Mem. S.A.It. Vol. 87, 289

Memorie della

Chemical abundances of multiple stellar populations in globular clusters

The role of asymptotic giant branch stars

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Abstract. Multiple stellar populations in globular clusters pose serious challenges to our understanding of the chemical evolution, star-formation mechanisms and nucleosynthesis. Despite a huge observational effort, none of the available scenarios is able to satisfactorily explain the observed chemical and photometric patterns to date. Asymptotic giant branch (AGB) stars of various mass-ranges, depending on the observed chemical features, are among the proposed polluters of the intra-cluster medium from which second-generations of stars formed. I summarise the observed properties of the multiple stellar populations in globular clusters and where the AGB scenario is able to qualitatively meet – or not – the observational constraints.

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

1. Introduction

The presence of different stellar populations in globular clusters (GCs) has shattered once and forever the assumption that these objects are the best examples of simple stellar populations. Recent discoveries have revealed that their complexity is far greater than previously thought. New photometric analyses reveal that all GCs show multiple and complex photometric features along the entire color–magnitude diagram. There is a surprising heterogeneity in the number and properties of the stellar populations, with no two GCs being exactly the same. More and more GCs with intrinsic dispersions in heavy elements and in the bulk metallicity are being discovered.

This complex observational scenario is posing serious challenges to our understanding of GCs, to their origin and evolution, the mechanisms of star formation, and nucleosynthesis themselves. The main proposed scenarios for the multiple stellar populations in these systems require multiple, or extended, episodes of star formation. Asymptotic giant branch stars (AGBs, D'Ercole et al. 2008), fast-rotating massive (Decressin et al. 2007), and supermassive stars (Denissenkov et al. 2015) have been proposed to be the stellar nucleosynthesis sites for the material of second-generation stars. An alternative scenario suggests that mass transfer in massive binaries might cause the observed chemical variations, with no need of multiple episodes of star formation (Bastian et al. 2013). However, none of these models is able to satisfy all observational constraints, suggesting that some not-yet-understood mechanism may have occurred.

Figure 1 is a periodic table which highlights all the elements observed to vary in Galactic GCs. Here, I summarise the main chemical observational scenario of multiple stellar populations and discuss the possible role of AGBs in the chemical evolution of these stellar systems.

2. Light elements variations

It is well known from several decades that star-to-star variations in light elements like C, N, O, Na are typical features of GCs. More recently both photometry and spectroscopy have revealed that GCs also exhibit internal helium variations.

Thanks to high precision multi-wavelength photometry, stellar populations mildly or highly enriched in He have been found in all GCs analysed with appropriate high-precision *HST* data (Milone 2015). Given the difficulties in measuring He from spectra, it is more difficult to find direct spectroscopic evidence for He enrichments in GCs. However, the analysis of the IR He line for RGBs stars in ω Centauri and NGC 2808 suggests that stars with higher Na content have more He (Dupree & Avrett 2013; Pasquini et al. 2011). Highly He-enriched stars have been found on the blue horizontal branch of NGC 2808 in the temperature range $9000 < T < 11500$ K (Marino et al. 2014).

Chemical variations in CNONa are recognisable through multiple sequences on the color–magnitude diagram (CMD, e.g. Marino et al. 2008) or different locations on photometric diagrams which maximise the separation of stellar populations with different chemical abundances (Milone et al. 2013). Few GCs, those with the largest internal variations in He, also show significant variations in Mg and Al, that are anticorrelated (Norris & Da Costa 1995; Carretta 2015; Yong et al. 2003).

AGB stars have been proposed to be the viable nucleosynthetic site to produce the observed light elements variations. Specifically, intermediate-mass AGBs (~4-8 $M_{\odot}$) experience efficient *p*-capture reactions during hot bottom burning at the base of the convective envelope (e.g. Ventura et al. 2013; Karakas & Lattanzio 2014). The hot bottom burning can reach temperatures as high as $\sim 10^8$ K and ensure the production of heavier *p*-capture elements, such as Al and Si, which are observed to vary in a few GCs. The AGBs material is ejected via low-velocity winds and is more efficiently retained by the shallow potential well of GCs than faster SNe ejecta. In the AGB scenario, second generation GCs stars enriched in the H-burning products formed from these ejecta after a cooling-flow phase when the ejected material collects at the centre of the GCs potential well (D'Ercole et al. 2008).

However, if intermediate AGB stars can *qualitatively* account for many of the observed observational constraints, such as the enrichment in He, *p*-capture products, it is still challenging to explain the well-observed O–Na anticorrelation, wich is ubiquitous among Milky Way GCs. Indeed, at the high temperatures reached by hot bottom burning Na is expected to be destroyed, while second-population stars are Na-enhanced. I refer to Renzini et al. (2015) for discussion on this topic and for possible solutions.

3. *s*-Elements variations

At odds with typical GCs, whose internal variations affect only the light elements involved in *p*-capture reactions, a few GCs also display star-to-star variations in heavy elements. In particular, a class of GCs has been recently identified, showing internal variations in elements produced in the *slow* neutron-capture reactions (*s*-process elements). These variations are correlated to genuine variations in the overall metallicity. Elements whose production in the solar-system material is sharply ascribed to *rapid* neutron-capture reactions (*r*-process elements), such as Eu, do not show any signif-

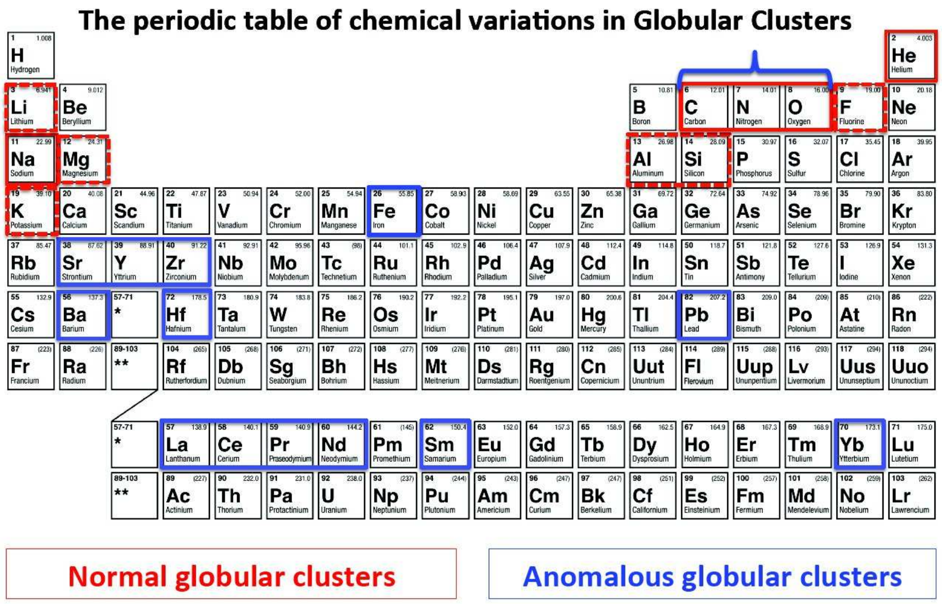

Fig. 1. Periodic table of chemical variations in GCs. Elements observed to vary in typical (normal) and *anomalous* GCs are highlighted in red and blue, respectively. The light elements highlighted in dash red are those for which variations have not been detected ubiquitously for the analysed clusters or whose abundances are only available for a few clusters. A blue parenthesis around C, N, O indicates that the sum of these elements varies in the *anomalous* GCs for which these elements have been investigated. Note that many elements highlighted in red vary in *anomalous* GCs, as well as in normal GCs.

icant variation. The list of these GCs, showing both Fe and *s*-process variations, currently includes: ω Centauri (e.g. Norris & Da Costa 1995; Marino et al. 2011a), M 22 (Marino et al. 2009; Marino et al. 2011b), NGC 1851 (Yong & Grundahl 2008; Carretta et al. 2011), M 2 (Yong et al. 2014), NGC 5286 (Marino et al. 2015), M 19 (Johnson et al. 2015). As low mass AGB stars are the most acknowledged stellar site where the *s* process occurs, the internal *s*-enrichment observed in these GCs points towards lower mass AGBs as polluters of the intracluster material from which *s*-rich stars formed. The chemical evolution of these objects has also been influenced, on different levels, by SNe, that contributed to increase the iron abundances.

In the few GCs with C, N, and O abundances available, internal variations in the overall C+N+O have been detected. To date, these *anomalous* variations[1] have been investigated and found in ω Centauri, M 22, and NGC 1851 (Marino et al. 2012a; Marino et al. 2011b; Yong et al. 2015). In each of these clusters stars with higher Fe and *s*-process elements content have higher C+N+O.

Anomalous GCs also exhibit anomalies on the CMD: they show photometric features, such as multiple sub-giant branches (SGBs; e.g. Milone et al. 2008), RGBs (e.g. Marino et al. 2011b) in the visual bands. All these features can be reproduced by the presence of stellar populations with different metallicity and C+N+O (Marino et al. 2012b).

To make the chemical evolution of these objects even more complex, both the *s*-elements/iron rich and the *s*-elements/iron poor populations exhibit their own light ele-

[1] C+N+O is uniform in typical GCs.

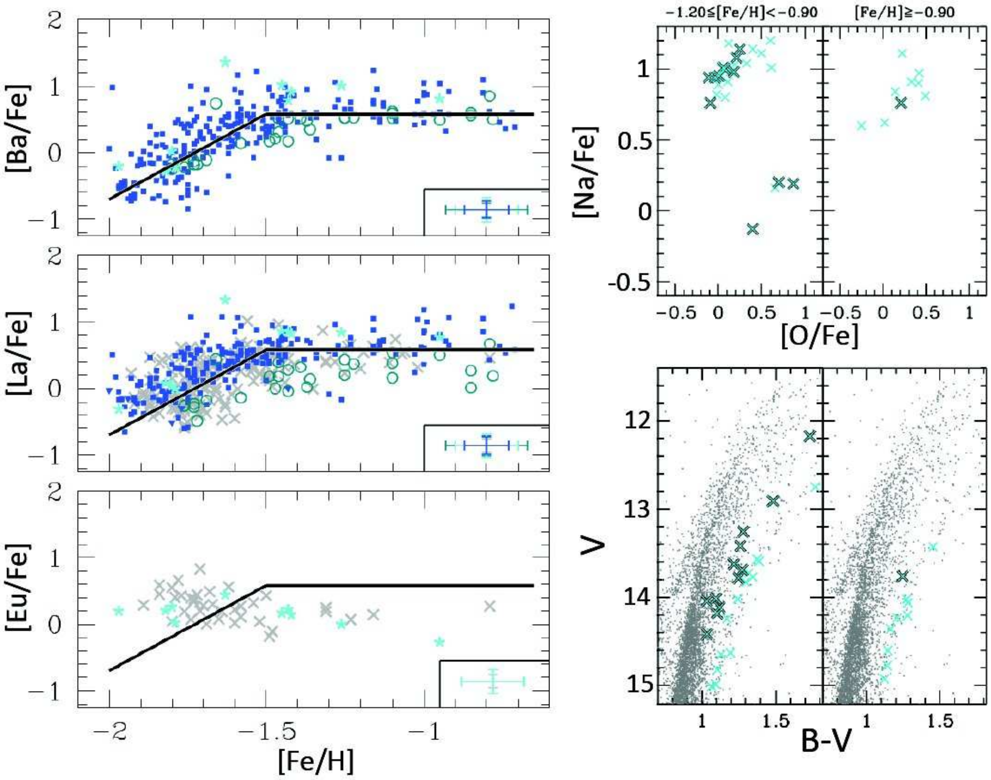

Fig. 2. *Left panels*: [Ba/Fe] (upper), [La/Fe] (middle), and [Eu/Fe] (lower) versus metallicity, [Fe/H]. Data are taken from different literature sources: (i) cyan stars are from Norris & Da Costa (1995); (ii) grey crosses from Johnson & Pilachowski (2010); (iii) blue squares from Marino et al. (2011a). *Right panels*: Na and O pattern in the most metal-rich stars of ω Centauri. The upper panel shows [O/Fe] versus [Na/Fe] grouped into different metallicity bins using data from Marino et al. (2011a). The lower panel shows the locations of these stars in the V versus $B-V$ CMD.

ments variations, e.g. their own Na–O, C–N, Na–Al (anti)correlation. This means that whatever scenario is used to interpret these objects, it should be able to account for an intricate intertwine of stellar populations.

In the halo field, CEMP/*s* stars abundances are well fit by low mass AGB models. In these stars the ^{13}C neutron source is dominant (Lugaro et al. 2012; Bisterzo et al. 2012). The abundance pattern of the *n*-capture elements in the *s*-rich stars of some *anomalous* GCs, NGC 5286 and M 2, is very similar to that observed in these field stars, even though no evidence for extremely high C enhancements have been found to date in the *s*-rich stars of anomalous GCs. However, we cannot exclude that the material from which *s*-rich stars formed was also exposed to the same mechanisms acting in *normal* GCs, and producing the light element (anti)correlations, somehow decreasing the level of C-enrichment.

Recently, Shingles et al. (2014) and Straniero et al. (2014), suggested that both AGB stars with a ^{22}Ne source and lower-mass AGB stars with ^{13}C pockets are required in order to account for the *s*-elements enrichment in M 22. The nucleosynthesis occurred in these stars can also explain the large *s*-process elements abundances in M 4 (relative to clusters with a similar metallicity like M 5). The contribution from stars with masses as low as 2.75-4.5 $M_\odot$ may be required to explain the enrichment, with the precise lower limit depending on which assumptions are made about ^{13}C-pocket formation in AGB models. Among *anomalous* GCs we observe much higher *s*-enrichments in NGC 5286 and M 2 than in M 22, so we may think that in these cases the contribution from lower mass AGB was higher, but future proper analysis would be enlightening to understand the higher *s*-enrichment.

As well as producing *s*-process elements, lower mass AGBs are also able to increase the C+N+O total abundance. As discussed above, the C+N+O is higher in *s*-rich stars at least for NGC 1851, M 22 and ω Centauri. This observational constraint corroborates the idea that in these objects lower mass AGB stars had a chance to contribute to the intra-cluster chemical enrichment and to the formation of second-generation stars.

4. Omega Centauri

It has been known for a long time that ω Centauri shows extreme variations in the chemical composition of its stars. These chemical variations affect both the light elements and the *s*-process/C+N+O/Fe composition, with the *r*-process element Eu being constant, so that this peculiar object can be considered *an extreme of the two classes of GCs, normal and anomalous*, discussed here.

Its He variations, as inferred from split main sequences, is as high as Δ Y ~0.15, implying the presence of stars composed of 40% by mass of helium. Even though higher-mass AGB stars are expected to deliver material exposed to H-burning, such as material enriched in He, current models cannot achieve such high values. Recently, Shingles et al. (2015) have shown that the final helium abundance can increase above Y~0.40 if the initial abundance is higher than the primordial abundance. We may think that, in a complex object like ω Centauri with its many stellar populations, second-generation AGBs, already enhanced in He, could have contributed to the self-enrichment of the cluster (Karakas et al. 2014).

Omega Centauri is a very intriguing object also in respect to the chemical patterns of the *p*-capture element (anti)correlations. Similarly to the more simple examples of *anomalous* GCs, it displays Na–O and C–N anticorrelation among stars with different Fe and *s*-process element abundances. However, it is the only GC where a correlation between O and Na is observed, although only in the most metal-rich stars (Marino et al. 2011a, see Fig. 2). This chemical pattern, at odds with the typical Na–O anticorrelation, agrees with the pure *p*-capture processed material expected in intermediate-mass AGBs (D'Antona et al. 2011).

Concluding, ω Centauri, to date, is the GC displaying the most striking chemical constraints in favour of chemical internal enrichment due to AGBs nucleosynthesis. Similarly to the other *anomalous* GCs, intra-cluster pollution from SNe also occurred to explain the wide range in Fe.

5. Conclusions

The light elements chemical variations observed in typical Milky Way GCs have been interpreted according to various scenarios, either implying multiple stellar generations (Decressin et al. 2007; D'Ercole et al. 2008; Denissenkov et al. 2015) or mass transfer in massive interacting binaries (Bastian et al. 2013). All these scenarios have serious shortcomings in reproducing the exact observed chemical patterns. A detailed discussion of these scenarios and how they meet the observational constraints is presented in Renzini et al. (2015). Here I have summarised the observational evidence and how the AGBs can – or not – meet the various observed constraints.

AGB stars are viable polluter candidates for the chemical variations of hot H-burning products in GCs, but current nucleosynthesis models cannot reproduce the O–Na chemical pattern. To date, a definitive solution for the light elements variations in normal GCs has not been found, and possibly all the present scenarios can be revised or improved to match the observed chemical patterns.

The place where instead the AGB pollution seems to be more robust is in *anomalous* GCs, that display a chemical pattern consistent with an enrichment from *s*-process material, and C+N+O enhancements, both consistent with chemical enrichment from low-mass AGBs. Furthermore, in ω Centauri we do observe an O–Na correlation for metal-richer stars, in agreement with what is expected from intermediate-mass AGB ejecta. It is worth noticing, however, that the same mechanism producing O–Na anticorrelations in normal GCs, has been active also in *anomalous* GCs, including the more metal-poor stars of ω Centauri, that exhibit similar patters at various metallicities. The AGBs pollution in these objects may have occurred on top of these mechanisms.

Acknowledgements. I warmly thank Amanda Karakas for useful discussions on AGB stars, and Antonino Milone for our conversations on multiple stellar populations in GCs.

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