion taking into account the large variety of chemical signatures in GCs (spread in light elements, always; also in heavier elements and metallicity, in some cases) the most honest summary I can give you from the spectroscopic evidence is this: a genuine, bona fide old globular cluster is a system where a chain of events (not yet well understood) concurred to form at least two stellar generations with small age differences and huge variations in the content of products of hot H-burning nucleosynthesis.

6 Acknowledgements

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