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Yields from low metallicity, intermediate mass AGB stars:

Their role for the CNO and lithium abundances in Globular Cluster stars

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Abstract. We present the results of extensive computation of the Thermal Pulse phase AGB evolution of stars of metallicities in mass fraction $2 \times 10^{-4} \leq Z \leq 0.01$, for those masses in the range $2.5 \leq M/M_\odot \leq 6$, which suffer the Hot Bottom Burning (HBB) phase. The evolution is fully computed, by assuming a mass loss rate consistent with the observations of the Magellanic Clouds lithium–rich stars, and modelling convection with the Full Spectrum of Turbulence model by Canuto and Mazzitelli. The results are discussed in the framework of their importance for the evolution of proto–Globular Clusters, whose spectra show that the stars are very probably formed from matter contaminated by the ejecta of these stars, or have accreted it after formation. The main results we find are the following: 1) for metallicities $Z \leq 10^{-3}$, masses above $\sim 4\ M_\odot$ suffer complete CNO cycling in HBB, so that they show at the surface the result of this process, and the oxygen abundance is reduced; 2) most models suffer the third dredge up. Although carbon is processed to nitrogen by HBB, the oxygen burning is so strong in the lowest metallicities (2×10^{-4}) that *carbon becomes more abundant than oxygen*: in other words, low-metallicity intermediate mass stars may show up as carbon stars due to the drastic oxygen burning; 3) if Globular Cluster stars are contaminated by matter processed through these phases, *we must expect a non negligible helium enhancement* in their composition: from a Big Bang abundance $Y = 0.24$, e.g., we might expect an abundance $Y = 0.28$. This may have no practical consequences if pollution concerns only the *external parts* of the stars, but is very important if the stars formed as a whole from a helium rich environment. 4) The lithium yields, although not important for galactic chemical evolution, are very interestingly close to the initial Big Bang abundance: processing by HBB is the only way in which we can obtain substantial amounts of gas which have gone through full CNO burning, but preserve a reasonable abundance of lithium.

Key words. stars: AGB and post-AGB – ISM: abundances – globular clusters: general

1. Introduction

It is more than 20 years that we know that in many GCs there are inhomogeneities in the CNO chemistry. While this was fully clear for the red giants (see references in Kraft 1994 and Cannon et al. 1998) and there were already hints that similar inhomogeneities could be present in the subgiants and even at the turnoff (TO) – e.g. Bell et al. (1983), Briley et al. (1991) (for 47 Tuc), Carbon et al. (1982) (for M92), Suntzeff & Smith (1991) (for NGC 6752) –, recent high-resolution spectroscopic data confirm that the inhomogeneities are also present at evolutionary stages in which no non-canonical deep mixing mechanism can be taken into serious consideration. In particular, even the oxygen – sodium anticorrelation found for red giants (Kraft et al. 1993) has now been confirmed for the TO and subgiants of NGC 6752 (Gratton et al. 2001). A common interpretation of the abundance spreads is that either the gas from which the GC stars formed (Cottrell & Da Costa 1981), or the stars themselves (D'Antona et al. 1983), have been contaminated by the ejecta of matter processed through HBB (selfpollution). This hypothesis is still to be explored with quantitative models (see, e.g. Thoul et al. 2002 for a preliminary approach), but first of all it is necessary to understand in detail the chemistry of the possible contaminating matter.

An appealing possibility to explain the complex patterns of GC stellar abundances is that pollution is provided by the ejecta of a generation of intermediate mass AGB stars. In this context, it is important to follow the evolution through Thermal Pulses (TPs) of these stars, as a function of their initial metallicity and mass, to begin to develop more precise hypotheses on the possible chemical evolution of proto GCs.

Theoretical models of HBB at the bottom of the convective envelopes of massive have been first developed to reproduce the observations of these stars in the Magellanic Clouds

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(Smith & Lambert 1989, 1990; Plez et al. 1993), which show that most of the luminous AGBs are lithium rich. The temporary enhancement of lithium in the atmosphere can be achieved by the chain ^{3}He + ^{4}He $\rightarrow$ ^{7}Be $\rightarrow$ ^{7}Li, provided that non-instantaneous mixing is allowed for in the models (Cameron & Fowler 1971). Both the computations achieved by considering only envelope models (Sackmann et al. 1974) and those of full evolutionary models (Sackmann & Boothroyd 1992) were successfull in providing lithium production consistent with the observations. In addition to the lithium formation, nuclear processing by HBB is very important, as it contributes to the chemical evolution of the Galaxy (Renzini & Voli 1981). Unfortunately, the yields are dependent on two main uncertain physical inputs of these stars, namely the modelling of mass loss, and the efficiency of convective transport. For these parameters, we can try to use semiempirical calibration, but we must accept to extrapolate the adopted calibrations for a range of metallicities for which no experimental data are available.

In this paper, we deal with the results of our extensive computation of the Thermal Pulse phase AGB evolution of stars of $2 \times 10^{-4} \leq Z \leq 0.01$, for those masses in the range $2.5 \leq M/M_\odot \leq 6$, which suffer HBB. Partial results have already been presented elsewhere (Ventura et al. 2000, hereinafter VDM00, Ventura et al. 2001 –VDMG01– Romano et al. 2001). We have recently shown (VDMG01) that, for metallicities from 2×10^{-4} to 10^{-3} the HBB temperatures of the most massive AGB stars are so large that the full CNO cycling is operating. This means that the matter lost from these stars is oxygen poor, and may play an important role in the selfpollution. It is then crucial to fully show the qualitative and quantitative model results, to explore their implications for the chemical composition of GCs.

In the following Sect. 2 we summarize the physical inputs of the models, the assumptions for convection and the calibration of the mass loss rate. Sect. 3 underlines the main results for lithium, helium and CNO isotopes, showing the evolution of models of different mass and metallicity, and the chemistry variations along the evolution. We show that the third dredge-up is achieved in these stars, in spite of adopting the strict Schwarzschild criterion to fix the boundaries of convective regions, as already found in other independent computations (Straniero et al. 1997). We show that oxygen is depleted, especially at the lowest metallicities and for the most massive star models. In addition, we find that the $Z = 2 \times 10^{-4}$ stars have such a strong oxygen burning that *they become carbon stars* mainly because of the oxygen depletion. In Sect. 4 we present in table and plots the yields from these computations and discuss them in terms of mass and chemistry, for the main constituents. Section 5 discusses again the galactic lithium evolution, and resumes the main constraints which these results pose on models of selfpollution of Globular Clusters.

2. Input of the models

We remind that we compute *complete evolutionary models* starting from the pre–main sequence, and following all the phases of stellar evolution up to the thermal pulse phase in a self–consistent way. This is the basis necessary to get any quantitatively meaningful population synthesis. Full stellar models are also needed to understand how a change in the physical inputs may modify the models, and consequently may modify a population synthesis approach. The input physics of the models has been described in several previous papers. The numerical structure of the ATON2.0 code, as well as a complete description of the physical inputs, can be found in Ventura et al. (1998). The description of the modeling of lithium production is in Mazzitelli et al. 1999 (MDV99). The diffusive scheme which is adopted to calculate selfconsistently the nuclear processing in the convective envelope is described in VDM00, together with the approximation adopted for the overshooting from the formal convective regions. Here we describe the treatment of the most crucial macrophysics inputs.

i) Treatment of convection: many researchers have shown that the modalities of HBB depend on the convection model adopted to describe the stellar structure: the more efficient is convection, the smaller is the mass which can achieve lithium production (e.g. MDV99). Models employing the "Full Spectrum of Turbulence" (FST) model by Canuto & Mazzitelli (1991) achieve HBB for $Z = 0.01$ at 3.5 $M_\odot$ while MLT models with relatively small mixing length to pressure scale height ($\alpha = l/H_\mathrm{p}$) achieve it only at masses $\gtrsim 4.5\ M_\odot$. In this paper, we adopt for convection the FST model by Canuto et al. (1996). In spite of being a local model, our experience with this convection treatment shows that it provides a good performance, both for stars with quite small convective regions, where convection is inefficient, and for stars with deep and highly efficient convection (D'Antona et al. 2002).

ii) Overshooting: the extent of overshooting during the previous evolutionary phases is a crucial parameter: models with core–overshooting, in fact, have a larger C–O core mass at the beginning of the TP phase than models of the same mass and chemistry, not including overshooting. Consequently, their luminosity is larger, and smaller initial mass can achieve HBB. VDM00, for a metallicity $Z = 0.01$, find e.g. that the inclusion of overshooting in the stellar models (which mainly enlarges the helium core mass at the beginning of the TP phase) lowers by $\sim 0.5\ M_\odot$ the minimum mass which can achieve HBB.

Another important, but still very uncertain input of the models is the degree of overshooting below the convective region, if any, which may help in dredging up carbon and producing a C-star (Ventura et al. 1999; Blöcker et al. 2000; Herwig 2000). In this work, we do not include any overshooting below the convective envelope: nevertheless, dredge up from the helium layers actually occurs for the low-metallicity models. This has profound influence on the yields, as we will see. In terms of the dredge-up parameter λ, defined as the fraction of the increment of core mass over an interpulse period which is dredged-up to the surface at the subsequent thermal pulse, we find that the less massive models with metallicities $Z = 2, 6 \times 10^{-4}$ attain along their evolution values of λ as large as $\lambda \sim 0.5$, while models of the same metallicity with initial masses close to the limit for carbon-oxygen ignition in a not-degenerate core reach $\lambda \sim 0.3$. For higher metallicities ($Z \leq 10^{-3}$) we find slightly lower λ's, ranging from $\lambda \sim 0.2$, the maximum value obtained along the evolution of the massive models, up to $\lambda \sim 0.4$ ($M_\mathrm{ZAMS} \leq 4.5\ M_\odot$).

We consider that the amount of dredge up in these models is *the minimum* which occurs in nature: any overshoot will increase it. In summary, the computations presented in this work include only "asymmetric" overshooting, in the definition by MDV99: that is, overshooting only out of the hydrogen and helium burning core. Overshooting below the formal convective envolope is not included.

iii) Mass loss: the mass loss rate during the AGB phases is computed by Blöcker's (1995) formulation, which is based on Bowen's (1988) detailed numerical hydrodynamic and thermodynamic calculations carried out for the dynamic atmospheres of models for long period variables evolving along the AGB both for solar and smaller than solar metallicities (Willson et al. 1996). The mass loss rate $\dot{M}$ becomes strongly dependent on luminosity during the AGB evolution. Blöcker (1995) starts from the usual Reimer's formulation, which is inadequate to describe the fast increase of the mass loss rate during AGB, (e.g. Habing 1996) and introduces a further dependence on a power of the luminosity. The complete expression is:

$$\dot{M} = 4.83 \times 10^{-9} M^{-2.1} L^{2.7} \dot{M}_{\rm R} \quad (1)$$

where $\dot{M}_{\rm R}$ is the canonical Reimers rate expressed by $\dot{M}_{\rm R} = 4 \times 10^{-13} \eta_{\rm R} \frac{LR}{M}$, L, R and M being the luminosity, radius and mass of the star expressed in solar units. Tuning of the parameter $\eta_{\rm R}$ has been performed by VDM00, who conclude that $\eta_{\rm R} = 0.01$ is the best choice to be consistent with the observations of the Magellanic Clouds lithium–rich AGB stars (Smith & Lambert 1989, 1990; Plez et al. 1993; Smith et al. 1995). Of course this calibration is not "final", but at least it is not completely ad hoc. When we extend this calibration to chemistries different from the metallicity of the Magellanic Clouds, we add further uncertainty on the results.

2.1. How different are the results by changing the most critical parameters?

To get an idea of the difference which can be achieved in these models making one assumption or another, we show in Fig. 1 two very different evolutions for a star of 4.0 $M_{\odot}$ having $Z = 0.01$. The ^{13}C/^{12}C, CNO abundances, luminosity, and lithium are compared for the two cases. In the first case, we assume for the mass loss rate $\eta = 0.05$ and include overshooting below the convective region (see Ventura et al. 1999 and VDM00 for details). The second case has $\eta = 0.01$ and no overshooting (the assumptions made for all the present models). We see that the luminosity evolution and the thermal pulse behaviour is very different in the two cases: if overshooting from the base of the external convective envelope is accounted for, TPs become less frequent, due to the large penetration of the external mantle into the H-burning shell, mixing the products of CNO burning throughout the whole external region, thus delaying the accumulation of helium, which is essential to ignite the following TP. On the other hand, the larger mass loss rate implies smaller luminosities by $\Delta M_{\rm bol} \sim 0.3$–$0.4$ mag. Otherwhise, the *chemical* evolution is not as different as we could envisage: carbon dredge up is such that the global nitrogen abundance becomes a factor $\simeq$2 larger. The model with the larger η has a lower HBB temperature, so that oxygen is not touched, while it is reduced by $\simeq$0.1 dex in the $\eta = 0.01$ model. Otherwhise, the C/N and N/O abundance ratios are not very different. The most critical difference in chemistry is undoubted in *the total lithium yield*: as the lithium rich phase is very short lived, a factor five higher mass loss rate implies that *more lithium is lost during the phase in which it is produced*, so that the yield is more significant.

We conclude that the results presented in this paper can be taken as representative of the CNO abundances and abundance ratios in the matter lost from AGB stars, within a factor two or three, and that a special care must be taken when dealing with the lithium abundances.

2.2. Presentation of the results

In the classical definitions useful to study the galactic chemical evolution, it is common to present the resulting chemistry in terms of mass of the ejecta or of yield for each element. We follow here the notation by Maeder (1992) and Portinari et al. (1998), and denote by $E_i(M,Z)$ the mass in solar masses for the element i recycled to the interstellar medium by the star of mass M and metallicity Z.

We perform an integration of the quantity $X_i^{\rm surf}(M,t) \times \dot{M}(M,t)$ extended along the whole lifetime of the star during which the mass is lost, so it takes into account all the envelope mass lost until the star reaches the White Dwarf (WD) stage. Actually, we did not extend the computations to the planetary nebula ejection, so that we assume that the envelope remaining on the star at the end of the computations is ejected preserving for each element the final abundance $X_i^{\rm f}$. We indicate the mass of the star at the end of the computations as $M_{\rm rem}$, which is generally ~0.5–0.9 $M_{\odot}$ larger than $M_{\rm WD}$. The quantities $E_i(M,Z)$ are computed from our evolutionary tracks as:

$$\begin{aligned} E_i(M,Z) \; = \; & \int_{t_{\rm in}}^{t_{\rm WD}} [\dot{M}(M,t){\rm d}t] \times X_i^{\rm surf}(M,t) \\ & + (M_{\rm rem} - M_{\rm WD}) \times X_i^{\rm f}. \end{aligned} \quad (2)$$

Wind ejecta are calculated for H, ^{3}He, ^{4}He, ^{7}Li, ^{12}C, ^{13}C, ^{14}N, ^{16}O, ^{17}O, ^{18}O. For an easier understanding, we present in Table 1 the mass fraction abundances of the elements in the ejecta, that is

$$X_i(M,Z) = E_i(M,Z)/(M_{\rm in} - M_{\rm WD}). \quad (3)$$

Furthermore, to give a quick feeling of how important is the stellar processing, in the figures we will show also the ratio of abundance of the element i in the wind matter, with respect to the initial abundance, or we will plot the abundance in the ejecta and compare it directly with the initial abundance.

We have explored the mass range in steps of 0.5 $M_{\odot}$. For each composition, Table 1 contains the results for the stars which are massive enough to suffer HBB and not massive enough to ignite Carbon. As a reference point, the first line for each metallicity contains the solar-scaled abundances of the elements considered, with the only exception of lithium, for which we considered an initial abundance of 10^{-8} at the beginning of each evolution. Also, all the models presented here

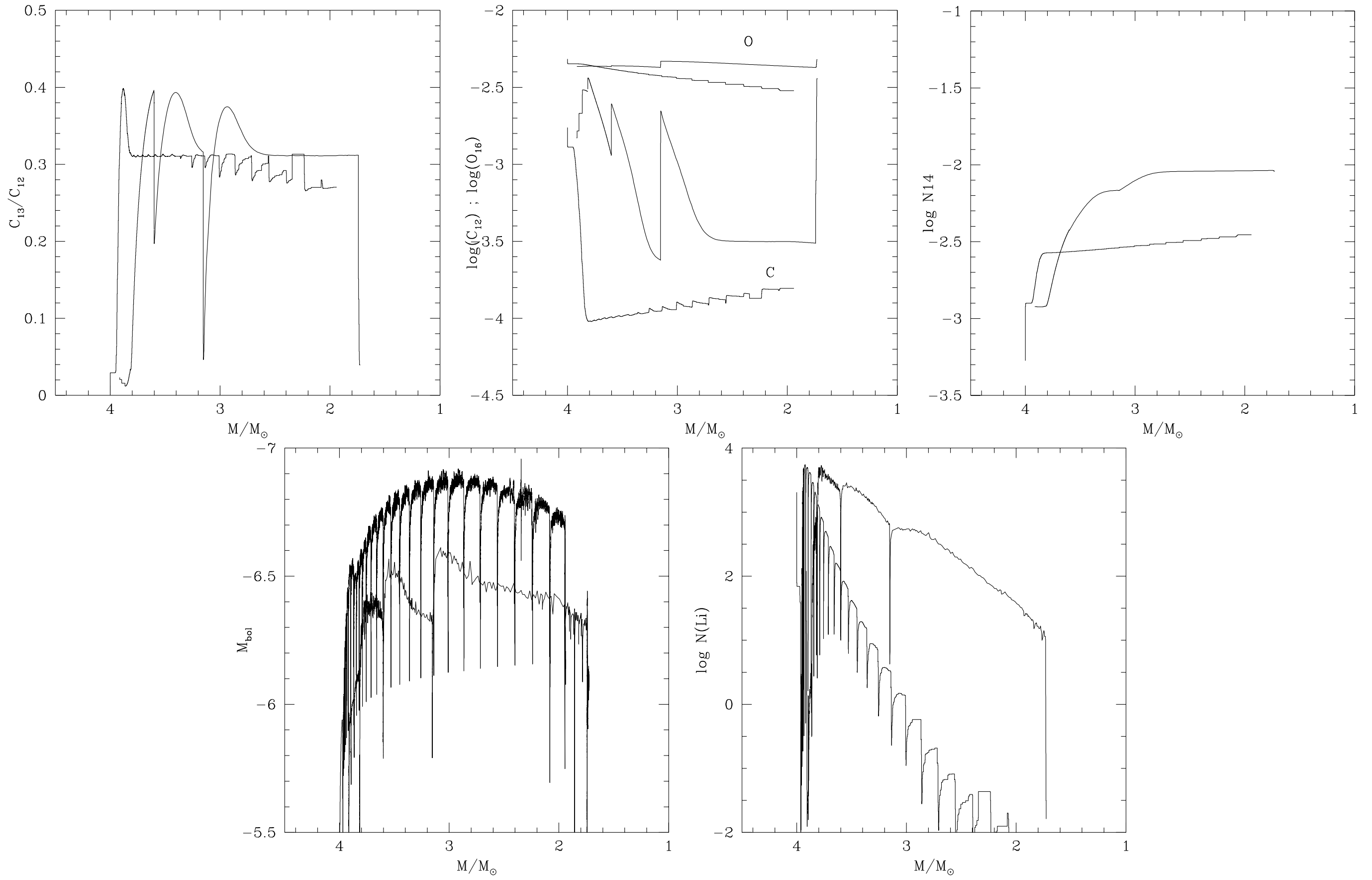

Fig. 1. Comparison of chemical abundances and luminosity, as a function of the total mass, along the evolution of a 4 $M_\odot$ having $Z = 0.01$. The case with the strongest mass loss ($\eta = 0.05$) is identified because the thermal pulses are very few, and dredge up of carbon is more effective due to the inclusion of overshooting below the hydrogen convection region.

have been calculated by assuming zero initial abundances of ^{3}He, ^{13}C,^{17}O and ^{18}O.

We will use two main plots: *i)* for a star of a given initial mass, we use as independent variable the mass along the evolution. For each element, this provides an immediate feeling of the "eye average" abundance in the ejecta; *ii)* in addition, we will plot the global results by showing the abundance in the ejecta as a function of the total mass.

3. Model results

3.1. The CNO abundances

Figure 2 shows the abundance of carbon, nitrogen and oxygen in the matter lost from four models having mass and metallicity labelled at the top of each frame. The CN cycle operates in all sequences, keeping the C/N ratio at its equilibrium value, although we see that dredge up is operating, and the carbon abundance (after a first initial drop) increases with decreasing total mass. We see that also oxygen is cycled to nitrogen: the extent of ON cycling is larger at smaller metallicities. In the $Z = 2 \times 10^{-4}$, 5 $M_\odot$ model, oxygen is so much reduced due to the very large HBB temperatures that the star is transformed in a carbon star along its whole AGB evolution! This phenomenon occurs also for the 6×10^{-4} 5.5 $M_\odot$ model, and barely occurs for the 5 $M_\odot$ of $Z = 10^{-3}$. Only in the models of $Z = 4 \times 10^{-3}$ oxygen is preserved at about its initial value for all masses. Nitrogen is enhanced by a factor as large as 30 for the lowest metallicities computed: taking into account that our models make very conservative assumptions on the third dredge up, we conclude that *the low-metallicity intermediate mass stars are important producers of primary nitrogen.*

Figure 3 shows the carbon and oxygen abundance along the evolution of a 3 $M_\odot$ of $Z = 2 \times 10^{-4}$. We see that this star becomes a carbon star in its "classic" definition, as the O abundance is not affected by HBB, but the C/O ratio becomes larger than unity due to the dredge up, *and in spite of the HBB*. We show an interesting consequence of HBB and of the careful treatment of non instantaneous mixing in the bottom panel of Fig. 3: the surface ^{13}C/^{12}C ratio is on average very large. Although it drops to low values at each episode of dredge up, HBB quickly brings it back to the equilibrium value. Consequently, low-metallicity, relatively high mass carbon stars will be characterized by a large ^{13}C/^{12}C, contrary to common expectations[1].

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[1] This result is consistent with the analysis of the very-low-metallicity star HE0024-2523 (Lucatello 2002 and references therein) whose atmosphere has been probably polluted by an AGB companion evolved now into a white dwarf, during a common envelope phase. The stellar abundances ([C/Fe]~ 2.6 and ^{12}C/^{13}C ~5) are broadly consistent with the predictions of the models shown here (if we take into account the smaller metallicity of the star).

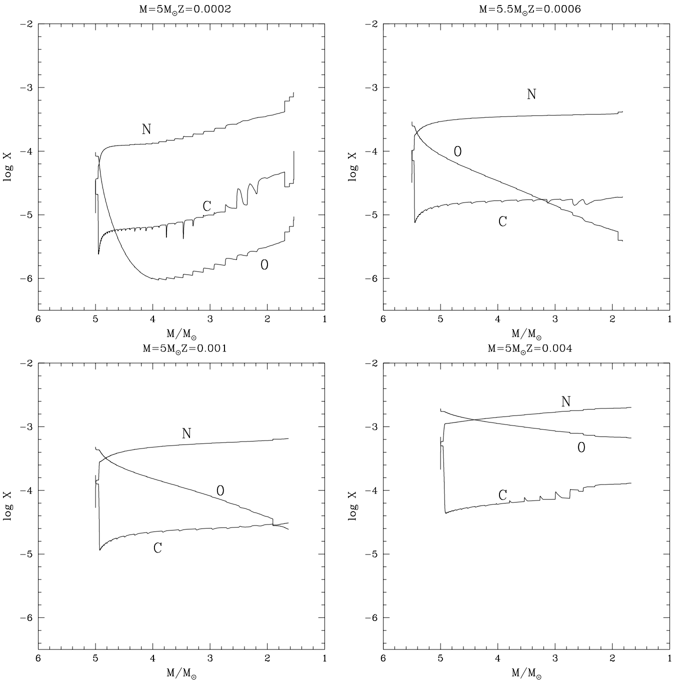

Fig. 2. The run of C, N and O along the evolution of the 5 $M_\odot$ (or 5.5 $M_\odot$ for $Z = 0.0006$). Notice that the oxygen depletion increases with decreasing metallicity. Carbon is slowly increasing along the evolution, due to the spontaneous dredge up shown by the models, but is cycled to nitrogen. Notice that, independently from this dredge up, *the* $Z = 0.0002$ *model becomes a carbon star* due to the strong oxygen depletion. This also occurs in the late stages of the 5.5 $M_\odot$ evolution for $Z = 0.0006$, but the global yield has C > O only for the lowest metallicity.

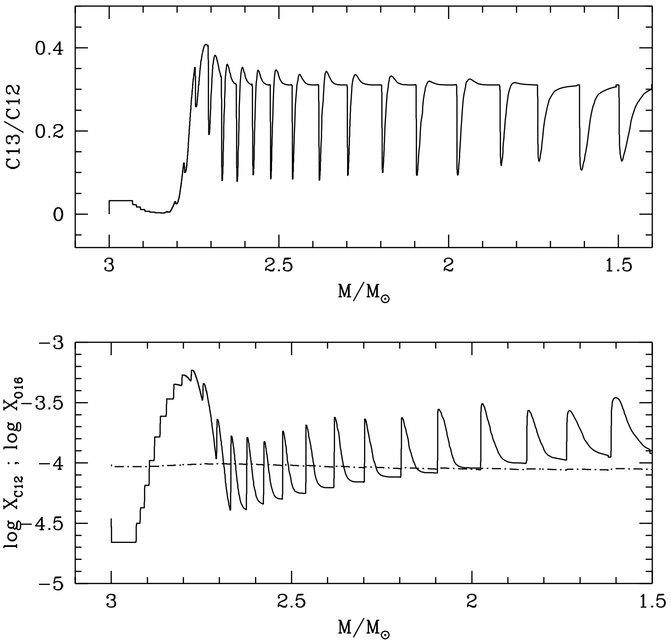

Fig. 3. The lower panel shows the carbon (full line) and oxygen (dot-dashed line) abundance along the evolution of a 3 $M_\odot$ having $Z = 2 \times 10^{-4}$. The top panel shows the ^{13}C/^{12}C ratio. Also lithium is produced in the first phases of the HBB evolution, but it is already depleted when the star becomes a carbon star (C/O >1).

Only in the models of $Z = 4 \times 10^{-3}$ oxygen is preserved at about its initial value for all masses. Notice that nitrogen is enhanced by a factor as large as 30 for the lowest metallicities computed, and remember that our models make very conservative assumptions on the third dredge up. Consequently, *the low-metallicity intermediate mass stars are important producers of primary nitrogen.*

3.2. The helium abundance

Fig. 4 shows the helium content in the ejecta, as a function of the initial mass. Helium is increased, mainly due to the second dredge up, which is generally present for the masses which suffer HBB. A small increase in the envelope helium is achieved also during the TP phase, if the third dredge up is operating, but this is much less important. For instance, in the 5 $M_\odot$ of $Z = 10^{-3}$, which has an initial $Y = 0.242$, the second dredge up brings the helium abundance to $Y = 0.286$, and the third dredge up during the TPs increases it up to 0.289.

3.3. The lithium abundance

The initial abundance assumed for lithium in the models is not important for the stellar energetics, so we have always assumed $\log N(\mathrm{Li}) = 3.2$, that is the population I abundance. However, lithium is generally depleted previous to the TPs, and the lithium yield is then not dependent on the assumed initial abundance, but only on its production and destruction during the AGB evolution, which is also the phase in which most of the stellar envelope is lost. For the lowest-metallicity stars considered, we may assume that they had initially the Big Bang lithium abundance, which we naively identify with the abundance at the surface of the population II field stars, $\log N(\mathrm{Li}) = 2.2 \pm 0.1$ (Bonifacio & Molaro 1997). The lithium yields obtained in this investigation have already been presented by VDMG01. The interesting characteristics of the HBB processing is that we are in the presence of matter which is highly CNO processed, even with dramatic oxygen reductions as in the case of $Z = 2 \times 10^{-4}$, while lithium is generally reduced, but by only a factor from two to six. This situation is typical *only for this kind of evolution: any other physical situation which may give origin to CNO cycled ejecta, will totally deplete lithium*. This peculiarity of AGB stars is due to the fact that they traverse a phase in which lithium becomes overabundant by a factor 100 or more, with respect to the initial abundance, and even if they lose only a small fraction of the mass when lithium is so high, this lithium–rich matter has a high weight in determination of the final average abundance in the ejecta.

On the other hand, we have seen in Fig. 1 that the assumptions on the mass loss are crucial to determine the final exact lithium abundance: in fact, if the mass loss rate is very high just when lithium is produced, the matter lost will be very lithium rich. We will discuss this problem in Sect. 6.

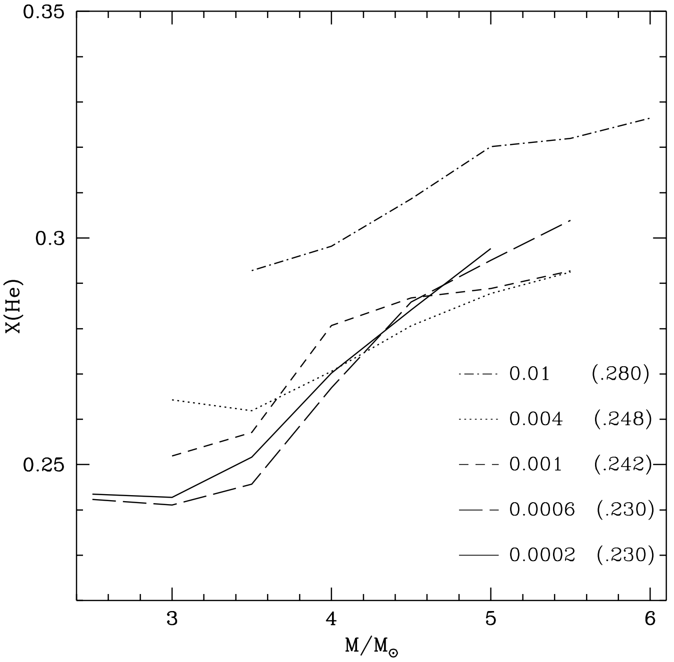

Fig. 4. Helium abundance in the matter lost, for the computed Z, as function of the total initial mass. The initial assumed helium abundance is given in parenthesis for each labelled metallicity.

4. The global results

Figure 5 shows the abundance of the CNO elements in the ejecta as open squares, and the initial (solar scaled) assumed abundances as black squares, to provide an easy feeling of the importance of processing for each element. Two masses (4 and 5 $M_{\odot}$) are shown, each represented by an open square (the larger mass shows more processed material). Figure 6 shows the logarithmic difference for the abundance of elements from ^{4}He to ^{17}O for the models of 5 $M_{\odot}$ of different metallicity. The helium enhancement is only by a few percent and does not appear clearly from this figure. Lithium is depleted by a factor 6.3 for $Z \leq 6 \times 10^{-4}$, but only by a factor 2–3 for $Z \geq 10^{-3}$. We regard this number as uncertain by as much as a factor three or four: if the mass loss rate is a factor three larger than what we have assumed, e.g., the lithium abundance is at most reduced by a factor two for the lowest Z, and it becomes larger than the initial abundance for $Z = 0.004$. Carbon is always reduced, by a factor 3 to 10, in spite of the third dredge up. Being this latter more efficient at low metallicity, the larger carbon abundance comes from the $Z = 2 \times 10^{-4}$ models. ^{13}C is always very much enhanced, the ratio ^{13}C/^{12}C is close to the equilibrium CN value of 0.3. ^{14}N is obviously enhanced, from a factor 6 to 20, the largest value being reached for the lowest metallicities, due to the more efficient ON processing, *oxygen is always reduced*: by a mere factor ~2 for the $Z = 4 \times 10^{-3}$ track, to a huge factor 25 for the $Z = 2 \times 10^{-4}$ track. The ejecta for 2×10^{-4} are definitely more carbon than oxygen rich. For $Z = 6 \times 10^{-4}$ carbon is still a bit larger than oxygen. At $Z = 10^{-3}$ we recover C/O < 1.

We have already discussed that the abundance in the ejecta are dependent on several input parameters: An inspection of Fig. 2, however, shows that the most critical result we obtain, namely the characteristic "carbon star type" of the matter lost from the massive lowest metallicity matter, does not depend on the efficiency of the third dredge up, but on the assumed efficiency of convection, from which the amount of oxygen cycling depends.

5. Model predictions

5.1. Rediscussion of the galactic chemical evolution of lithium

Based on the lithium yields from these models, Romano et al. (2001) have computed the galactic chemical evolution of lithium and concluded that the massive AGB stars *do not* contribute significantly to the lithium galactic enrichment, contrary to previous suggestions. D'Antona & Matteucci (1991) had first introduced the AGB stars in the lithium chemical evolution, based on the recent (at the time) observations of the lithium-rich luminous AGB stars in the Magellanic Clouds. The yields they used were mainly educated guesses on the possible production by these stars. With those generous yields, D'Antona & Matteucci (1991) concluded that AGB stars were indeed important lithium producers. For similar assumptions, Matteucci et al. (1995) obtained the same result. The present models, full evolutionary computations, and not educated guesses, on the contrary suggest that the lithium yields of massive AGBs are not so important (VDM00, Romano et al. 2001). Very recently, Travaglio et al. (2001) have re–examined the role of AGB stars in the galactic lithium evolution, based on their own models, finding a result at variance with Romano et al. (2001), that is, they conclude again that AGBs are important contributors to the lithium content of population I stars.

It is necessary then to clarify why Romano et al. (2001) and Travaglio et al. (2001) get so different results. Although the study of galactic chemical evolution needs a mixture of ingredients, some of which are not well known and must be guessed, the mass loss rate during important evolutionary phases can not be considered a totally free parameter. Travaglio et al. (2001) obtain interesting yields from their model computations by assuming a "superwind" mass loss *which occurs at the same time* of lithium production. They adopt the nucleosynthesis from a unique set of models (which are not computed with this high mass loss) and assume that the models do not vary too much with the mass loss prescriptions. We have shown, with the help of Fig. 1, that this is not a bad approximation for the lithium evolution (at least until we change the mass loss rate in our own models by a mere factor 5, from $\eta = 0.01$ to $\eta = 0.05$). More complete is Table 1 in VDM00, which shows that the lithium yield from our models increases by a factor 5 with respect to the the "standard" models of $\eta = 0.01$, if one adopts $\eta = 0.1$. *Not even the value* $\eta = 0.1$ *however, is sufficient to give a significant galactic contribution to lithium, as shown by Romano et al. (2001, their Fig. 3).* Of course, an ad hoc mass loss artificially enhanced exactly at the lithium production peak may give a more important production, as shown by Travaglio et al. (2001), but would require computation of full models to be confirmed. However, *such a huge mass loss would be inconsistent with the observations of the luminous Li–rich AGB*

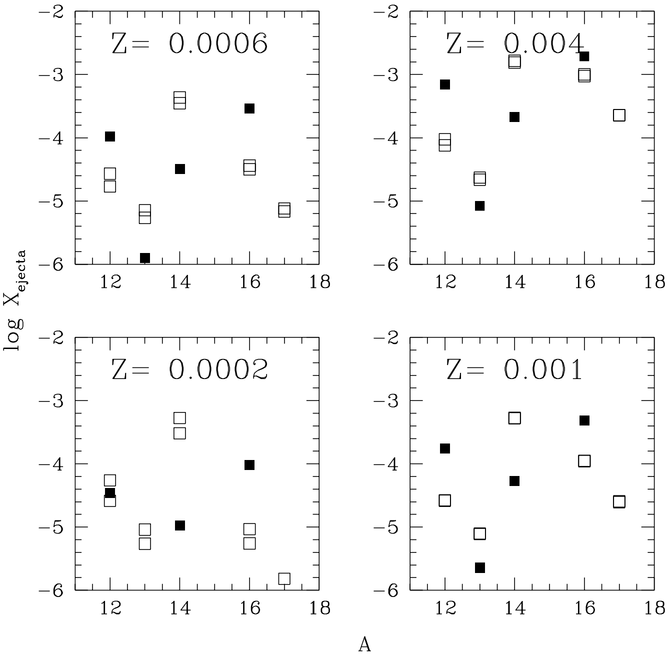

Fig. 5. Abundances for the elements from ^{12}C to ^{17}O in the ejecta of 4 and 5 $M_{\odot}$ stars, compared with the (solar scaled) initial abundances. The more massive star shows more extreme processing.

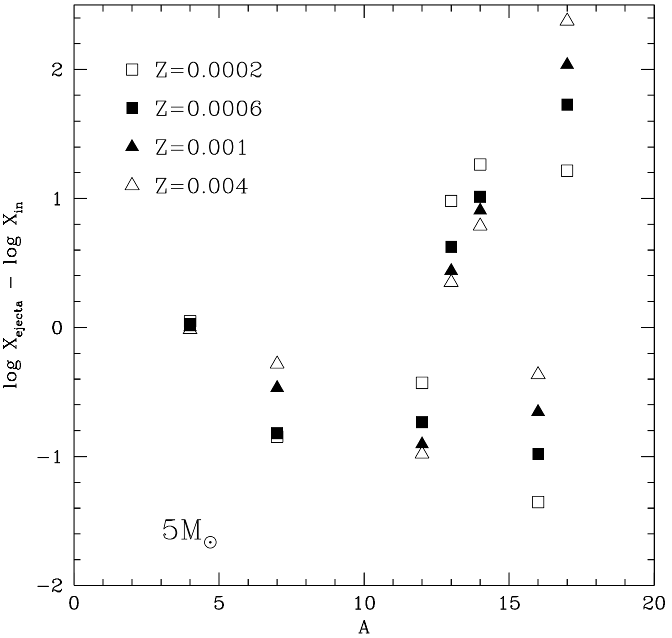

Fig. 6. Abundances of elements from helium to ^{17}O in the ejecta of 5 $M_{\odot}$ are shown with respect to the initial abundance for the four different metallicities.

stars in the Magellanic Clouds. VDM00 in fact have shown that even the models with $\eta = 0.1$, which are not able to give an interesting contribution to lithium, are not compatible with the observations: these Li–rich stars show no sign of obscuration by a thick circumstellar envelope, and are rich in s–process elements, features which allowed us to put an *upper* limit to the mass loss rate. Even if we regard that there is a large uncertainty on this limit, it is easy to understand that a huge mass loss at the peak of lithium production would *not* allow the survival of the lithium–rich stars as very luminous objects in the Clouds: these objects would be as obscured by the circumstellar envelope, as the many other obscured AGBs which are commonly found in the Clouds (e.g. Wood et al. 1992; van Loon et al. 1999).

Going to smaller metallicities, it is very probable that the mass loss is even reduced with respect to the rates obtained for the metallicities of the Magellanic Clouds, so we regard the scarce contribution of massive AGBs to the galactic evolution of lithium as a solid result.

5.2. The abundances in Globular Clusters stars

Now that the observations of spectra of TO stars in Globular Clusters are clarifying that the chemical anomalies were already present in the matter from which the stars formed, these computations may constitute an important framework for the understanding of the formation and the first phases of evolution of Globular Clusters. In the following, we only stress a few important points.

The problem of the chemical composition and chemical inhomogeneities of GC stars has been discussed very much in the recent literature. We must face these general broad problems:

1. most GCs are very homogeneous in the iron content, so that the gas from which they formed is well mixed with respect to possible ejecta from supernovae;
2. some clusters look very homogeneous also in CNO abundances (e.g. NGC 6397) but their *nitrogen* abundance is much larger than in “normal” non-processed matter; In addition, the stars in NGC 6397 show a *very “normal” – population II– lithium* abundance (Bonifacio et al. 2002);
3. other clusters show clear signatures of variations in the CNO abundances, both in the giants and at the turnoff, either as a spread, or as a bimodality. The CNO variations, where examined, are also correlated with O-Na and Mg-Al anomalies.
4. so far as known, there can be a lithium spread in the TO abundances, but *definitely lithium is present* in the TO stars, at levels compatible with the Big Bang abundances.

The models we have shown cannot help quantitatively in describing the GC anomalies involving Na, Mg and Al (for which we are preparing further full model computations involving a matrix with 30 elements), but it may help understanding the CNO and lithium variations, and give interesting predictions.

1: If the nitrogen abundance is much larger than that expected on the basis of the solar ratios (or the subdwarfs ratios) in homogenous clusters, we must be in the presence of CN cycled material (or even CNO cycled material). This may be a result of massive or intermediate mass stars evolution. We have seen that our models indeed predict production of primary nitrogen. But the normal lithium abundance in the NGC 6397 stars (see Bonifacio et al. 2002, also for a discussion) is difficult to be understood in this context. The best hint of solution is probably that the gas from which the stars formed has been contaminated with a small amount of gas in which the nitrogen abundance was even much higher than predicted by our models, so

Table 1. Average abundances in mass fraction in the ejecta from the computed evolutions.

M	$M_{\rm wd}$	^{3}He	^{4}He	^{7}Li	^{12}C	^{13}C	^{14}N	^{16}O	^{17}O	^{18}O	t(H)	t(AGB)
Z = 0.01		1.52-5	0.28	1.00e-8	1.73-3	2.08-5	5.32-4	4.83-3	2.02-6	1.13-8		
3.5	.860	8.08-6	2.93-1	5.36-10	2.43-4	4.72-5	3.16-3	3.91-3	4.21-4	1.09-8	8.315	8.400
4.0	.912	2.26-6	2.98-1	7.90-10	1.69-4	4.25-5	3.12-3	3.45-3	5.62-4	1.36-8	8.174	8.250
4.5	.943	1.51-6	3.09-1	1.00-09	1.56-4	4.27-5	3.10-3	3.41-3	5.86-4	1.18-8	8.055	8.125
5.0	.976	1.17-6	3.20-1	1.60-09	1.50-4	4.31-5	3.12-3	3.40-3	5.53-4	1.08-8	7.950	8.016
5.5	1.01	1.02-6	3.22-1	2.32-09	1.44-4	4.25-5	3.00-3	3.60-3	5.02-4	6.66-9	7.860	7.923
6.0	1.05	1.33-6	3.26-1	4.98-09	1.48-4	4.42-5	2.89-3	3.79-3	4.15-4	6.03-9	7.780	7.838
Z = 0.004		6.08-6	0.248	1.00e-8	6.92-4	8.32-6	2.13-4	1.93-3	8.08-7	4.52-9		
3.0	.834	3.31-5	2.64-1	7.07-10	4.15-4	6.94-5	2.67-3	1.75-3	5.95-5	5.35-9	8.475	8.565
3.5	.890	5.00-6	2.62-1	4.89-10	1.40-4	3.20-5	2.42-3	1.18-3	2.18-4	3.97-9	8.317	8.392
4.0	.932	2.33-6	2.71-1	4.73-10	1.51-4	2.69-5	1.96-3	9.84-4	2.24-4	3.15-9	8.182	8.251
4.5	.958	1.32-6	2.81-1	4.38-10	1.14-4	2.48-5	1.77-3	9.24-4	2.23-4	3.60-9	8.068	8.132
5.0	.989	9.06-7	2.88-1	5.20-10	9.47-5	2.34-5	1.65-3	9.43-4	2.26-4	3.01-9	7.968	8.030
5.5	1.03	6.76-7	2.92-1	6.28-10	7.58-5	2.17-5	1.55-3	1.00-3	2.27-4	2.53-9	7.881	7.940
Z = 0.001		1.52-6	0.242	1.00e-8	1.73-4	2.08-6	5.32-5	4.83-4	2.02-7	1.13-9		
3.0	.859	1.97-5	2.52-1	5.79-10	1.84-4	4.16-5	2.54-3	4.08-4	4.39-5	1.29-09	8.429	8.507
3.5	.922	6.04-6	2.57-1	3.50-10	5.88-5	1.58-5	1.17-3	1.95-4	4.28-5	5.60-10	8.276	8.348
4.0	.966	3.10-6	2.81-1	2.63-10	4.55-5	1.16-5	7.88-4	1.12-4	2.55-5	3.02-10	8.149	8.223
4.5	.983	1.62-6	2.87-1	1.54-10	4.38-5	1.13-5	7.47-4	9.35-5	2.22-5	2.43-10	8.040	8.102
5.0	1.04	1.10-6	2.89-1	3.46-10	2.65-5	7.76-6	5.32-4	1.12-4	2.55-5	2.48-10	7.947	8.008
5.5	1.05	7.08-7	2.93-1	3.06-10	2.61-5	7.91-6	5.25-4	1.10-4	2.48-5	2.35-10	7.862	7.918
Z = 0.0006		9.12-7	0.23	1.00e-8	1.04-4	1.25-6	3.19-5	2.90-4	1.21-7	6.78-10		
3.0	.800	1.80-4	2.42-1	1.50-11	2.00-3	6.63-6	7.77-5	2.94-4	1.95-6	1.68-08	8.441	8.520
3.5	.862	1.92-5	2.41-1	5.49-10	1.73-4	3.71-5	2.41-3	2.50-4	2.72-5	9.23-10	8.288	8.359
4.0	.923	6.45-6	2.46-1	3.07-10	8.45-5	1.82-5	1.24-3	1.18-4	2.54-5	3.72-10	8.164	8.229
4.5	.955	3.07-6	2.67-1	2.53-10	6.06-5	1.36-5	8.81-4	5.90-5	1.31-5	1.67-10	8.056	8.118
5.0	.987	1.61-6	2.86-1	1.81-10	4.27-5	9.98-6	6.22-4	3.72-5	7.96-6	9.12-11	7.963	8.020
5.5	1.02	9.17-7	2.95-1	1.53-10	2.71-5	7.16-6	4.33-4	3.16-5	6.80-6	7.06-11	7.880	7.934
Z = 0.0002		3.04-7	0.23	1.00e-8	3.47-5	4.17-7	1.06-5	9.67-5	4.03-8	2.26-10		
2.5	.809	1.51-4	2.43-1	1.08-10	2.13-3	8.63-5	7.64-5	1.06-4	7.67-7	9.59-09	8.595	8.689
3.0	.870	1.44-5	2.43-1	5.92-10	1.46-4	3.50-5	2.40-3	9.12-5	1.19-5	3.46-10	8.417	8.497
3.5	.930	6.48-6	2.52-1	3.66-10	7.57-5	1.77-5	1.23-3	4.20-5	8.86-6	1.47-10	8.265	8.341
4.0	.963	2.75-6	2.70-1	2.31-10	6.04-5	1.29-5	7.33-4	1.76-5	3.38-6	5.23-11	8.148	8.212
4.5	.996	1.37-6	2.84-1	1.74-10	5.47-5	9.14-6	5.31-4	9.26-6	1.52-6	2.10-11	8.042	8.102
5.0	1.03	7.31-7	2.98-1	1.44-10	2.59-5	5.45-6	3.04-4	5.52-6	8.87-7	1.02-11	7.951	8.007

that lithium would not be significantly altered. Otherwhise, we must admit a very fine tuning of the lithium yield of the ejecta of the contaminating matter (see point **2**), a hypothesis which is not appealing.

2: One of the interesting characteristics of the HBB AGB stars as source of contamination for the GC matter is that they *produce lithium* in large amounts, so that lithium is never totally depleted in the ejecta. This may be a very important help in reproducing the abundances of GC stars, even when they show a strong signature of full CNO cycling, but seem to preserve a non-negligible lithium content. Notice that this is very different from the requirement that these stars are important for the galactic lithium evolution: we have noticed in Sect. 5.1 that there should be a very peculiar calibration of the mass loss with the peak phase of lithium production, as assumed by Travaglio et al. (2001), a completely ad hoc parametrization.

3: The complete CNO cycling which occurs in low-metallicity massive AGB stars may be at the basis of one of the most interesting anomalies of the chemistry of stars in several GCs, the oxygen spread, which in some clusters reaches a factor close to ten as in M 13 and NGC 6752 (Pilachowski et al. 1996; Sneden 1999; Gratton et al. 2001). Notice that *the oxygen poor contaminating matter is also helium rich.* In other words, *the GC stars with low oxygen must also have high helium.* This result is not dependent on the details of the models, as most of the helium enhancement is due to the second – and not to the third – dredge up. If selfpollution has occurred on the gas, or even if it occurred on the formed stars, but has reached the stellar core, the larger helium abundance will affect the stellar evolution *even from the main sequence*, and bear consequences on the morphology of the evolutionary paths, and in particular of the horizontal branch (HB) stars

(Montalban et al. 2002, in preparation; see also Cannon et al. 1981), that is on some aspects of the "second parameter" problem[2].

4: The CNO abundances we have derived may form the basis of synthetic evolution models which we may compare to the GC observations. The most unexpected result we have shown is that the IMS ejecta at very low metallicity are so oxygen-depleted that carbon is larger than oxygen. If there were stars formed from matter contaminated with such ejecta, they would have carbon star characteristics, also during the main sequence. Metal poor GCs like M 92, although showing CN anomalies do not show so extreme compositions. Selfconsistent models of the clusters evolution must be developed before we can reject the models.

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[2] The correlation between the HB morphology and the chemical anomalies has been long recognized and tentatively attributed to the helium enhancement in the envelopes of HB stars, due to very deep mixing (Langer & Hoffman 1995; Sweigart 1997). Weiss et al. (2000) show however that the associated chemical anomalies in the red giants, in this case, would be much stronger than those observed.