SELF-ENRICHMENT IN GLOBULAR CLUSTERS: IS THERE A ROLE FOR THE SUPER-ASYMPTOTIC GIANT BRANCH STARS?

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ABSTRACT

In four globular clusters (GCs) a nonnegligible fraction of stars can be interpreted only as a very helium-rich population. The evidence comes from the presence of a “blue” main sequence in ω Cen and NGC 2808, and from the very peculiar horizontal-branch morphology in NGC 6441 and NGC 6388. Although a general consensus is emerging on the fact that self-enrichment is a common feature among GCs, the helium content required for these stars is \( Y \geq 0.35 \), and it is difficult to understand how it can be produced without any—or, for ω Cen, without a considerable—associated metal enhancement. We examine the possible role of super-AGB stars, and show that they may provide the required high helium. However, the ejecta of the most massive super-AGBs show a global CNO enrichment by a factor of \( \approx 4 \), due to the dredge-out process occurring at the second dredge-up stage. If these clusters show no evidence for this CNO enrichment, we can rule out that at least the most massive super-AGBs evolve into O-Ne white dwarfs and take part in the formation of the second-generation stars. This latter hypothesis may help to explain the high number of neutron stars present in GCs. The most massive super-AGBs would in fact evolve into electron-capture supernovae. Their envelopes would be easily ejected out of the cluster, but the remnant neutron stars remain in the clusters, thanks to their small supernova natal kicks.

Subject headings: globular clusters: general — stars: AGB and post-AGB — stars: formation — stars: neutron

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1. INTRODUCTION

The majority of the inhomogeneities in the chemical composition of globular cluster (GC) stars—see, e.g., Sneden (1999) and Gratton et al. (2004)—appear due to primordial enrichment by hot-CNO-cycled material processed in stars belonging to a first stellar generation. Either massive AGB envelopes subject to hot bottom burning (e.g., Ventura et al. 2001, 2002) or the envelopes of fastly rotating massive stars (FRMSs) (Decressin et al. 2007) are an ideal environment for manufacturing elements through nuclear reactions in which proton captures are involved. A second stellar generation would then be born from the ejecta of these stars, either directly or diluted with pristine material. There are however problems with these scenarios. For the AGB progenitors, problems concern the chemistry of the anomalous stars (see Demissenkov & Herwig 2003; Ventura et al. 2004; Fenner et al. 2004; but consider also Ventura & D’Antona 2005) and the requirements for the mass budget necessary to produce a second stellar generation that, today, is generally about as numerous as the first one (D’Antona & Caloi 2004; Bekki & Norris 2006; Prantzos & Charbonnel 2006). The FRMS model is somewhat less problematic concerning the constraints on the IMF, but poses, in any case, severe problems for “normal” GCs, which show a unique metallicity for all stars (with the notable exception of ω Cen): this model requires that the envelopes of these stars contribute to the second star formation stage, but the supernova ejecta are expelled from the clusters and do not enrich the second-generation matter by heavy elements.

Both scenarios predict that the stars showing chemical anomalies also must have enhanced helium abundance. Helium and the hot-CNO products in the FRMSs come to the stellar surface by means of the chemical mixing associated with the transport of angular momentum through the stellar radiative layers, during the hydrogen-burning phase. In the case of AGBs, the helium enrichment is mainly due to the second dredge-up (2DU), which precedes the thermal pulse phase. Also, the third dredge-up (3DU) contributes to helium enrichment in the envelopes, but a further observational constraint is that the sum of CNO abundances remains remarkably constant in normal and anomalous stars (e.g., Cohen & Meléndez 2005). Consequently, the masses which can be responsible for the chemical enrichment must be high enough to be subject to a few episodes of the 3DU, which brings into the envelope the products of helium burning.

A variation in helium content is immediately reflected in the morphology of the horizontal branch (HB), which amplifies any evolutionary difference among the cluster stars. Helium enrichment by a small factor (up to \( Y \sim 0.28–0.30 \)) allowed in fact an easy interpretation of some puzzles posed by the HB (blue tails, gaps) (D’Antona et al. 2002; D’Antona & Caloi 2004). Helium variations from the MS location are much harder to detect, but the clustering of \( \approx 20\% \) of ω Cen stars into a “blue” MS (Bedin et al. 2004) was soon interpreted as an MS having an abnormally huge helium content (\( Y \sim 0.40 \)) (Norris 2004; Piotto et al. 2005). In contrast to ω Cen, NGC 2808 does not show a metallicity spread (Carretta et al. 2006). Nevertheless, evidence for the presence of a blue MS in this cluster has been found by D’Antona et al. (2005), who interpreted it, again, as built up by stars having \( Y \sim 0.40 \), and were able to correlate them with the bluest side of the HB. Piotto et al. (2007) showed that the MS of this cluster is actually made up of three separate MSs, the bluest of which, including 10%–15% of stars, must have a helium content \( Y \sim 0.35–0.40 \). The presence of blue MS has not yet been found in other clusters: observationally...
Fig. 1.—Triangles plus dotted line show the helium content in the ejecta of AGB stars as function of the C-O core mass, in the computations by P. Ventura & F. D’Antona (in preparation). The initial masses are, from left to right, 4, 4.5, 5, 5.5, 6, and 6.3 $M_\odot$. Triangles plus solid line show the helium abundance in the envelope after the 2DU in the super-AGBs by Pumo (2006). Masses from left to right are 7.5, 8, 8.5, 9, and 9.5 $M_\odot$. Circles show the ratio of total CNO abundance ($F_{\text{CNO}}$) with respect to the initial value for the same models.

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it is a very difficult problem, and, in addition, this may be a characteristic of the most massive clusters only.

Huge helium overabundances are also needed to explain all the main features of the anomalous HB of the metal-rich clusters NGC 6441 and NGC 6388 (Caloi & D’Antona 2007), including (1) the long extension in luminosity of the red clump; (2) the fact that RR Lyrae stars have a very long average period, which is unusual for a cluster of high metallicity; and (3) the extension into the blue of the HB. This analysis also requires that $\sim 15\%$ of the HB population have $Y > 0.35$.

All these observations and their interpretation in terms of helium enrichment must be taken very seriously, but no chemical-enrichment mechanism is able to produce the huge amount of helium required for about 15%–20% of the stars in these four clusters without dramatically impacting the metal abundance (Karakas et al. 2006; Romano et al. 2007). It is clear that the presence of this extreme population requires some very particular dynamical and chemical conditions to be understood. Nevertheless, the first step is to look for progenitors which may at least provide the required high helium abundance in their ejecta.

The most massive FRMSs may be able to eject huge quantities of helium (Decressin et al. 2007). Concerning the AGB stars, Karakas et al. (2006) pointed out that $Y \sim 0.40$ is not predicted by AGB models, and this could, in the end, rule out AGB stars as progenitors of the second stellar generation. A scant $Y \sim 0.29$ was the maximum abundance computed from AGB evolution in the models by Ventura et al. (2002) for 5.5 $M_\odot$, while a single value $Y = 0.375$ is quoted by Karakas et al. (2006) for a 5 $M_\odot$ model by Campbell et al. (2004). P. Ventura & F. D’Antona (in preparation) have now completed a new computation of massive AGBs, whose results revise upward the previous ones (see below). The maximum AGB mass in these recent computations is 6.3 $M_\odot$, and the possible role of super-AGB stars has not yet been considered. Such models are difficult to compute, as carbon burning in semidegeneracy has to be followed, and the uncertainty in the mass-loss rate hampers any conclusions on their final evolution, either toward electron-capture supernovae (ecSNe) or toward O-Ne white dwarfs.

In the light of recent super-AGB star models described in Pumo (2006), in this Letter we discuss the possible role of these stars for the self-enrichment of GCs. We discuss both the helium abundance and the total CNO abundance versus core mass which can be built up by the most recent AGB and super-AGB models. We find out that the matter lost by the envelopes of super-AGBs may indeed be a good candidate for the high helium population of the four GCs discussed above. However, in the higher mass tail of the stars developing an O-Ne core the total CNO is increased by a factor $\sim 4$. Observations of the super-He-rich stars may be able to check this result.

If all the stars in the GCs having a high He population have standard CNO, as found for all the chemically anomalous stars in many GCs, the most massive super-AGBs must evolve into ecSNe. This conclusion would give further support to the idea that the presence of a large population of neutron stars in GCs implies that they were born with supernova kicks low enough not to be ejected by the cluster, as expected by the ecSN event (e.g., Ivanova et al. 2007).

2. SUPER-AGB STELLAR EVOLUTION

AGB stars develop a degenerate carbon-oxygen core and mass loss prevents them from reaching the mass limit for degenerate explosive carbon ignition. Super-AGBs are defined as stars which ignite carbon in conditions of semidegeneracy, thus nonexplosively, but are not able to ignite hydrostatic core burning in the resulting O-Ne core. Consequently, degeneracy increases in the core and these stars may undergo thermal pulses (e.g., Iben et al. 1997; Ritossa et al. 1999; Siess 2006), and lose mass as “normal” (but quite massive and luminous) AGB stars. Depending on the competition between the mass-loss rate and core growth, they may then evolve into massive O-Ne white dwarfs (Nomoto 1984) or as ecSNe, electrons being captured first by $^{24}$Mg and $^{24}$Na, then by $^{20}$Ne and $^{20}$F nuclei when the core mass reaches the Chandrasekhar mass. The 2DU occurs also in super-AGBs, and as in the massive AGBs, it reduces the mass of the H-exhausted core (e.g., Pumo & Siess 2007), while the helium abundance increases in the external hydrogen envelope (e.g., Siess & Pumo 2006). If mass loss is strong enough to avoid the super-AGBs evolving to ecSNe, as soon as super-AGBs evolve in the GCs, the supernova epoch is finished, and we may hypothesize that the second phase of star formation begins from the super-AGB ejecta.

3. HELIUM AND CNO IN MASSIVE AGBs AND SUPER-AGBs

As a function of the carbon-oxygen core mass $M_*$, we report in Figure 1 the helium content in the AGB ejecta of metallicity $Z = 10^{-3}$, for the models from 4 to 6.3 $M_\odot$ by P. Ventura & F. D’Antona (in preparation), including $\alpha$-element enhancement in the opacities, and core overshooting. An important difference from the Ventura et al. (2002) models is the following: in the present models, also overshooting at the bottom of the convective envelope is included, adopting the same parameter which describes core overshooting. This latter is calibrated to account for the width of the MS of intermediate-mass stars. The effect of the envelope overshooting is to enhance the extent of the 2DU: when the initial mass is fixed, the remnant core
mass at the beginning of the AGB evolution is smaller and the resulting helium content in the envelope is larger, as can be seen by comparing the values of Figure 1 with Table 1 in Ventura et al. (2002).

We also plot the helium content at the 2DU for the super-AGB models of metallicity $Z = 10^{-5}$ from 7.5 to 9.5 $M_{\odot}$ (Pumo 2006) computed without overshooting. In this case $M_1$ is the C-O mass after the 2DU. $M_1$ is indeed the important physical parameter which determines the final fate of the star. The initial mass difference between the AGB models with overshooting and super-AGB models without overshooting is, for the same core mass, $\sim1 M_{\odot}$. For super-AGBs, we do not have the helium mass fraction of the ejecta, but these stars do not go through efficient episodes of 3DU, so the plotted value is a good approximation. As we see, the super-AGB models reach a helium content in the ejecta larger than the standard AGBs, and well approaching the values needed to be consistent with the super-He-rich stars in GCs. The new AGB models and the super-AGB models shown here, computed with a different program and input physics (Siess 2006; Siess & Pumo 2006), are in good agreement with each other, at the same core mass. From Figure 1 we see that indeed the super-AGBs could be the progenitors of the very high helium population found in the most massive GCs. For a Salpeter initial mass function, the mass budget in the ejecta from 6.5 $M_{\odot}$ (the minimum mass for super-AGB evolution, considering models with overshooting) to 8 $M_{\odot}$ (see below) is about 50% of the mass budget contained in the ejecta of normal AGBs from 5 to 6.5 $M_{\odot}$. Therefore, from the super-AGBs mass budget, a 15% fraction of very high helium stars can be born, with the same mechanism which can give origin to another $\sim30$% of moderately helium-rich stars, as in the cluster NGC 2808 (D’Antona et al. 2005). How these stars can form directly from the super-AGB ejecta, so that their helium abundance remains as large as the required $Y \geq 0.35$, is a different problem.

Figure 1 also shows the total CNO enrichment $F_{\text{CNO}}$, the sum of CNO abundances with respect to their initial sum, in the ejecta of AGBs and at the 2DU for the super-AGBs. The AGB enrichment is larger than $\sim 2$ for $M \leq 0.9 M_{\odot}$, that is, for $M \leq 5 M_{\odot}$. As we have noticed, the sum of CNO abundances apparently is constant (within a factor 2) in GC stars. On this basis, we should conclude that stars of $M < 5 M_{\odot}$ should not contribute to the second stellar generation—unless their ejecta are diluted with pristine matter, so that the constancy of CNO is preserved. For the super-AGBs, we also find a sharp increase of $F_{\text{CNO}}$, reaching a factor 4 for the largest mass under examination. This is due to the occurrence of the so-called dredge-out process in this model (Iben et al. 1997; Ritossa et al. 1999). The helium mass fraction and the overall CNO content are the most robust predictions from these theoretical computations, due to the large uncertainties associated with both the extension of the 3DU and the strength of hot bottom burning (HBB) within super-AGB models (e.g., Izzard & Poelarends 2006; Siess & Pumo 2006). We also comment on the individual abundances providing $F_{\text{CNO}}$. The CNO abundances given for $M \leq 6.3 M_{\odot}$ are the average mass fractions of the ejecta. As HBB is very efficient, the values provide very small carbon abundances ($X_{\text{C}} \simeq 1.1 \times 10^{-4}$ for $4.5 M_{\odot}$ models down to $X_{\text{C}} \simeq 1.6 \times 10^{-5}$ at 6.3 $M_{\odot}$) and low oxygen (from $X_{\text{O}} \simeq 6.3 \times 10^{-4}$ at 4 $M_{\odot}$ to $X_{\text{O}} \simeq 10^{-4}$ at 6.3 $M_{\odot}$); nitrogen is very high, especially in the 4 $M_{\odot}$ model, where the effect of the 3DU is more visible ($X_{\text{N}} \simeq 2.6 \times 10^{-3}$). On the contrary, for the super-AGBs, we consider the values at the 2DU. The carbon abundance increases from $X_{\text{C}} \simeq 8.9 \times 10^{-5}$ for the 7.5 $M_{\odot}$ model to $X_{\text{C}} \simeq 8.1 \times 10^{-4}$ at 9 $M_{\odot}$. The nitrogen abundance is about constant ($X_{\text{N}} \simeq 2.4 \times 10^{-4}$), whereas the oxygen abundance is constant ($X_{\text{O}} \simeq 3.8 \times 10^{-4}$) up to 8.5 $M_{\odot}$, and increases up to $X_{\text{O}} \simeq 4.4 \times 10^{-4}$ for the 9 $M_{\odot}$ model: this is due to the deeper sinking of the 2DU when increasing the mass. In the 9.5 $M_{\odot}$ model, the dredge-out process raises $X_{\text{C}}$ to $1.8 \times 10^{-3}$ and $X_{\text{N}}$ to $7.7 \times 10^{-3}$. The following evolution will reduce oxygen and carbon and increase nitrogen, if HBB is as efficient in these stars as it is in the massive AGBs (this depends on the convective model adopted; see Ventura & D’Antona 2005). As for the 3DU, there are different and incomplete results in the literature (see Izzard & Poelarends 2006 for a summary). In any case, it can only act to increase the values of total CNO abundances given in Figure 1.

How many stars would be affected if all the super-AGBs contribute to the second stellar generation? If all the super-AGBs contribute to the very helium-rich population, the fraction of high-CNO stars, assuming a Salpeter IMF, would be $\sim10$%! This is a small fraction of the cluster stars, if we consider that the super-He-rich stars are 15%–20% of the total population, but spectroscopic observations of a large sample of stars could falsify this hypothesis.

4. DO THE MOST MASSIVE SUPER-AGBS EXPLODE?

Should the constancy of CNO be observationally confirmed also for the most helium-rich population showing up in the quoted four clusters, we will be able to conclude that the most massive super-AGBs did not take part in the process of forming the second stellar generation in GCs. This may mean (1) that there were reasons, independent of the super-AGB evolution, for which the self-enrichment process was effective either only at earlier ages (due to the envelopes of massive stars) or at a later age (during the normal, massive AGB evolution), or (2) that the self-enrichment was forbidden by the injection into the cluster gas of the energy due to the ecSN explosion of the stars which undergo the dredge-out. Although the explosion energy of such an event is significantly lower than inferred for core-collapse SNe (Dessart et al. 2006), it is probably more than sufficient to expel the SN ejecta from most clusters. The conclusion then would be that at least a fraction of super-AGBs must evolve into ecSNe, reinforcing the idea that an ecSN channel for super-AGB stars could occur (see, e.g., Siess & Pumo 2006; Poelarends et al. 2007; Pumo & Siess 2007).

5. NEUTRON STARS IN GLOBULAR CLUSTERS

The final fate as ecSNe of—at least a fraction of—super-AGBs is also required by the recent suggestion that neutron stars (NSs) in GCs should be mainly formed by the ecSN channel.

The high number of NSs in GCs, whose presence is revealed mainly by the very high number of millisecond pulsars, remains a puzzle. The massive GC 47 Tuc was predicted to contain more than 1000 NSs (see, e.g., Pfahl et al. 2002). Now this figure can perhaps be reduced to $\sim300$–600 (Heinke et al. 2005). The velocity distribution of young pulsars in the Galaxy shows that, at formation, the NS receives a “natal kick,” most likely due to the asymmetry in the supernova ejecta (Fryer 2004). Pfahl et al. (2002) have shown that only up to 8% of NSs can be retained in the clusters. The kick velocity distribution which they used (Hansen & Phinney 1997) has been recently updated by Hobbs et al. (2005), who find a higher mean velocity and velocity dispersion. Using these new data, simulations of the retention factor by Ivanova et al. (2007)
show that almost no NSs can be retained for an escape velocity of 40 km s$^{-1}$. A natural way to solve this problem is to hypothesize that there is a stellar population that evolves into ecSNe, which probably have much smaller natal kicks (Ivanova et al. 2007), possibly proportional to their reduced explosion energy. This is also suggested by the existence of a class of massive X-ray binaries with small eccentricities. Van den Heuvel (2007) also supports the evidence of two channels for NS formation—with either small or large natal kicks—from an examination of double neutron star binaries.

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