Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
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The role of AGB stars in the evolution of globular clusters

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Abstract. The results from high-resolution spectroscopy and accurate photometry have challenged the traditional paradigm that stars in globular clusters (GC) are simple stellar populations, rather suggesting that these structures harbor distinct groups of stars, differing in the chemical composition, particularly in the abundances of the light elements, from helium to silicon. Because this behavior is not shared by field stars, it is generally believed that some self-enrichment mechanism must have acted in GC, such that new stellar generations formed from the ashes of stars belonging to the original population. In this review, after presenting the state-of-the-art of the observations of GC stars, we discuss the possibility that the pollution of the intra-cluster medium was provided by the winds of AGB stars of initial mass above $\sim 3\ M_{\odot}$. These objects evolve with time scales of $40 - 100$ Myr and contaminate their surroundings with gas processed by p-capture nucleosynthesis, in agreement with the chemical patterns traced by GC stars.

Keywords. stars: abundances, stars: AGB and post-AGB, stars: evolution, globular clusters: general

1. Introduction

The observations collected in the last three decades have definitively challenged the traditional, long-standing belief, that GC stars provide the best example of a simple stellar population.

A series of studies, based on high-resolution spectroscopy, showed that star-to-star differences in the surface chemical composition exist in practically all the GC analyzed, which define well defined abundance patterns, the most clear being the C-N and O-Na anti correlations (Osborn 1971; Cottrell & Da Costa 1981; Kraft 1979; Gratton *et al.* 2001; Gratton *et al.* 2004; Carretta *et al.* 2009a; Carretta *et al.* 2009b). More recent results, based on high-resolution infrared spectroscopy, obtained by the Apache Point Observatory Galactic Evolution Experiment (APOGEE; Majewski *et al.* 2017), have further investigated the Mg-Al anti correlation patterns exhibited by stars in twelve GC, showing that the spread in the magnesium abundances detected is highly sensitive to the metallicity of the cluster (Mészáros *et al.* 2015).

On the photometric side, the first studies on the argument of multiple populations of GC were focused on the interpretation of the extremely peculiar morphology of the horizontal branch (hereafter HB) of some GC, such as NGC 2808 (D'Antona & Caloi 2004), M3 and M13 (Caloi & D'Antona 2005), NGC 6441 (Caloi & D'Antona 2007); the working hypothesis of all these investigations was that the morphology of the HB of each cluster is essentially determined by the distribution of the helium contents of the stars in the cluster, with the faintest and bluest objects being those most enriched in helium. This understanding was confirmed by independent studies, focused on the main sequence (hereafter MS) of some clusters with an extended and clumpy HB, which showed that a difference in the helium mass fractions among stars of the same cluster was required to reproduce the MS spread (or splitting, Bedin *et al.* 2004; Piotto *et al.* 2005, 2007; D'Antona *et al.* 2006).

The combination of the observational results given above confirm that the clusters showing the most extended chemical patterns are those hosting stars enriched in helium. This is a clear evidence that GC harbor one or more stellar components, formed from gas which was exposed to p-capture nucleosynthesis. Because this behavior is not shared by field stars, a self-enrichment mechanism, likely favored by the depth of the gravitational well in the central regions, was active in GC, so that new stellar generations formed from the ashes of the gas lost by stars belonging to the original, first generation (FG) of the cluster.

The recent years have witnessed a growing interest and a lively debate regarding the modalities with which such a self-enrichment occurred and the identification of the possible polluters.

In this review we will describe the "self-enrichment by AGB" scenario, according to which the actors of the pollution of the intra-cluster medium were stars of mass in the range $3.5 - 8\ M_{\odot}$, evolving through the AGB phase. In the context of this mechanism, originally proposed by D'Antona *et al.* (1983), later reconsidered on more solid grounds by Ventura *et al.* (2001), AGB stars belonging to the FG of the cluster evolved within ~ 100 Myr and contaminated their surrounding with gas exposed to p-capture activity, triggered by the hot temperatures which these stars attain at the base of the envelope, higher than ~ 40 MK, as a consequence of the ignition of hot bottom burning (HBB, Renzini & Voli 1981; Blöcker & Schönberner 1991). These stars can be considered as valuable polluters, because the gas which they eject is enriched in helium, as a consequence of the second dredge-up (SDU) episode (see e.g. Ventura 2010).

In the initial part of the present contribution we will provide a summary of the most relevant observational results from high-resolution spectroscopy and photometry of GC stars, thus fixing the main pre-requisites that the contaminant gas must fulfill. We will then discuss whether the ejecta from massive AGB stars can cope with such an observational evidence and provide a gross description of how stellar formation takes place in GC when self-enrichment by AGB stars is active.

2. Multiple populations in Globular Clusters: observational evidences

The possibility that GC stars harbor a significant fraction of stars contaminated by advanced p-capture nucleosynthesis was first deduced on the basis of results from high-resolution spectroscopy, which evidenced in all the GC examined the presence of stars with an anomalous chemical composition; initially, the most outstanding and confirmed chemical patterns were the O-Na and C-N anti-correlations, suggesting the exposure of the gas from which these stars formed to nuclear activity, based on p-capture reactions.

These studies were completed by investigations aimed at interpreting results from photometry, initially focused on understanding the peculiar morphology of the HB of a few clusters, then concentrated on the interpretation of the splitting of the main sequences and the giant branches of GC stars in the color-magnitude diagrams, depending on the combination of filters used. The outcome of these investigations was the identification of

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stellar populations enriched in helium, which further confirms the signature of p-capture processing in the gas from which part of the stars formed.

2.1. *Chemical patterns of globular cluster stars*

The detection of stars with anomalous chemistry dates back to a few decades ago, when it was clear the presence of star-to-star differences in the chemical composition of the sources observed (e.g. Kraft 1979). More recent studies outlined that the chemical patterns are present in all the galactic GC: Carretta *et al.* (2009a, 2009b) showed that the O-Na trend is a common feature of all GC, though with some dissimilarities from cluster to cluster, in the extension and the slope of the anti-correlation.

The recent results from APOGEE have shown that some GC exhibit a well defined Mg-Al anti-correlation: among twelve GC investigated, the study by Mészáros *et al.* (2015) showed that a significant depletion of Mg is present only in metal-poor clusters. These results, combined with the discovery of an extremely large Mg spread among the stars in the metal poor cluster NGC 2419 (Mucciarelli *et al.* 2012), indicate that the Mg-Al pattern, unlike the O-Na trend, is more sensitive to the metallicity, thus providing more information regarding the nucleosynthesis at which the contaminated material was exposed.

2.2. *The discovery of helium-rich stars in globular clusters*

In a seminal paper devoted to the analysis of the various factors which affect the distribution of stars along the HB, D'Antona *et al.* (2002) suggested that the peculiar morphology of the HB of some GC can be explained by hypothesizing a helium distribution among the stars in the cluster. A helium difference would have a minor impact on the morphology of the MS turn off, but would largely affect the distribution of the stars across the HB. This idea was successfully applied to interpret the HB of NGC 2808 (D'Antona & Caloi 2004), M13 (Caloi & D'Antona 2005), NGC 6441 (Caloi & D'Antona 2007), M3 (Caloi & D'Antona 2008), 47 Tuc (Di Criscienzo *et al.* 2010), NGC 2419 (Di Criscienzo *et al.* 2010, 2015). In some of these clusters, particularly NGC 2808 and NGC 2419, the bluest and faintest objects in the HB were interpreted as stars formed from gas enriched in helium, with a helium mass fraction $Y \sim 0.36 - 0.37$.

The hypothesis of differences among the helium abundances of GC stars was further reinforced by the discovery of MS splitting in NGC 2808 (D'Antona *et al.* 2005; Piotto *et al.* 2007) and from additional results, mainly based on HST photometry, which confirmed the complexity of the stellar population puzzle of some GC (Milone *et al.* 2012, 2013; Piotto *et al.* 2013; Milone *et al.* 2017).

2.3. *Spectroscopic and photometric evidences of multiple populations in GC*

To assemble the observational results from high-resolution spectroscopy and photometry, we discuss at the same time the helium enrichment of GC stars, deduced on the basis of the morphology of the HB and, when present, the MS broadening or splitting, and the extent of the p-capture nucleosynthesis. For the latter we use as a key indicator the magnesium spread among the stars of the same cluster; this is because, as stated previously, the activation of the Mg-Al-Si nucleosynthesis requires higher temperatures compared to the other nuclear channels involved (such as the CNO and the Ne-Na burning), thus it is more sensitive to the physical conditions of the gas from which the contaminated stars formed.

The results representing the state-of-the-art of the observations collected so far are shown in Fig. 1, where we report the helium enrichment as a function of the Mg spread, for clusters with different metallicity (see the color coding on the right side of the figure).

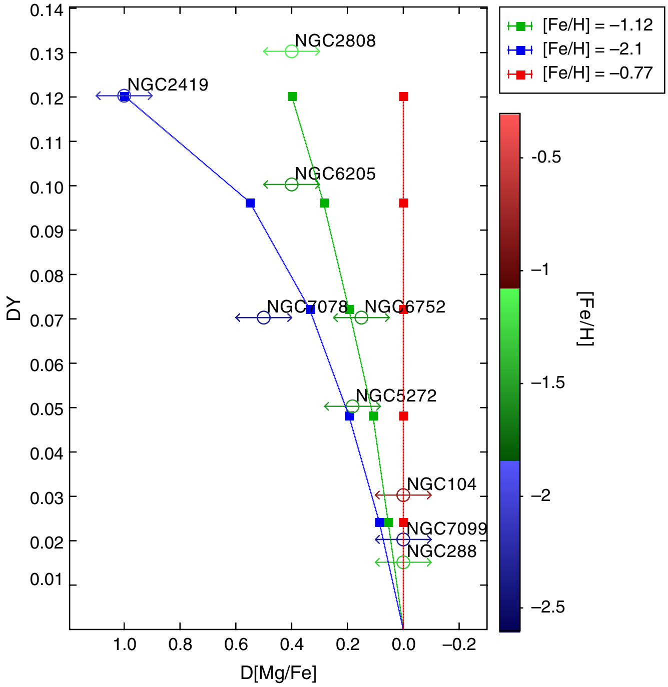

Figure 1. The magnesium and helium spread for some galactic globular clusters, for which the helium spread has been estimated.The color coding corresponds to different metallicities, as reported on the right, vertical axis. The dilution curves were obtained by mixing the AGB ejecta with various percentages of pristine gas for the metallicities [Fe/H] = −0.77 (red), [Fe/H] = −1.12 (green) and [Fe/H] = −2.1 (blue).

The most relevant results shown in Fig. 1 are the following:

(*a*) The helium enrichment is independent of metallicity. The two clusters exhibiting the largest helium spread, namely NGC 2419 and NGC 2808, have different metallicities, but the helium enhancement required to explain their very peculiar HB is practically the same ($\delta Y \sim 0.12 - 0.13$).

(*b*) The Mg spread, δMg, is sensitive to the metallicity of the cluster: the higher the metallicity, the lower δMg. No significant spread in magnesium has been observed so far in metal-rich clusters, even when a O-Na pattern is detected. For a given metallicity, δMg is correlated to the helium enrichment.

(*c*) At a given metallicity, some clusters show up the presence of a highly contaminated stellar population, whereas in other GC the surface chemistry is very homogeneous, quite similar to FG stars. This suggests that in the first case part of SG stars formed directly from the ejecta of the polluters, whereas in the latter case strong dilution with residual pristine gas in the cluster occurred.

2.4. *The indication from the observations to identify the polluters*

The observational results collected so far stimulated the search for a self-enrichment mechanism, which favored the formation of stars with a chemical composition contaminated by p-capture nucleosynthesis. The polluter stars of the FG must have evolved sufficiently fast, say below ~ 1 Gyr, because the observations of the MS of the clusters do no exhibit any trace of a significant age spread.

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Based on the observational results described above, we may conclude that the polluting stars must fulfill the following pre-requisites:

(*a*) The gas ejected must be enriched in helium. The highest helium must not exceed $\sim 38\%$, corresponding to a net enrichment of $\delta Y = 0.13$. This is necessary to reproduce the peculiar morphology of the HB of clusters such as NGC 2419 and NGC 2808.

(*b*) The material lost by the polluters must show the imprinting of p-capture nucleosynthesis, able to reproduce the chemical patterns observed, particularly the C-N, O-Na and Mg-Al anti-correlations.

(*c*) While the helium enrichment is independent of metallicity, the extent of the p-capture experienced, identified with the spread in the Mg content of stars in the same cluster, must depend on the metallicity: the ejecta of the polluters must be Mg poor, but the Mg spread must decrease with metallicity and must vanish for the chemical composition of metal-rich clusters.

3. The ejecta of AGB stars

An appealing possibility regarding pollution in GC is that the gas from which new generations of stars formed was provided by stars evolving through the AGB phase. If this is the case, the attention must be focused on stars of initial mass above $\sim 3 - 4\ M_{\odot}$, because lower mass stars reach the C-star stage, thus the gas which they eject into the interstellar medium show a great enrichment in carbon (Karakas & Lattanzio 2014; Lattanzio, this volume), which is at odds with the observational evidences collected so far. We will consider only stars of mass in the range $3.5\ M_{\odot} \leq M \leq 8\ M_{\odot}$, to which we will refer in the following as "massive AGB stars".

3.1. *The helium enrichment in the gas from massive AGB stars*

Massive AGB stars produce helium-rich gas. This is shown in Fig. 2, showing the average helium in the ejecta of stars of different mass. The results refer to non rotating models of different metallicity, published by various research groups. The helium enrichment is mainly achieved during the second dredge-up (SDU) episode, which takes place after the end of the core helium burning phase, when the surface convection penetrates inwards, until reaching stellar layers previously touched by p-capture processing. The helium mass fraction increases with the mass of the star, because the higher the mass, the deeper is SDU. The helium enrichment is practically independent of metallicity. These findings are rather robust, as confirmed by the agreement among the results published by different groups. The reason for this is that SDU occurs before the beginning of the thermal pulses phase, thus the description of this phenomenon is only scarcely affected by the uncertainties related to AGB modelling, mainly related to convection modelling (Lattanzio, this volume).

Interestingly, the largest enrichment in helium, occurring in very massive AGB stars, is $\delta Y \sim 0.13$, which corresponds to mass fractions $Y \sim 0.37$. This is in agreement with the values required to fit the very peculiar HB of NGC 2808 and NGC 2419 (see Fig. 1). This upper limit in the helium enrichment would shift upwards if rotation was considered: for realistic rotation rates it is found that the helium abundance after the SDU reaches $Y \sim 0.40$ in the most massive AGB stars (A. Dotter, private communication).

3.2. *The signature of p-capture processing in the winds of AGB stars*

The ejecta from massive AGB stars definitively show the signature of p-capture nucleosynthesis. This is due to the activation of HBB at the base of the convective envelope,

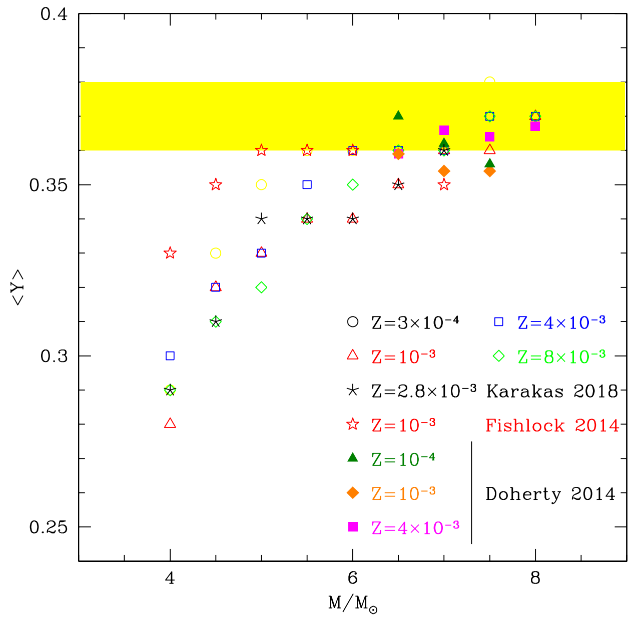

Figure 2. The helium abundance in the ejecta of AGB stars as a function of the initial mass. In the plot we show results from AGB models of various metallicities published in Ventura *et al.* (2013, 2014), low-metallicity models by Doherty *et al.* (2014), Doherty *et al.* (2014) and Karakas *et al.* (2018). The yellow shaded region indicates the helium values required to fit the faintest stars in the HB of NGC 2808 and NGC 2419.

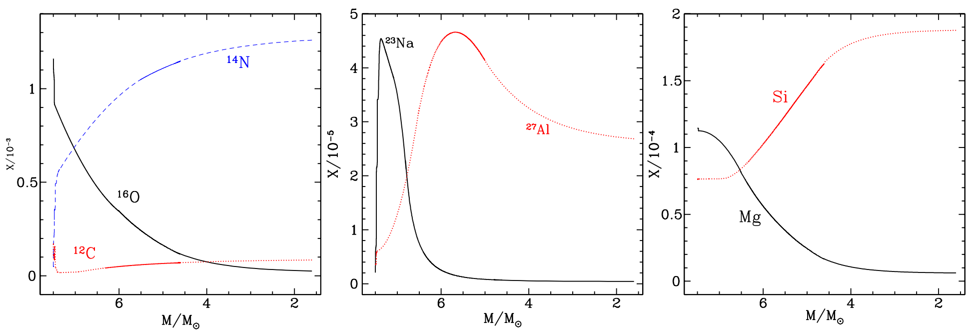

Figure 3. The variation of the surface mass fraction of the CNO elements (left panel), sodium and aluminum (middle), magnesium and silicon (right) during the AGB evolution of a star of initial mass 7.5 $M_\odot$, with the same chemical composition of NGC 2808 stars. The current mass of the star is reported on the abscissa.

as soon as the temperature in that region of the star, $T_{\rm bce}$, exceeds ~ 40 MK, which requires core masses $M_{\rm c} > 0.8\ M_\odot$.

The example shown in Fig. 3 refers to an AGB model of initial mass 7.5 $M_\odot$, recently used by Di Criscienzo *et al.* (2018) to study the multiple populations in NGC 2808. The figure reports the evolution of the surface chemical composition of the star, in terms of the mass fractions of the CNO elements (left panel), sodium and aluminum (middle panel) and magnesium and silicon (right panel). The abscissa shows the current mass of the star, to better understand the yields expected.

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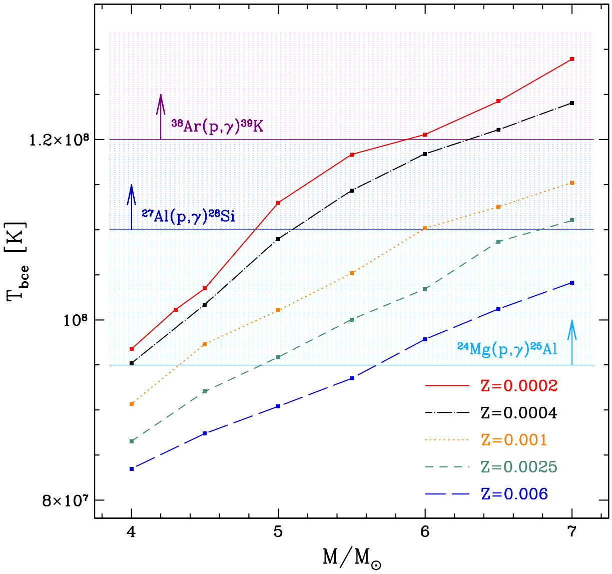

Figure 4. The temperature at the base of the convective envelope of AGB models of different mass, reported on the abscissa. The five lines correspond to different metallicities. The threshold temperatures required to activate proton capture reaction on ^{24}Mg, ^{27}Al and argon nuclei are also indicated

We notice in the left panel the effects of the full activation of the CNO cycle, with the synthesis of significant amounts of nitrogen at the expenses of carbon and oxygen. The extent of the oxygen depletion is extremely sensitive to $T_{\rm bce}$: while at temperatures in the range 40 MK $< T_{\rm bce} <$ 80 MK only CN cycling is activated, for temperatures above 80 MK oxygen is depleted efficiently.

The middle panel shows the behavior of sodium and aluminum, two species involved in both production and destruction channels, thus extremely sensitive to the temperature at which the nucleosynthesis takes place. In both cases we note an initial phase during which the two species are produced, owing to the ignition of ^{22}Ne and magnesium burning, followed by evolutionary stages when both Na and Al are destroyed by ^{23}Na$(p,\alpha)^{20}$Ne and ^{27}Al$(p,\alpha)^{24}$Mg reactions; the latter reactions are characterized by a steeper sensitivity to the temperature than the corresponding production rates, thus they become dominant when the temperature exceeds a given threshold.

The right panel of Fig. 3 shows the effects of a very advanced p-capture processing, with the depletion of the surface magnesium and the synthesis of silicon, the signature of the activation of the Mg-Al-Si nucleosynthesis, which requires temperatures $T_{\rm bce} \geq 90$ MK.

3.3. *The role of metallicity on the chemistry of AGB stars*

While the above arguments hold on general grounds, the overall situation is indeed extremely complex, because the degree of the nucleosynthesis experienced at the base of the envelope is sensitive to $T_{\rm bce}$, which, in turn, depends on both the core mass and the metallicity of the star.

This is described in Fig. 4, which shows the typical temperature at the base of the envelope of AGB stars of different initial mass (reported on the abscissa) and various metallicities, indicated with different lines and colors in the figure. The general trend with mass in that higher mass stars experience higher $T_{\rm bce}$, because they develop more massive cores at the beginning and during the AGB phase.

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Besides the role of the initial mass it is clear in Fig. 4 the effect of metallicity, with lower Z stars reaching hotter temperatures at the base of the surface convective zone. This is consistent with the general behavior of stars supported by H-burning shells, where the gradients of the thermodynamic variables, primarily temperature, are steeper the lower the metallicity, which reflects into a higher efficiency of the shell in metal poor stars.

In Fig. 4 the temperatures attained by massive AGB stars are compared with the ignition temperatures of different nuclear channels. While in metal-poor stars the ignition of the Mg-Al-Si nucleosynthesis is activated in all the masses considered, in AGB stars with metallicity typical of metal-rich GC advanced nucleosynthesis can be ignited only in the most massive stars.

This has an important consequence on the yields from this class of objects and on the role that they might play in the self-enrichment of GC. In metal-poor clusters, provided that part of the SG formed from undiluted or scarcely diluted AGB ejecta, we expect to observe stars with the imprinting of advanced nucleosynthesis, showing up magnesium poor chemistry, and Al and Si enrichment. The Mg depletion is expected to become smaller and smaller as the metallicity increases, according to the results showed in Fig. 4. This trend with metallicity is not expected for the helium in the ejecta, because the latter depends on the extend of SDU, which is practically independent of metallicity.

We may therefore conclude that, at least on qualitative grounds, the yields from massive AGB stars share all the requisites, discussed in the previous section, required to reproduce the observational evidences collected so far, summarized in Fig. 1.

4. The role of AGB stars in the self-enrichment of Globular Clusters

The AGB yields described in the previous section have been successfully applied to explain the O-Na anti correlations observed in M3, M13, NGC 6752 (D'Antona & Ventura 2007), the O-Na and C-N patterns detected in M5, NGC 6388, NGC 6441 Ventura & D'Antona 2008, in NGC 6397 and M15 (Ventura & D'Antona 2009). Additional studies of this kind regard the interpretation of the extreme chemical composition of some stars in the metal-poor cluster NGC 2419 (Ventura *et al.* 2012), the chemical patterns exhibited by stars in 47 Tuc (Ventura *et al.* 2014), the O-Na, Mg-Al and Al-Si trends observed in NGC 2808 (Di Criscienzo *et al.* 2018). Dell'Agli *et al.* (2018) have recently interpreted the recent results from APOGEE, outlining how the trend with metallicity of the Mg-Al and Mg-Si trend can be nicely explained by invoking pollution from AGB stars.

In these studies the chemical patterns of the different clusters have been explained considering the pollution from AGB stars of the FG, using the yields of the same metallicity of each cluster, diluted at different extent with pristine gas. Dilution is an essential ingredient to explain most of the observations collected so far. These works were complemented by a series of studies, which tackled the argument of the formation of SG stars in GC with a dynamical approach.

In the seminal papers by D'Ercole *et al.* (2008, 2010) it is proposed that SG stars formed after the gas ejected from massive AGBs settled in the innermost regions of the cluster, under the effects of radiative cooling; we therefore expect that SG stars are initially more concentrated towards the center of the cluster in comparison with the FG. Such a model offers a valuable explanation of the significant fraction of SG stars observed, far in excess of what is expected considering the gas provided by massive AGBs (see e.g. Renzini *et al.* 2015): the gradual loss of stars from the outskirts of the cluster, which mainly involves FG stars, provokes a gradual increase in the SG/FG ratio, which poses the basis for a general context, where the clusters we observe nowadays are the relics of more massive structures, which lost $\sim 90\%$ of the stellar mass.

An exhaustive discussion on the factors affecting the temporal evolution of the radial distribution of the SG/FG ratio in GC is given in Vesperini *et al.* (2013), whereas the modalities with which pristine gas is re-accreted from the external regions of the clusters after the end of the type II SN explosions is described in D'Ercole *et al.* (2016). An interesting summary of the various modalities with which the formation of SG stars may occur in GC is given in the study by D'Antona *et al.* (2016), devoted at explaining the formation of 5 population in NGC 2808, as witnessed by the results from photometry, presented by Milone *et al.* (2015).

All the results obtained so far indicate that the general framework, which considers that massive AGB stars were the protagonists of self-enrichment in globular clusters, is robust and supported by the observational evidence. While additional investigations, possibly extended to extra-galactic GC, are required to draw definitive conclusions, it appears that pollution from AGB stars, for what concerns both the chemistry of the ejecta and the dynamics of formation of the SG, may account for the variety of situations observed, which make each cluster a unique case.

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Discussion

Marigo: What is the current situation regarding star-to-star differences in the CNO abundances of globular cluster stars?

Ventura: Initially, it was believed that the CNO is constant. More recent results suggest a possible spread of a factor of two in some globular clusters. This could be explained by a longer formation of the second generation, until times when carbon-rich gas by stars of mass 3-3.5 solar masses is ejected into the interstellar medium. On the observational side, a small increase in the overall CNO of second generation stars seems more compatible with the morphology of the horizontal branch of some metal poor clusters.

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