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The first phases of life of stars in Globular Clusters: an example of the problems of modern stellar structure computation

Francesca D'Antona[1,2]

[1] INAF Osservatorio di Roma, via di Frascati 33, 00040 Monteporzio e-mail: `dantona@mporzio.astro.it`
[2] IASF-CNR, via Roma, Italy

Abstract. There is now a growing agreement about the primordial nature of many —if not all— of the inhomogeneities in the chemical composition of globular cluster stars. The best candidates to produce "self—pollution" are identified with the matter lost in winds of low velocity from Asymptotic Giant Branch (AGB) stars, especially of high mass, evolving during the first phases of life of the Clusters. In fact, our recent AGB models have shown that massive AGBs stars are able to cycle Oxygen to Nitrogen (in the complete CNO cycle) at the very hot ($\sim 10^8$K) bottom of their convective envelopes. These AGB models contain much of the difficulties still inherent in the computation of stellar structure, some of which are briefly addressed in this talk.
We suggest that the globular cluster stars are formed in two main generations, the first one having the composition of the primordial gas cloud, the second one formed *directly* from the AGB ejecta. This hypothesis provides a useful and conceptually simple key to interpret some —but not all— HB peculiarities (e.g. the "blue tails" and possibly some gaps in the HB star distribution) and the distribution of abundance anomalies. If the model is correct, in the end we can use the abundance anomalies to falsify (or calibrate) our AGB models.

Key words. Abundances in Globular Cluster stars – AGB models – problems of convective mixing – self–pollution

1. Introduction

The recent observations of abundance spread among Globular Clusters stars, now observed also at the turnoff (TO) and among the subgiants (e.g. Gratton et al. (2001)) are leading many researchers to attribute these anomalies to some process of "self– pollution" occurring during the first stages of the life of the cluster, during the epoch in which the Supernova explosions were already finished (bringing easily away from the clusters their high velocity ejecta) and the massive Asymptotic Giant Branch (AGB) stars were evolving. At an

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Send offprint requests to: Francesca D'Antona
Correspondence to: INAF Osservatorio di Roma, 00040 Monteporzio

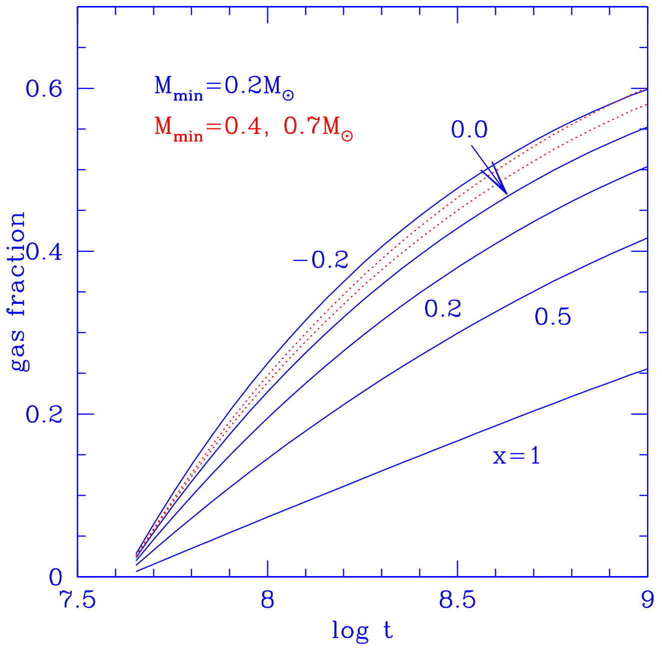

Fig. 1. As function of time, we show the cumulative mass in the ejecta from the first generation of AGB stars which are contained in the initial population having an IMF of index x, and the minimum mass as labeled. We can suppose that the second star forming phase lasts for a time of 2–3×10^8yr, so that we need a very flat IMF (low values of x) if there has to be a considerable fraction of mass in the second generation stars.

epoch starting less than ∼ 10^8yr from the birth of the first stellar generation, the massive AGBs lose mass through low velocity winds, so that it is reasonable to speculate that these winds remain into the cluster and can be either accreted on the already formed stars (D'Antona, Gratton, & Chieffi (1983)) or be mixed with residual gas and give origin to a new stellar generation (Cottrell & Da Costa (1981)).

I outline the line of reasoning which led us to suggest that the spread in chemical abundances is actually due to the birth of successive generation of stars, directly from the ejecta of the massive AGBs of the first generation. If this is the explanation, we also require that the Initial Mass Function (IMF) of the first stellar generation should have been considerably "flat" (with a power law index close to –1, in the notation in which Salpeter's index is –2.35) in the mass range 3–8$M_\odot$. This hypothesis has several interesting consequences on the interpretation of the morphology of extended horizontal branches (HB) in some globular clusters (although it it is not the solution of the 'second parameter' problem) and even of the presence of gaps in the distribution of the HB stars.

I comment on the complexity of AGB modeling, and on the role of convection, which remains one of the critical problems in our understanding of the stellar structure, and quote some other astrophysical cases in which convection still represents a major uncertainty.

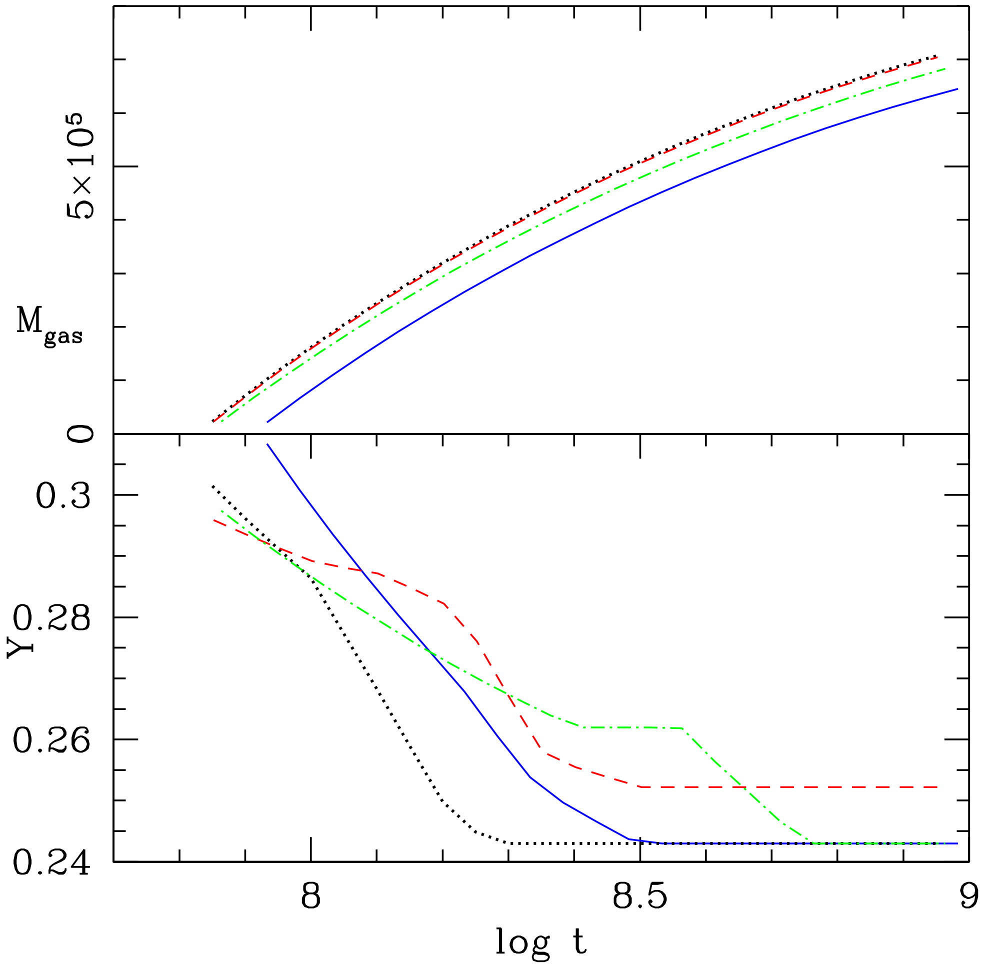

Fig. 2. As a function of time, the top part shows the cumulative mass of gas ejected during the evolution of the first generation AGBs, while the bottom shows the corresponding helium abundance Y in the ejecta. The simulation follows the evolutionary results by Ventura, D'Antona, & Mazzitelli (2002), for the following initial metal abundances: 1) $Z=2\times10^{-4}$ (full line); 2) $Z=6\times10^{-4}$ (dotted line); 3) $Z=1\times10^{-3}$ (dashed line); 4) $Z=4\times10^{-3}$ (dot-dashed line).

2. The AGB models for population II

The most striking abundance anomaly in GC stars is the spread in Oxygen which can reach a factor ∼ 10 in the intermediate metallicity clusters like M13 and NGC 6752. This spread extends to the TO and subgiant stars, as shown by Gratton et al. (2001), and therefore can not be inputed to 'in situ' mixing. At the same time of the Gratton et al. (2001) observations, Ventura et al. (2001) found that the process of 'Hot Bottom Burning' (HBB), that is the nuclear processing which occurs at the basis of the convective envelope of massive AGBs, takes place at such a large temperature ($\simeq 10^8$K) that the full CNO cycle operates and converts Oxygen into Nitrogen. Therefore the envelopes of these massive AGBs have an O abundance much smaller than the initial. The processing is more efficient in the most massive AGBs, and progressively less efficient in the lower masses, which have smaller temperatures at the basis of the convective envelope.

Therefore, the spread in Oxygen can be attributed to this process. More recent computations by our group (Ventura et al. 2003, in preparation) show that the reduction in Oxygen occurs together with an increase in the ^{23}Na abundance, explaining the O-Na anti correlation found in these stars.

3. The AGB modeling

These AGB models are quite difficult to be computed, and the results of the computations are then uncertain and must be carefully explored. In particular, we have the necessity of modeling the AGB through its thermal pulses. Remember that there is still no agreement on the modalities of occurrence of the 'third dredge up' which brings Carbon and Helium from the helium inter shell into the hydrogen rich envelope, giving origin to the phenomenon of the Carbon stars. Further, the modalities of HBB depend on the assumptions adopted for convection. Finally, mass loss (totally parametric, or at least not well understood) modifies the envelope structure and thus the stellar yields, by adding another free parameter.

Many problems are linked to the treatment of convection in its three aspects:

1. the convective model, that is the computation of fluxes and temperature gradients. For instance, we generally adopt the so called Full Spectrum of Turbulence (FST) model by Canuto & Mazzitelli (1991) and Canuto, Goldman, & Mazzitelli (1996), which provides a very efficient convection, helping in reaching the large temperatures at the bottom, needed for the ON processing;
2. the treatment of overshooting, that is, the treatment of the extra-mixing out of the formal borders of convection;
3. the time dependence of mixing: for those elements for which the nuclear lifetime is of the order of the convective mixing lifetime, the assumption of instantaneous mixing leads to incorrect results. We fully couple the nuclear evolution matrix to the mixing, treated as a diffusion (Ventura, Zeppieri, Mazzitelli, & D'Antona (1998)).

Notice however that all today's AGB models are parametric, and we are far from a selfconsistent description of convection in any of these three aspects.

The necessity of having a 'true' convection model is exacerbated in these very difficult AGB phases, in which we must know not only the stellar $T_{\rm eff}$, but also the temperature stratification in the convective region, from which the nucleosynthesis depends. It is less obvious, but this necessity is present for ALL the other stellar structures, unless we calibrate them model by model. For many phases, however, the Mixing Length theory (MLT) is generally still used as a black box, in which we enter with a $T_{\rm eff}$, and exit with the temperature at the bottom of the superadiabatic convective envelope. Of course, these models have no predictive power. This is particularly evident in the computation of the pre-main sequence phase, in which we can schematize the problem by asserting that it is not possible to achieve, with the same convection parametrization, both the solar $T_{\rm eff}$ and the observed lithium depletion and $T_{\rm eff}$ location of the pre-main sequence (D'Antona and Montalbán (2003)).

One method often employed to compute AGB phases is to use a 'synthetic model' approach, parametrizing the main relations (e.g. core mass vs. luminosity, characteristics of the thermal pulses, dredge up) and exploring only the behavior of detailed envelope models. This is an interesting way of achieving results, avoiding the enormous numerical difficulties of computing full models through thermal pulses, even with huge mass loss rates, but it can have some predictive power only if it is based on real model computation: *new* results can come only by new models, and it is necessary to state clearly that we must invest on the development of new tools of base physics!

4. An hint on the modalities of self–pollution

The models of AGB which show Oxygen depletion, also show a noticeable helium enhancement: the helium content can be as high as Y=0.30 or more, although starting from a bare Y=0.24 (the Big Bang abundance). This enhancement is due mainly to the so called 'second dredge up' phase, which is much less model dependent than the third dredge up associated with the thermal pulses, so we can rely on this. Now, if self-pollution is due to the matter lost from AGBs, the Globular Cluster stars should have a population having the initial helium content, and an additional population more or less enriched in helium. By looking at models with high helium, the most relevant feature is the well known result that the mass evolving at each time is smaller, the larger is the helium content. A simple interpolatory formula based on our models (D'Antona et al. (2002), D'Antona and Caloi (2003)), depending on the metallicity Z (for Z close to $\sim 10^{-3}$) and on the helium mass fraction Y provides, for the mass at the helium flash at age t:

$$\log M/M_{\odot} \simeq [-0.282 + 0.092(Y-0.24)]\times$$

$$\log t + [2.768 - 1.693(Y-0.24)] + 12(Z-10^{-3})$$

Thus the mass differs by $\sim 0.05\mathrm{M}_{\odot}$ for a difference in helium by 0.04. This is not a great difference, apart than on the horizontal branch (HB). In fact, if the same mechanism of mass loss operates on the standard helium and on the enhanced helium stars along the giant branch and at the helium flash, the final mass in HB will be several hundredths of solar mass smaller, and therefore will have a *bluer* location. This has been suggested by D'Antona et al. (2002), who also show that the hypothesis of a population of stars having enhanced Y *from the start* (that is, from the main sequence) can explain the existence of extended blue tails in the HB of some clusters, which also show, independently, the mentioned huge oxygen spreads.

In this hypothesis, the helium abundance of the matter lost from the AGB *must not be diluted* with other residual matter in the cluster, and the helium enrichment must be present also *in the core* of the main sequence stars, in order to affect their lifetimes and provide the mass difference for a fixed value of the cluster age. So, we are led to think about a second phase of star formation, directly occurring from the AGB ejecta! Is there enough matter to be consistent with the abundance spreads? Up to a half of cluster stars indeed show the abundance anomalies. Let us make the simple hypothesis that the IMF of the first generation stars follows a power law of the type $dN/dM \propto M^{-(1+x)}$ (x is 1.35 for Salpeter's IMF) and let us look at the fraction of gas ejected from the AGBs as function of time, with respect to the initial total mass of the gas, for different values of x. From Fig. 1 we see that the index must be much smaller than Salpeter's –about 0– if we wish to get some 40-50% of gas in the ejecta, to justify the chemical anomalies. Whether this is possible requires much work indeed, but in our hypothesis the chemical anomalies are giving us interesting hints about the IMF of dense stellar systems. Notice that a flat IMF of the first generation, if extended to somewhat more massive stars, can also explain the embarrassing large number of neutron stars present in clusters and revealed as millisecond pulsars.

5. Gaps in the Horizontal Branches

Fig. 2 shows the gas ejected from AGBs (top) and its helium content (bottom) as function of time for several metallicities of the cluster. The evolutionary times and helium yields of the ejected matter are taken from our models in Ventura, D'Antona, & Mazzitelli (2002). We see that the helium content variation can even be not fully monotonic with time. Further, it is possible that the star formation stops abruptly at some epoch (due, e.g., to the presence of strong UV sources such as the planetary nebulae from relatively low mass progenitors). In cases like these, we will have a discontinuity between the helium content of the first generation (probably the Big Bang abundance) and the *lowest* helium content of the second generation. This can justify a discontinuity in mass along the red giant branch, which reflects in a discontinuity in mass along the HB. D'Antona and Caloi (2003) will show that this is a possible reason for the huge gap in the distribution of stars along the HB of some clusters, such as the lack of stars present in NGC 2808 exactly at the position of the RR Lyrae. The HB stellar distribution, as well known, amplifies any small physical difference in the previous evolution, and this is true also for the possible helium variation.

6. Conclusions

A lot of work remains to be done to understand the chemical abundances in Globular Clusters, but we think that the outline described here is in a correct direction and may provide a key for the interpretation of several characteristics, both of abundance anomalies and of the HB distribution. Let me stress again that the problem of the so called 'second parameter' in Globular Clusters is by no means solved by the inclusion of this further parameter (a helium spread and gap between a first and a second generation), because the first generation stars are *always* present in all clusters. Therefore, e.g., we can not get rid of the red HB stars of M3, in order to obtain a fully blue HB like that of M13, by invoking simply two stellar generations with different helium content. But it is possible that this way of looking at the problem may help in discriminating among the possible second parameter candidates.

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