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Globular clusters: a chemical roadmap between anomalies and homogeneity

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Abstract. For several decades, globular clusters have been considered the best example of simple stellar populations, hosting coeval and chemical homogeneous stars. The last decade of spectroscopic and photometric studies has revealed a more complex view of their chemical composition, with a high level of homogeneity in their iron content but star-to-star variations in some light elements. This contribution summarizes the main evidence about the chemical anomalies in the stellar content of the globular clusters, discussing also some peculiar objects with intrinsic dispersions in their iron content.

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

1. Introduction

Globular clusters (GCs) are usually considered as the best example available in the nature of simple stellar populations (SSPs), aggregates of stars with the same age and initial chemical composition (see e.g. the seminal paper by Renzini & Buzzoni 1986). GCs as SSPs are valuable tools to approach several aspects of the astrophysics: they allow to check the predictions of the stellar evolution theory, to study the chemical enrichment history of the parent galaxy, and to investigate the properties of unresolved stellar populations (because for GCs in the Milky Way and in nearby galaxies we have simultaneously the resolved and integrated information).

A large number of photometric and spectroscopic evidence collected in the last decades has conclusively established that the stars in a GC do not share the same initial chemical composition. In fact:

(i) some elements have been observed to vary in all the GCs, like C, N, O, Na and Al;
(ii) some elements have been observed to vary only in some GCs, like He, Li, Mg, Si, K;
(iii) finally, there is a bunch of *strange beasts* characterized by a more or less pronounced Fe star-to-star variations.

As a general *golden rule* we can define as genuine GCs all the massive, stellar systems that are homogeneous in their Fe (and Fe-peak) content. Generally, all the stars in a GC have the same iron content. Iron is produced by both Type II and Type Ia Supernovae (SN). Thus, stellar systems with an intrinsic Fe dispersion in their stellar content did retain the SN ejecta in their gravitational well, while systems like the genuine GCs did not retain these ejecta.

Willman & Strader (2012) performed a comparison between the intrinsic Fe spread (calculated by taking into account the uncertainties in each individual star) of GCs and other stellar systems, like dwarf spheroidal galaxies and ultra-faint dwarfs, finding that the GCs are characterized by intrinsic Fe spreads smaller than 0.05 dex, while dwarf systems have Fe spread larger than 0.2 dex. Thus, the level of homogeneity in the Fe content represents the main chemical fingerprint to distinguish GCs from other (more complex) stellar systems. Obviously, this definition does not allow to distinguish between GCs and less massive stellar systems without Fe spread, like the open clusters. In this context, it is important to recall that all the GCs properly observed so far with large samples of high-resolution spectra exhibit also star-to-star variations among the light elements (C, N, O, Na, Mg and Al), known since forty years ago. Even if the precise mechanism able to produce this kind of chemical variations are still debated and under scrutiny (see Section 3.1), these chemical anomalies are observed only in GCs (and not in open clusters or in field stars), and they are considered as typical feature of the GCs.

2. Strange beasts

Up to now, only 5 (out of ~150) Galactic GCs exhibit intrinsic Fe spreads, namely Omega Centauri, Terzan 5, M54, M22 and NGC1851. Throughout this contribution, I refer only to the GCs for which chemical abundances from high-resolution spectroscopy and large sample of stars are available. Other 2 GCs have been proposed to have a Fe spread, namely NGC 5824 and NGC 3201. The analysis of NGC 5824 presented by Saviane et al. (2012) is based on the Ca II triplet (as a proxy of the metallicity) but chemical analysis based on the direct measurement of Fe lines are still lacking. Recently, Simmerer et al. (2013) found an appreciable spread among the stars of NGC 3201, by using high-resolution spectra of 24 giants. However, other analysis always based on high-resolution spectra (Carretta et al. 2009; Munoz et al. 2013) seem to contradict this finding, without clear hints of intrinsic Fe spreads. The normalized metallicity distributions of the 5 *beasts* are shown in Fig. 1 and briefly explained as follows:

(1) Omega Centauri — The most famous case of GC-like system with a intrinsic Fe variation is Omega Centauri, whose metallicity distribution has been investigated by several authors (see e.g. Freeman & Rodgers 1975; Pancino et a. 2002; Johnson & Pilachowski 2010; Marino et al. 2011). Its metallicity distribution is very large (covering up to 1.5 dex) and multi-modal, with at least 5 peaks. However, the most popular scenario is that Omega Centauri is not a genuine GC but it is the remnant core of a tidally disrupted dwarf galaxy.

(2) Terzan 5 — Another case of multmodal and broad Fe distribution is Terzan 5, a GC located in the inner bulge and known to harbor two red clumps in its color-magnitude diagram (Ferraro et al. 2009). These two red clumps are associated to two different Fe abundances at about [Fe/H]=–0.30 and [Fe/H]=+0.30 dex (Ferraro et al. 2009). The same Fe difference has been observed among the giant stars (Origlia et al. 2011), with the detection of an additional, third component at [Fe/H]~–0.8 dex (Origlia et al. 2013). The metallicity distribution of Terzan 5 turns out to be very large (about 1.5 dex) with at least 3 distinct peaks (see also the contribution by D. Massari to this conference). The striking chemical similarity between Terzan 5 and the bulge seems to suggest that Terzan 5 could be the remnant of one of the pristine fragment that contributed to form the Galactic bulge (Ferraro et al. 2009).

(3) M54 — A different case is provided by M54, a massive GC immersed in the nucleus of the Sagittarius remnant. Carretta et al. (2010a) analyzed with FLAMES@VLT 76 stars of M54, finding a broad (~0.7 dex) but uni-modal distribution.

(4) M22 — This cluster has been suspected to harbor an intrinsic Fe spread since thirty years ago (Pilachowski et al. 1982) even if other analysis have ruled out such a variation (Cohen 1981; Gratton 1982). Recently, Marino et al. (2009) and Marino et al. (2011) performed the analysis of high-resolution spectra for a total of 35 stars of M22, finding a broad

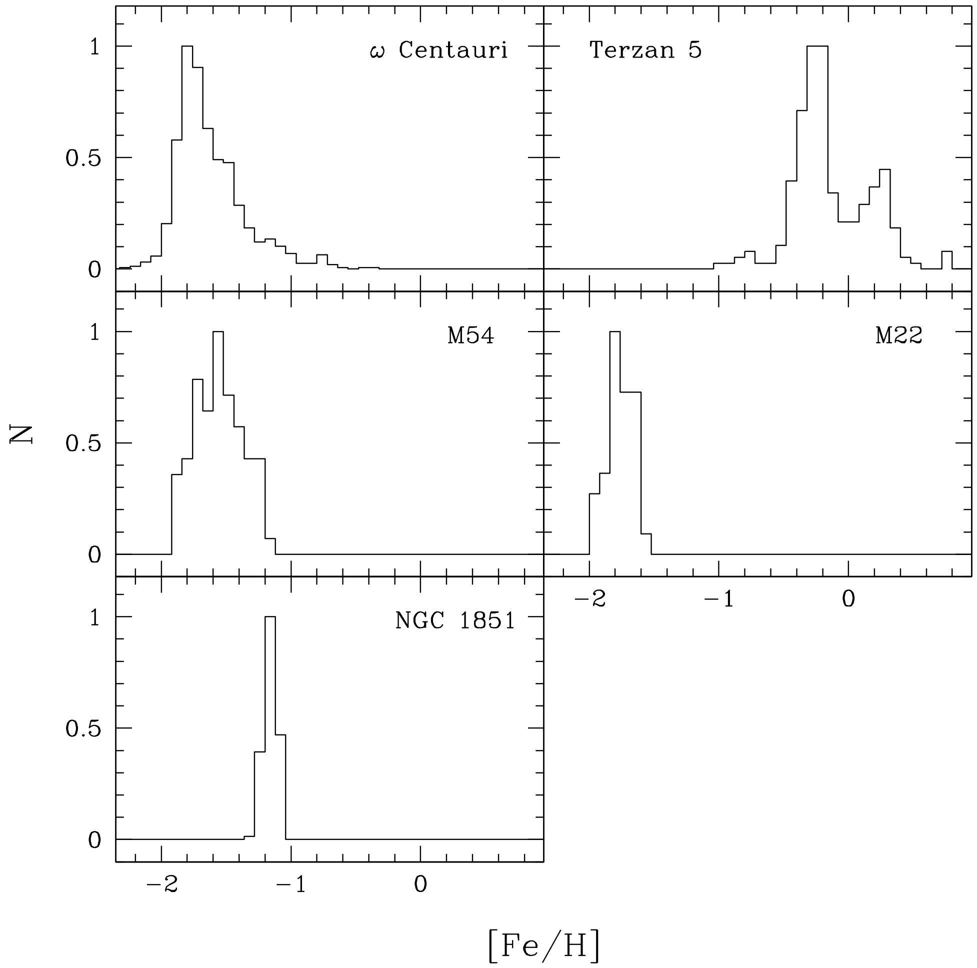

Fig. 1. Normalized metallicity distribution for the 5 GC-like systems with an intrinsic Fe spread: Omega Centauri (Johnson & Pilachowski 2010), Terzan 5 (Massari et al., in prep.), M54 (Carretta et al. 2010a), M22 (Marino et al. 2009, 2011) and NGC 1851 (Carretta et al. 2010b).

but unimodal metallicity distribution (ranging from [Fe/H]∼–2 dex to ∼–1.6 dex). Also, M22 is known to harbor a split at the level of the subgiant branch, with two distinct branches associated to different abundances of s-process elements (Marino et al. 2012).

(5) NGC1851 — Based on the analysis of 124 stars, Carretta et al. (2010b) claim a small intrinsic Fe dispersion for this cluster. When the metallicity distribution is roughly divided in two groups, the *metal-poor* stars turn out to be more centrally concentrated with respect to the *metal-rich* ones, suggesting a kinematical difference between the two groups of stars (in fact, Carretta et al. 2010b, proposed a merging as possible origin of NGC 1851). Note that other works did not found hints of intrinsic inhomogeneity (Yong & Grundahl 2008; Villanova et al. 2010) even if based on smaller samples. Also, the analysis by Willman &

Strader (2012) suggests that the observed Fe spread is fully compatible with those in other GCs. Like M22, also NGC 1851 exhibits a split in its sub-giant branch, likely explainable with a difference in the total C+N+O. The C+N+O in NGC 1851 is still a controversial and open issue. Yong & Grundahl (2008) measured a spread in the C+N+O content of about 0.6 dex among 4 bright giants in NGC 1851. These results have not been confirmed by the analysis of 15 giants by Villanova et al. (2010), finding no differences in their C+N+O.

3. Elements that vary

3.1. C, N, O, Na, Mg, Al

The first evidence of inhomogeneity in the chemical content of GCs has been provided from the study of CN and CH features in the brightest giants by using low-resolution spectroscopy. Osborn (1971) detected for the first time 2 CN-strong stars in M5 and M10, and following studies (Norris et al. 1981; Smith & Norris 1982; Briley et al. 1993; Martell & Smith 2009; Pancino et al. 2010) have revealed that the GCs show a bimodality in their CN absorption and anti-correlation between CN and CH strengths, both among giant and dwarf stars. CN-strong/CH-weak stars, observed only in GCs, can be interpreted as having some amount of CNO processed material in their atmospheres. The use of high-resolution spectroscopy for giant stars in GCs has allowed to link these CN/CH anomalies to other chemical anomalies. CN strength is correlated with Na and Al (Cottrell & Da Costa 1981) and anti-correlated with O (Sneden et al. 1992). Also, anti-correlations between O and Na exist, as discovered by the Lick-Texas group (see Fig. 16 in Ivans et al. 2001, for a summary).

Currently, the Na-O anti-correlation is recognized as a typical feature of all the old and massive GCs, as widely demonstrated by the homogeneous survey of more than 1000 giants in 19 GCs performed by Carretta et al. (2009). These anomalies have been observed also in old, massive extra-galactic GCs, like in Fornax (Letarte et al. 2006) and in the Large Magellanic Cloud (Mucciarelli et al. 2009).

A similar feature, often observed in some GCs, is the anti-correlation between Al and Mg. The label of "anti-correlation" could be improper, because most of the GCs show a large Al spread coupled with an unique value of Mg (in a given cluster), while the Mg-poor stars seem to be very rare. Up to now, GC stars with [Mg/Fe]<0 have been detected only in NGC 2808 (Carretta et al. 2009), in NGC 1786 (Mucciarelli et al. 2009) and NGC 2419 (Mucciarelli et al. 2012).

All the spectroscopic evidence collected so far (i.e. CN-CH anti-correlation, CN bimodality, Na-O anti-correlation, Mg-Al anti-correlation) are commonly interpreted as the signature of material processed through the high temperature extension of the proton-capture reactions (like NeNa and MgAl cycles). Several theoretical models have been proposed in order to describe the formation and early evolution of GCs, for instance D'Ercole et al. (2008), Decressin et al. (2010), Bekki et al. (2011), Conroy & Spergel (2011) and Valcarce & Catelan (2011). However, the basic idea behind these models is that the clusters formed with a chemical composition that well resembles that observed in the field stars. Then, they experience a period of star formation activity, with new stars born from a gas polluted by ejecta from the first generation stars that have processed material through the hot H-burning. Different kinds of polluter stars have been proposed, i.e. the asymptotic giant branch (AGB) stars and the fast-rotating massive stars. In both cases, a short (<100 Myr) phase of star-formation should occur in the early stage of the life of GCs.

Generally speaking, we used to separate the stars in a GC in two classes, a *first generation* including stars with chemical abundances similar to those observed in field stars of similar metallicity (thus, Na-poor/O-rich/CN-weak stars), and a *second generation* including Na-rich/O-poor/CN-strong stars. Obviously, this is a brutal but efficient classification. Considering our current knowledge and understanding of the GCs, we cannot exclude that the star-formation in a GC occurs in a continuous way and not with discrete bursts (as the classification in first and second generations seems to suggest). This scheme is contradicted by the Na-O anticorrelation, that appears to be continuous (with the only exception of M4, see Marino et al. 2008), while other findings (like the CN-bimodability and the red giant branch splitting observed in the color-magnitude diagrams including the U-band filter) seem to support this scenario.

Note that none of the current models are able to fully reproduce the observed chemical patterns, requiring some fine tuning in most of the main parameters. Currently, a number of issues remain open and unsolved, like the nature of the polluters, the need of dilution of polluting gas with unprocessed material or the relative fraction between first and second generation stars.

3.2. Helium

The CN-strong and Na-rich/O-poor stars are expected to be also enriched in helium, whatever the polluter stars are, being helium the main product of the H-burning. The occurrence of (mild or strong) enhancement in Y (up to Y~0.4) has been proposed as the cause of the main sequence splitting and the peculiar horizontal branch morphology in the cases of Omega Centauri (Bedin et al. 2004), NGC 2808 (Piotto et al. 2007; Dalessandro et al. 2011), NGC 2419 (di Criscienzo et al. 2011) and NGC 6397 (Milone et al. 2012).

The direct measurement of the He abundance in GC stars is a quite hard task, first of all because of the small number of available He diagnostics. The chromospheric line at 10820 Å can be observed in giant stars but it needs very high signal-to-noise and resolution spectra, and it is also heavily sensitive to the adopted modeling of the stellar chromosphere. This line has been used to infer the He abundance in giant stars of Omega Centauri (Dupree et al. 2011; Dupree & Avrett 2013) and NGC 2808 (Pasquini et al. 2011). The latter provided a differential analysis between two giant stars of NGC 2808 with different Na abundances. Their analysis points out a difference in Y between the two stars of at least 0.17, with the Na-rich stars being more He enriched than the Na-poor ones.

Only a few photospheric lines can be detected among the horizontal branch stars, with effective temperatures between ~9000 K and ~12000 K (the latter corresponding to the *Grundahl Jump*, Grundahl et al. 1999). Villanova et al. (2009) performed a chemical analysis in 4 horizontal branch stars in NGC 6752, finding an average value <Y>= 0.25, with values of [O/Fe] and [Na/Fe] compatible with those observed in the so-called first cluster generation. Also, the analysis of 6 HB stars in M4 by Villanova et al. (2012) provides a higher He abundance, with an average value <Y>= 0.29, coupled with high values of [Na/Fe] and low values of [O/Fe]. Recently, Marino et al. (2013) measured the He abundance in 17 horizontal branch stars of NGC 2808, finding an average value of <Y>= 0.34. These first findings strongly support the scenario where second generation stars are also enriched in He.

3.3. Lithium

Lithium remains a key-element in the study of the formation and evolution of GCs but also an unresolved riddle. It is destroyed at temperatures of about $2.5{\cdot}10^6$ K, thus it cannot survive at the typical temperatures of the hot H-burning, larger than $\sim10^7$ K. A reasonable expectation is that the second generation stars should be depleted in Li. Also, some kind of correlations/anti-correlations between Li and the elements involved in the chemical anomalies are expected, in particular Li-Na anticorrelations and Li-O correlations. Thus, the Li abundance could represent a formidable *smoking gun* to disentangle the nature of the polluter stars able to create the second generation stars.

The observational evidence collected so far provides us a scenario not easy to explain, giving us more questions and doubts than answers. Some GCs show clear or weak hints of Li spread and anti/correlations with Na or O, like 47 Tucanae (Bonifacio et al. 2007), NGC 6752 (Shen et al. 2010), NGC 6397 (Lind et al. 2009) and M4 (Monaco et al. 2012). On the other hand, other works seem to rule out Li spreads, like in M4 (D'Orazi & Marino 2010; D'Orazi et al. 2010; Mucciarelli et al. 2011).

However, the small variation of Li associated in some cases to large variations of Na and/or O remains an open issue, and the current theoretical models are not able to reproduce this finding. The models where the chemical anomalies are driven by AGB stars are able to explain a Li production through the Cameron-Fowler mechanism, but it needs a high degree of fine-tuning, in order to produce exactly the same amount of Li previously destroyed. The models based on fast-rotating massive stars do not include Li production mechanisms, invoking dilution processes to partially explain the very similar Li abundances between first and second generations.

3.4. Potassium

Potassium is a *new entry* among the elements observed to vary only in some GCs. In fact, the only cluster observed so far harboring a large dispersion of K is NGC 2419 (Mucciarelli et al. 2012; Cohen & Kirby 2012). This cluster shows two distinct groups of stars, the first characterized by *normal* values of [Mg/Fe] and [K/Fe] (compatible with those observed in other GCs), the second with extreme values for both the abundance ratios, reaching [Mg/Fe]$\sim$−1.4 dex and [K/Fe]$\sim$+2.0 dex. These values are unusual for GC stars but these Mg-poor/K-rich stars represent $\sim$40% of the studied samples. Also, a Mg-K anti-correlation is clearly detected, suggesting that these anomalies can be explained within the self-enrichment scenario. Interestingly enough, the fraction of Mg-poor stars well resembles that proposed by di Criscienzo et al. (2011) for the extreme He-rich population with Y= 0.4, according to the morphology of the horizontal branch of NGC 2419.

Ventura et al. (2012) identified the Mg-poor, K-rich stars as the signature of an extreme nucleosynthesis driven by AGB and super-AGB stars, because K can be produced by proton capture on Argon nuclei during the normal nuclear reactions that create the observed chemical anomalies.

The first investigations about possible K spreads among the stars of other GCs have not shown chemical patterns similar to those observed in NGC 2419 (Carretta et al. 2013).

4. Some thoughts about globular clusters

The deep investigations about the chemical composition in the GCs performed in the last decade (and gathered by the massive use of high-resolution spectrographs) has for some aspects changed our view of the GCs, unveiling a quite complex formation process.

Only to provide a simple, mental scheme to put some order among this evidence, we can divide the GCs in three classes: (1) the genuine GCs, characterized by homogeneity in their Fe content, that show a uni-modal and narrow metallicity distribution; (2) the GCs with large but uni-modal metallicity distribution, like M54, M22 and NGC1851, even if an enlargement of their studied samples is mandatory in order to unveil possible secondary peaks; (3) a third group of systems, including only Omega Centauri and Terzan 5 with broad and multi-modal metallicity distribution, that cannot be considered genuine GCs, but stellar systems undergoing complex chemical enrichment histories.

Can we continue to use genuine GCs as simple stellar populations, in spite of their chemical anomalies and the proposed self-enrichment scenario? A reasonable answer is yes (but with some cautions). In fact: (1) They are homogeneous in Fe and almost any other elements, with the exceptions of C, N, O, Na, Mg and Al. Thus we can continue to use them as tracers of the chemical composition of the host galaxy, by focusing our attention on the elements (the majority) that do not show intrinsic star-to-star variations. (2) They are still single-age stellar systems. The star formation in the GCs occurs within short timescales ($<$ 100 Myr). This timescale is much smaller than the GC age and the age differences between GC sub-populations with different chemical compositions (in terms of light elements) cannot be appreciated at the level of the turnoff. (3) Their integrated colors can be still used to calibrate and study unresolved stellar populations, like the GCs outside the Local Group, because the effect of the chemical anomalies on the integrated colors is negligible (with the only caution to exclude colors including U filters, heavily affected by C and N variations, see Sbordone et al. 2011).

Are the GCs strictly speaking simple stellar populations? The answer is no, but they have never been considered so. Are the GCs the simplest simple stellar populations available in the Universe? The answer is clearly yes, whatever complex their formation scenario is.

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