Predictions for selfpollution in Globular Cluster Stars

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ABSTRACT

Fully evolutionary models have been built to follow the phases of Asymptotic Giant Branch (AGB) evolution with mass loss, for metal mass fractions from $Z = 2 \times 10^{-4}$ to $Z = 4 \times 10^{-3}$. The Hot Bottom Burning (HBB) at the base of the convective envelope is followed by fully coupling nuclear burning and non instantaneous mixing. The models also show the occurrence of a spontaneous (not induced by overshooting) third dredge-up. For the first time we find that temperatures close or even larger than $10^8$K are achieved at low $Z$: the full CNO cycle operates at the basis of the envelope, the $^{16}O$ abundance for the most metal poor models of mass 4 and 5 $M_\odot$ is drastically reduced, and sodium and aluminium production by proton capture on neon and magnesium can occur. Lithium is first largely produced in the envelope and then burned completely, so the average lithium abundance in the expelled envelope is a factor up to 5 times smaller than the initial one, but it is never completely depleted.

These results may be relevant for the evolution of primordial massive Globular Clusters: we suggest that the low mass stars may have been polluted at the surface by accretion from the gas lost from the evolving intermediate mass stars at early ages ($1-2 \times 10^8$yr). In this hypothesis, we should expect that the polluted stars show smaller abundance of oxygen, larger abundances of products of advanced nucleosynthesis as Na and Al, and lower, but never negligible, abundances of lithium. The abundance spreads should be smaller in clusters of higher metallicities, where the lithium in the polluted stars could be larger than in the non polluted stars.

Subject headings: stars: abundances — stars: AGB and post-AGB — stars: evolution
1. Introduction

In recent years, determination of chemical abundances in Globular Cluster stars has confirmed the inhomogeneity of their surface composition for what concerns the abundances of the light elements from lithium to aluminium (see, for reviews, Smith 1987 and Kraft 1994). In particular, red giants in some GCs show a Na–O anticorrelation (e.g. Kraft et al. 1997) which seems the clear sign of ‘in situ’ processes, by which some still unexplained deep mixing mechanism brings at the stellar surface the products of complete CNO cycling occurring deep in the stellar interiors (e.g. Langer, Hoffman & Sneden 1993). This hypothesis is until now not confirmed by computation of adequate stellar models. In addition, the deep mixing should take place only in GC stars, as the analogous stars in the field are much more homogeneous in abundances.

Also the lithium abundances at the Turnoff (TO) of some GCs show spreads which are larger than the spread among similar halo stars (King, Stephens & Boesgaard 1998; Pasquini & Molaro 1997), which, in the range of GCs metallicities, are known to be very homogeneous ($\log N(Li) = 2.24 \pm 0.05$, Bonifacio & Molaro 1997; see also Ryan, Norris & Beers 1999), possibly indicating that we are witnessing the abundance left by the Big Bang nucleosynthesis. Of course, any lithium spread can not be linked with simplicity to advanced nucleosynthesis, being lithium a very fragile element, which would be completely destroyed at the temperature necessary to produce sodium. In addition, for any spread of abundances at the TO, it is not possible to invoke ‘in situ’ mechanisms, apart from gravitational settling and thermal diffusion (e.g. Chaboyer et al. 1992). In this context, Gratton et al. (2001) have obtained recently very important results: the TO and subgiant stars in the GC NGC 6752 show an oxygen spread anticorrelated with sodium, and a Mg-Al anticorrelation, which certainly can not be explained by any ‘in situ’ process.

A different model for the GC stars inhomogeneities, not necessarily alternative with
the ‘in situ’ scenario (see, e.g. Denissenkov et al. 1998), has been put forward in the eighties: the ‘selfpollution’ or ‘self-enrichment’ hypothesis. The idea is that the field stars and the GC stars are born in a very different environment which plays a role in their evolution. The surface composition of the GC stars which we see today evolving, in fact, may have been contaminated by accretion from the ejecta of more massive stars which have evolved during the past history of the cluster. Cottrell & Da Costa (1981) suggested that the observed sodium and aluminium variations were the results of reactions occurred in an early generation of intermediate mass stars. These stars are also the best candidates to produce accretion on the already formed stars. In fact, we would not expect accretion on stars from possible supernova ejecta; in addition, we already know that today there is practically no gas or dust in the center of GCs, probably due to the strong UV flux from blue Horizontal Branch and post-AGB stars, which helps in removing the mass lost from red giants (Faulkner & Freeman 1977).

However, the intermediate mass stars (M ≃ 3 – 6 M⊙) lose mass by low velocity stellar winds, which can remain into the cluster, if it is massive enough, and concentrate in the core. These stars, in addition, suffer a very fast evolution through the hot Planetary Nebulae region, before becoming white dwarfs (Wood & Faulkner 1986, Vassiliadis & Wood 1994), so that their input UV energy is not enough to expell the gas. In these conditions, the low mass stars, passing through the central regions of the GC, may accrete it in appreciable quantities. This hypothesis was put forward first by D’Antona, Gratton & Chieffi (1983). Gratton (2001) has recently elaborated on this idea. An additional important feature of such a model is that the massive AGB stars have a very interesting envelope nucleosynthesis, as the basis of their convective envelopes becomes very hot during the evolution: they suffer ‘Hot Bottom Burning’ (HBB), which mainly produces -and burns- lithium, and cycles the CNO elements.
The interesting novelty in the self-pollution scenario is that today we are able to predict the main composition of the ejecta of the intermediate mass AGBs, as a function of the metallicity, by means of new, sophisticated models. We can in fact model in detail the Thermal Pulse phase, and have developed a code which can follow selfconsistently the chemical mixing and nuclear burning in the envelope. Further, we have been able to calibrate the mass loss during the AGB phase, based on observational properties of such AGB stars in the Magellanic Clouds. Before embarking in a detailed study of the modalities of the gas dynamics and of the accretion process, we first compute the nucleosynthesis expected in these stars, and therefore the possible main elements and isotopic ratios variations as a function of the initial mass and metallicity. We follow the evolution until the envelope mass is reduced to a relatively small fraction of the initial mass, and the models are reasonably close to the planetary nebula phase.

We have specifically computed the evolution of lithium, carbon isotopes, nitrogen and oxygen isotopes for intermediate mass stars ($3 \leq M/M_\odot \leq 6.5$), having metals mass fractions from $Z= 2 \times 10^{-4}$ to $Z = 0.01$. Full description of the results and the elements yields will be given in a forthcoming paper. We describe our models in Section 2, their input physics and important differences with previous computations. Section 3 shortly presents the results and Section 4 summarizes the possible main observational predictions.

2. The models

We have developed new models of TP AGB stars in the phase of Hot Bottom Burning (Mazzitelli, D’Antona & Ventura 1999). For a detailed description of the input physics see also Ventura, D’Antona & Mazzitelli (2000). In these models we follow in detail the nucleosynthesis of 14 elements ($^1H$, $^2D$, $^3He$, $^4He$, $^7Li$, $^7Be$, $^{12}C$, $^{13}C$, $^{14}N$, $^{15}N$, $^{16}O$, $^{17}O$, $^{18}O$, $^{22}Ne$) and 22 associated nuclear reactions. We do not follow therefore the detailed
nucleosynthesis of trace elements, but the decrease in the $^{16}O$ abundance, and the increase of $^{17}O$ monitor when the complete CNO Cycle is active. **For the phases of Oxygen cycling, the physical conditions at the envelopes bottoms are such that they allow production of sodium by burning of the original $^{20}Ne$ and $^{22}Ne$, and of aluminium through burning of the magnesium isotopes (e.g. Langer et al. 1993), but we cannot give quantitative estimates for the expected anticorrelations O-Na and Mg-Al. We are now planning computations including a network of 30 isotopes to solve the problem selfconsistently.**

The detailed lithium nucleosynthesis is followed directly in the evolutionary models, in which first the lithium remnant from the previous possible dilution phases is destroyed, then fresh lithium is produced through the reaction $^3He + ^4He \rightarrow ^7Be \rightarrow ^7Li$ (the ‘Cameron Fowler’ mechanism —Cameron & Fowler 1971), and finally it is burnt completely when the $^3He$ of the envelope is fully depleted. To follow selfconsistently the nuclear evolution, we use a scheme which couples the nuclear burning and chemical mixing in the envelope, as first included in full stellar models by Sackmann & Boothroyd (1992).

These are the first models which provide fully evolutionary results of nucleosynthesis by HBB in AGB for metallicities as low as the GCs metallicities. Detailed results for AGBs of $Z=0.02$ and $Z=0.005$ have been published by Forestini & Charbonnel (1997), but they followed explicitly only a few TPs and adopt an extrapolation for the rest of the evolution. Their models differ from ours in the choice of the treatment of convection\footnote{We adopt the ‘Full Spectrum of Turbulence’ (Canuto & Mazzitelli 1991) convection, in the formulation by Canuto, Goldman & Mazzitelli (1996). This model predicts HBB temperatures larger than in the solar-calibrated Mixing Length model adopted by Forestini & Charbonnel (1997), see D’Antona & Mazzitelli (1996). However, we tested that also MLT models with a solar calibrated mixing length reach very large HBB temperatures for the}
of a mass loss formalism, which probably underestimates mass loss. Denissenkov et al. (1998) also consider detailed nucleosynthesis in AGBs as possible source of self-pollution in GCs, but they adopt a ‘parametrized nucleosynthesis’ approach and do not compute full evolutions. The yields obtained do not depend sensibly on the mass loss formulation and on its calibration, apart from the lithium yield. We adopt Blöcker (1995) schematization for mass loss, and have recently sorted out a way of calibrating its free parameter on the basis of the Magellanic Clouds observations (Ventura et al. 2000), showing that the lithium yield varies more or less linearly with the mass loss rate. We make here the hypothesis that this calibration holds also for lower metallicity stars.

Among the other elements, we follow the carbon and nitrogen evolution. These abundances are affected by the occurrence of the ‘third dredge up’ (Iben 1975) of carbon from the helium shell. This process produces, at lower luminosities, the phenomenon of Carbon stars. The masses we consider here, due to the HBB, cycle carbon to nitrogen and do not appear as Carbon stars even if the third dredge up is operating. This process is however still not well understood: for the solar chemistry, most models, including ours, need a treatment of overshooting below the formal convective envelope to produce Carbon stars in the range of luminosity and metallicities for which they occur in nature. We have considered models in which Carbon stars are formed, by allowing a detailed consideration of non-instantaneous mixing by ‘overshooting’ (Ventura, D’Antona & Mazzitelli 1999), but we did not include this treatment in the present models, as at low metallicities the models achieve the third dredge up spontaneously. As we do not include overshooting below the convective bottom, however, our carbon and nitrogen abundances are to be considered as lower limits. Notice that the surface helium in these stars is not particularly peculiar: helium dredge-up in the HBB phase is negligible (contrary to the lowest computed metallicities and deplete oxygen.
models in which deep mixing is artificially enforced to explain ‘in situ’ the peculiarities of GC red giants, e.g. Weiss, Denissenkov & Charbonnel 2000). However these stars have suffered the second dredge up, so the helium content of the ejecta is $Y \sim 0.29$, to be compared with the initial $Y = 0.23$. Details will be published elsewhere.

3. Results

In presenting the results in the figures, we show the physical quantities along the computed evolutions as a function of the total ‘mass’, which is decreasing due to mass loss. In this way, we also have an immediate understanding of how much a phase is important for the chemical yields. Figure 1 shows the temperature at the bottom of the convective envelope ($T_{bce}$) along the evolution of models of 4, 5 and 6 $M_\odot$ (Z=0.01, left) and 3, 4 and 5 $M_\odot$ (Z=2×10$^{-4}$, right).

We notice that $T_{bce}$ for the same initial mass is larger the lower is the metallicity. The most massive and metal poor models reach surprisingly large values of $T_{bce}$, although we do not allow for any kind of overshooting below the formal convective region. Above $T_{bce} \approx 8 \times 10^7$K the CNO cycle is complete, and oxygen becomes depleted. Fig. 2 shows the evolution of the ratio between the surface oxygen abundance and the initial value for stars of 5$M_\odot$ for the computed metallicities. We see that for Z=0.01 the abundance when the total mass is reduced to $\sim 2M_\odot$ is not different. Depletion is more important for Z=4×10$^{-3}$ and 10$^{-3}$. The track of 2×10$^{-4}$ shows an initial reduction by a factor $\sim 100$, which in later phases is reduced to a factor $\sim 10$. Although our computations do not include the nucleosynthesis past oxygen, the drastic reduction of $^{16}O$ with the $^{17}O/^{16}O$ increasing up to $\sim 0.17$, indicates that we are in the presence of a very advanced nucleosynthesis. At these temperature and densities, Na and Al are produced by proton capture on the neon
and magnesium nuclei respectively.

Figure 3 shows the surface lithium as a function of the mass for the metallicities \(Z=4 \times 10^{-3}\) and \(2 \times 10^{-4}\). Assuming that all these stars start with an initial abundance equal to the population II abundance \(\log N(Li) = 2.2\), there is a short phase in which lithium is overproduced by a factor up to \(\sim 60\), followed by a more prolonged phase in which it is depleted by a factor \(\sim 10^4\). In the computation of the total yield, however, the phase of production is very important to balance the following total destruction. As a final result, lithium is depleted with respect to the Big Bang abundance, by a factor 4-5 at the lowest metallicities. At the lowest \(Z\), the phase of \(^7\)Li production lasts for a shorter time. In addition, the radii are smaller and the mass loss rate is lower. As a result, the total lithium depletion in the ejecta is maximum. In fact, at \(Z = 4 \times 10^{-3}\) the expected depletion is by at most a factor 2.

Figure 4 shows the lithium abundance in the ejected envelopes, as a function of the metallicity, including also the models for \(Z=0.01\) computed in Ventura et al. (2000). The horizontal line shows the ‘primordial’ abundance. This should surely apply to the most metal deficient GCs. We see then that for these clusters we expect that the polluted stars (in which oxygen is smaller) should have also a smaller lithium abundance.

For more metal rich GCs, such as, e.g., 47 Tuc, which has a metallicity of \(\simeq 4 \times 10^{-3}\), the situation is more complex. The scarce available data on lithium (see, e.g., the compilation by Romano et al. 1999) seem to indicate a value somewhat larger than the plateau value (\(\sim 2.3 - 2.4\)). Of course, the lithium in the halo stars at this metallicity may differ from the value in a GC. If we assume that the initial lithium at \(Z=4 \times 10^{-3}\) is still close to the Spite plateau, we see that the gas of the polluting stars is expected to be of a quite similar or scarcely smaller abundance. Our mass loss calibration must be believed only within a factor two or three, and this would alter the lithium abundances by the same factor, by
enhancing or reducing the mass loss rate in the phases of lithium production (Ventura et al. 2000). We might then expect in metal rich massive GCs either a lithium spread similar to that expected for low metallicity -if the initial lithium is a bit larger than the plateau value-, or the opposite behaviour: namely that the polluted stars have a lithium abundance larger than the initial one.

Notice that the lithium abundance in the ejecta is never very large, not even for the largest metallicities. This in fact was one of the results of our calibration of the mass loss rate (Ventura et al. 2000), and shows that massive AGB stars are not important contributors to the galactic lithium enrichment (Romano et al. 2001).

4. Predictions

If the self-pollution model is relevant for GCs, we can derive from our models some predictions:

• Metal poor GCs should show the largest spreads of abundances, and in particular a spread in oxygen, anticorrelated with Na, and probably an anticorrelation Mg–Al also, similar to what would be expected by ‘in situ’ very deep mixing in the advanced giant branch phases.

• Contrary to the expectation of the ‘in situ’ nucleosynthesis, these abundance anomalies are expected to be present also at the main sequence or on the subgiant branch. The results by Gratton et al. (2001) on the anticorrelation oxygen–sodium and magnesium–aluminium for turnoff and subgiant stars in the massive GC NGC 6752 are in agreement with this model.

• An interesting test to understand whether the oxygen variations are due to pollution from the envelopes of intermediate mass stars would be the detection of lithium
abundance correlated with the oxygen abundance. The process should in fact produce a spread in the lithium, of the same order, or smaller, than the oxygen variations. Fully CNO cycled stellar matter is characterized by a huge lithium depletion, but the envelopes of the polluting stars have also passed through a phase in which lithium had been extensively produced by consumption of the envelope $^3$He, and some of the mass processed in this way has been lost by wind. The ‘normal’ lithium detection of two turnoff stars in 47Tuc (Pasquini & Molaro 1997), which have significantly different (anticorrelated) CH and CN, are compatible with this model.

- The most metal rich clusters should be characterized by smaller degrees of elemental variations, but some correlation oxygen – lithium should remain. In fact, as we can not trust completely our mass loss calibration, it is well possible that the polluted stars present a lithium abundance larger than the initial one.

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Fig. 1.— We show the temperature at the bottom of the convective envelopes as a function of the stellar mass, along the evolution of stars of 6, 5 and $4 \, M_\odot$ ($Z=0.01$, left panel, from Ventura et al. 2000) and 5, 4 and $3.5 \, M_\odot$ ($Z=2 \times 10^{-4}$, right panel). Notice that $T_{\text{bce}}$ is over $10^8 \text{K}$ at the lower metallicity.

Fig. 2.— Logarithm of the Oxygen abundance with respect to the initial $^{16}O$ value along the evolution of stars of $5 \, M_\odot$ with different (labelled) metallicities. Models with $Z=0.01$ were taken from Ventura et al. (2000).

Fig. 3.— Lithium abundance along the evolution, for $Z=2 \times 10^{-4}$ (right) and $Z=4 \times 10^{-3}$ (left). Notice first the Lithium production due to HBB, then the drastic Lithium depletion, when the envelope $^3\text{He}$ is exhausted. Note the rapid drop of the lithium abundance following each pulse, due to the decrease of the temperature at the base of the envelope, which stops lithium production.

Fig. 4.— Lithium abundance in the ejected envelopes as function of the initial mass and metallicity. The maximum Lithium depletion with respect to the horizontal line, representing the primordial abundance, is by a factor $\sim 5$ for the $5 \, M_\odot$ of $Z=2$ and $6 \times 10^{-4}$. These abundances depend on the mass loss rate, which has been carefully calibrated for $Z=0.01$ (Ventura et al. 2000). Smaller rates can apply to the more metal poor environments, leading to a more or less proportional decrease in the ejected abundance.
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