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AGB stellar models: current uncertainties on the theoretical ejecta

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Abstract. AGB models of intermediate mass with chemistry typical of Globular Clusters (GCs) (i.e. Z = 0.001) were calcuated by varying the main physics inputs, namely the treatment of convection, the mass loss rate and the amount of extra-mixing from the bottom of the surface convective zone in the dredge-up phase following each thermal pulse (TP). We find that the physical and chemical evolution of these objects, and particularly the abundances of some trace elements (e.g. sodium), is largely dependent on the inputs used, which then undermines the predictive power of the models. The role that these stars may have played within the context of the self-pollution scenario of GCs is also commented.

Key words. Stars: abundances – Stars: evolution – Stars: AGB and post-AGB – Stars: abundances

1. Introduction

It is well known that GCs stars are far from representing a chemically homogeneous sample, because star-to-star variations are observed, and clear chemical anomalies, appearing as evident anticorrelations between the surface abundances of some species, are present: Oxygen is anticorrelated with Sodium, Aluminum is anticorrelated with Magnesium and Fluorine, etc. (Carretta 2003; Gratton et al. 2001; Gratton et al. 2004; Ramirez & Cohen 2002; 2003).

One of the most appealing explanations of such a surprising evidence, which has no analogy in the field stars, is the so called "self-pollution scenario" (Cottrell & Da Costa 1981; D'Antona et al. 1983; Ventura et al. 2001; 2002): the chemically "anomalous" stars formed in an interstellar medium that was precedently polluted by the ejecta of an early generation of intermediate mass stars. These sources a) evolve rapidly compared to the age of the cluster ($\sim$ 100 – 200 Myr); b) may reach during the Asymptotic Giant Branch (AGB) phase temperatures at the bottom of their convective envelope high enough to favour an advanced nuclosynthesis ("Hot Bottom Burning", hereinafter HBB) which might change their surface chemistry; c) suffer strong mass loss, potentially able to pollute the stellar environment.

A way of providing further robustness to the self-pollution scenario would be to build AGB stellar models whose yields are consistent with the observed patterns, i.e. a) rich in Sodium, Nitrogen and Aluminum; b) Oxygen, Fluorine and Magnesium poor; c) the total C+N+O increased at most by a factor of 2

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(Smith et al. 1996; Ivans et al. 1999); d) Magnesium isotopic ratios below unity (Yong et al. 2003).

Unfortunately, the theoretical modelling of the AGB phase turns out to be extremely sensistive to the physics adopted, so that models within the same range of masses and metallicities presented by different groups evidentiate strong differences both in the physical evolution, and in the surface chemical composition, so that the average chemical content of the ejecta, hence the possible role played by these sources in the self pollution scenario, are remarkably different (Denissenkov & Herwig 2003; Fenner et al. 2004) .

In this work we present a detailed exploration, aimed at understanding how much the AGB theoretical models are sensitive to the various uncertainties characterizing some of the input physics adopted, particularly for that concerning the treatment of convection, the mass loss rate, and the extent of the overshooting region below the bottom of the convective envelope during the third dredge-up (TDU) phase.

We discuss which combinations of the assumptions made are consistent with the self-pollution scenario.

2. The models

The AGB models presented and discussed in this paper were calculated by means of the ATON code for stellar evolution; a full description of the various physical inputs and on the numerical structure can be found in Ventura et al. (1998).

We briefly recall the main items mostly related to the models presented here.

The temperature gradient within regions unstable to convective motions can be found either via the traditional Mixing Lenght Theory (MLT; Vitense 1953), or by the Full Spectrum of Turbulence (FST) model. The interested reader may found in Canuto & Mazzitelli (1991) a clear and exhaustive comparison between the ideas and the physics on which the two models are based.

Various prescription for mass loss can be adopted: the traditional Reimers' formula, the Blocker's (1995) prescription, and the rate recommended for the AGB evolution of intermediate mass stars by Vassiliadis & Wood (1993). In this paper we will restrict our attention only on a Blocker-like prescription, varying the parameter η_R.

Nuclear burning can be fully coupled to mixing of chemicals within convective regions by solving for each element a diffusive-like equation (Cloutman & Eoll 1976), or, alternatively, the instantaneous mixing scheme can be adopted. Due to the sensitivity of the luminosity (hence, mass loss) of the models to the details of nuclear burning at the base of the convective envelope, we adopted for all the models here discussed the diffusive approach. Within this context, it is possible to assume some extra-mixing from the convective formal borders fixed by the Schwartzschild criterium by allowing and exponential decay of convective velocities; in this approach, the extent of the extra-mixing region is established by the overshooting parameter ζ, giving the e-folding distance of the velocity decay. A full description of the relevant equations can be found in Ventura et al. (1998).

The nuclear network, including 30 chemicals, is based on the NACRE (Angulo et al. 1999) compilation for cross-sections.

The input chemistry of the models is typical of GC stars, i.e. $Z = 0.001$ and $Y = 0.24$. In the standard cases only extra-mixing from the border of convective cores during the two major phases of nuclear burning in the central regions was allowed; a value $\zeta = 0.02$, consistent with the calibration presented in Ventura et al. (1998), was adopted.

3. The role of convection and mass loss

Ventura & D'Antona (2005a; b) studied the effects of the description of convection and of the rate of mass loss on the physical evolution of AGB stars of intermediate mass.

The treatment of convection showed up to be by far the physical input having the largest impact on the results. Using the FST prescription, which is much more efficient than the MLT, favours a smaller distance between the bottom of the envelope and the CNO burning shell peak, with the consequence that H and CNO rich material is transported to hotter regions, triggering a larger luminosity. This difference, appearing since the early AGB phase, is the reason of the strong differences between the physical evolutions of the models calculated with the two convective treatments: in the FST model the bottom of the surface convective zone is much hotter, thus favouring larger luminosities and mass loss, and a much faster overall AGB evolution.

On the chemical point of view, a more efficient convective treatment favours HBB conditions, which is found in all the FST models with masses $M \geq 3.5M_{\odot}$, with an efficiency increasing with mass, as expected.

In terms of the chemical ejecta that we expect from these intermediate mass AGB models, when convection is treated according to the FST prescription, we found the following differences compared to the MLT case:

1. HBB is strongly favoured, triggering a more advanced nucleosynthesis, with a strong destruction of Oxygen, Magnesium and Fluorine, and a larger production of Nitrogen and Aluminum.
2. The material expelled in the FST models is also carbon poor, because HBB favours carbon depletion at the bottom of the convective envelope, and the larger luminosity, trigerring a higher mass loss, reduces the number of TPs, hence of TDU episodes, that might potentially increase the surface carbon abundance.
3. The sodium content of the ejecta is also expected to be lower in the FST models compared to their MLT counterparts, since HBB conditions determine a rapid destruction of sodium, which follows a phase of sodium production (due to proton capture by ^{22}Ne nuclei) during the early AGB evolution. In the MLT case less sodium is destroyed due to the lower temperatures at the base of the surface convective zone, and a much larger number of TDUs episodes favours an overall increase of the sodium content of the ejecta.
4. The predictions of the two sets models are particularly different for that concerning the magnesium isotopic ratios: in the FST case, due to strong ^{24}Mg burning, the abundances of the two heaviest isotopes are greatly increased, with the consequence that in the more massive models ($M > 4M_{\odot}$) the magnesium isotopic ratios are expected to exceed by far unity.

Within the context of the self-pollution scenario, the ejecta from the FST models, compared to the MLT case, are expected to be much more consistent with the observational evidence, the only two major problems being the abundance of sodium and the magnesium isotopic ratios in the more massive models ($M \geq 5M_{\odot}$): the former is found to be lower than the initial value (at odds with the observations, which show an increase by ~ 0.4 dex), while ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg are expected to exceed unity (Ventura & D'Antona 2005a).

The sensitivity of the results obtained on the mass loss rate adopted was explored by calculating various sequences of models for the same chemical composition and range of mass by varying the parameter η_R included in Blocker's (1995) prescription. We will considered as "standard" the set of tracks calculated with $\eta_R = 0.02$, which comes from a precedent calibration of mass loss based on the luminosity function of super-rich lithium stars in the Magellanic Clouds (Ventura et al. 2000).

Basically, independently of mass, increasing mass loss leads to a shorter evolution, and to a less advanced degree of nucleosynthesis. The possibility of reaching the TDU conditions is also reduced, and in any case a smaller number of TPs is obtained.

We may therefore understand that for those elements that are depleted within the surface external regions because of HBB (i.e. Oxygen, Magnesium, Fluorine), the global yield will be still negative, but larger; the same holds for those chemical species that are dredged-up after any TP (e.g. carbon).

The yields of the FST models calculated with enhanced mass loss show a larger abundance of sodium, more consistent with

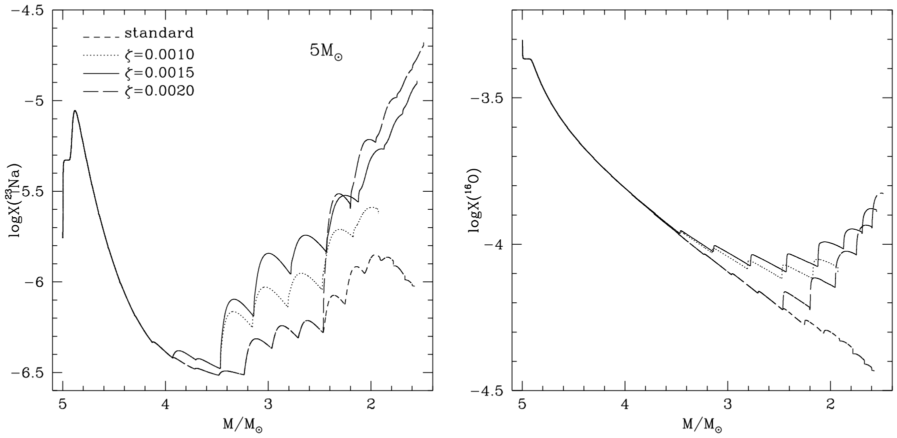

Fig. 1. Variation with mass of the surface abundance of Sodium (left), and Oxygen (right) during the AGB evolution of a model with initial mass $M = 5M_{\odot}$ calculated with various values of the extra-mixing parameter ζ.

the spectroscopic analysis of GCs chemically anomalous stars, but would also show a much smaller enhancement of Aluminum, and fail completely in reproducing the strong oxygen depletion, which seems to be a common point in the presumably polluted sample of stars in all the GCs so far examined (Ventura & D'Antona 2005b) .

Increasing the mass loss rate of the massive AGB models may increase the sodium content of the ejecta, but cannot reproduce the observed Oxygen - Sodium anticorrelation.

4. The treatment of the convective borders

In the exploration concerning the role played by convection and mass loss discussed in the previous Section, the inner extension of the envelope was determined simply according to the Schwartzschild criterium.

In order to understand how our predictions, particularly for what concerns the chemistry of the ejecta, may vary according to the inclusion of some extra-mixing, we assumed that, once TDU conditions were achieved, convective velocities decay from the base of the envelope inwards with an e-folding distance regulated by the parameter ζ. This exploration, which must be regarded as only a preliminary approach on a more systematic study upon the effects of the inclusion of some extra-mixing within the FST models, was run only on the $5M_{\odot}$ model.

The range of parameters spanned in this study was $0 \leq \zeta \leq 0.002$, that are much smaller than the values commonly used to simulate overshooting from convective cores to fit the observed main sequences of open clusters, which are in the range $0.02 \leq \zeta \leq 0.03$ (Ventura et al. 1998; Ventura & Castellani 2005).

A non vanishing ζ increases the extent of the TDU, mixing more material precedently touched by 3α burning in the envelope: the surface abundances of ^{12}C, ^{16}O and ^{22}Ne are consequently enhanced.

Fig. 1 shows the variation of the surface abundances of Sodium and Oxygen during the AGB evolution of models with initial mass $M = 5M_{\odot}$ for various values of ζ. We see that, though sodium is not directly dredged-up following each TP, its abundance increases with ζ, because it is later produced during the quiescent CNO burning phase via proton capture by ^{22}Ne nuclei. For completeness, in the figure it is also shown a model calculated with $\zeta = 0.002$ (dot-dashed line), in which the extra-mixing was added only in the latest evo-

Table 1. Oxygen, Sodium and CNO abundances of the ejecta of the $5M_\odot$ models calculated with different assumption concerning the extra-mixing from the bottom of the surface convective zone. For Oxygen and Sodium, we indicate as $[X] = \log X_{ejecta} - \log X_{initial}$; [^{16}O] was shifted by +0.3 dex to take into account the initial solar-scaled composition, which was not α enhanced. $R(C+N+O)$ indicates the ratio between the sum of the carbon, nitrogen and oxygen abundances in the ejecta and the initial value.

ζ	[^{16}O]	[^{23}Na]	R(C+N+O)
0.0000	−0.32	−0.18	1.08
0.0010	−0.26	0.01	1.35
0.0015	−0.22	0.37	1.62

lutionary phases, when the mass of the envelope was reduced to $\sim 1.5M_\odot$: we see that in this case the increase of oxygen determined by the TDU makes impossible any possibility of achieving oxygen depleted ejecta, particularly if the assumption of overshooting involves all the TPs. This suggests that, in order to have ejecta whose chemical content reproduces the observed patterns of GCs stars, we must assume a very modest amount of extra-mixing, i.e. $\zeta < 0.002$.

Tab. 1 shows the chemical content of the ejecta of the models calculated with different ζ's in terms of oxygen and sodium abundances, and of the C+N+O sum. The abundance of oxygen have been shifted by 0.3 dex, because the models have been calculated assuming a solar mixture.

As expected, the assumption of some extra-mixing from the bottom of the convective envelope increases both the surface abundances of Sodium and Oxygen, as well as the total C+N+O abundance. In particular, we see from Tab. 1 that the chemical content of the mass expelled by the model calculated with $\zeta < 0.0015$ is Oxygen depleted ($\sim$ 0.52 dex compared to the initial value) and sodium enhanced ($\sim$ 0.4 dex), which is in a satisfactory agreement with the chemical content of the most anomalous stars in all the GCs so far examined (with the only exception of M13, which shows a tail of very low oxygen content population; Sneden et al. 2004); also, the overall C+N+O is increased by only a factor $\sim$ 1.6, which is well inside the spread observed in all the stars examined (Ivans et al. 1999).

We therefore find that the assumption of some extra-mixing from the bottom of the surface convective zone of massive AGBs during the TDU phase leads to a general increase of the sodium content of the envelope, still keeping low the oxygen abundance. To provide a robust calibration of the extension of the extra-mixing region below the base of the surface convective zone of massive AGBs which allows to reproduce the observed patterns of GCs stars, many more models, spanning a wide range of mass and metallicity, must be computed; yet, the present study shows that a very modest amount of overshooting may potentially solve the issue of obtaining ejecta from massive AGBs sharing the two basic properties of being sodium rich and oxygen poor.

5. Conclusions

In this work we analized the impact of various physical inputs on the chemical content of the ejecta of intermediate mass stars. The main goal was to check the possibility that some combinations of assumptions lead to chemical ejecta consistent with the observed patterns characterizing GCs stars, in which we observed the presence of a well identified stellar population whose surface abundances, when compared to the standard stars in the same cluster, are enhanced in Aluminum and Sodium, depleted in Oxygen, Fluorine and Magnesium, and the CNO sum is rather uniform, the maximum variation observed being within a factor of 2.

We find that using the FST model for turbulent convection favours a very advanced nucleosynthesis at the bottom of the surface convective zone, with the result that Oxygen, Fluorine and Magnesium depletion are easily achieved, as well as Aluminum production. The C+N+O sum is almost constant, because the strong mass loss triggered by the large luminosity leads to a very small number of TPs, hence of TDUs, which might increase the carbon abundance. A deeply different behaviour is shown by the MLT models, in which the temperatures at the bottom of the surface convective zone never increase sufficiently to favour HBB, with the only exception of the most massive models.

In the FST case the only serious problem is the behaviour of sodium in the most massive ($M \geq 5M_{\odot}$) models, which, after an early AGB phase of production due to proton capture by ^{22}Ne nuclei, is later destroyed due to the high temperatures. If we allow some extra-mixing from the base of the convective zone during the TDU, we favour dredge-up of ^{22}Ne from the internal zones precedently touched by 3α burning, thus favouring sodium production during the following CNO burning phase. The assumed extra-mixing must be very modest (a factor of $\sim$ 10 smaller than it is commonly assumed during the MS phase), to prevent that too much oxygen is dredged-up in the same phase, thus increasing the oxygen abundance of the ejecta.

Much more work is needed in order to calibrate the amount of the extra-mixing which is necessary during the AGB evolution, since these results have been obtained for a unique mass and chemical composition.

References

Cayrel, R., Lebreton, Y., & Morel, P. 1999, Ap&SS, 265, 87

Angulo, C., et al. 1999, Nucl. Phys. A, 656, 3

Blöcker, T. 1995, A&A, 297, 727

Canuto, V.M.C., & Mazzitelli, I. 1991, ApJ, 370, 295

Carretta, E. 2003, Mem.S.A.It.Suppl., 3, 90

Cloutman, L. & Eoll, J.G. 1976, ApJ, 206, 548

Cottrell, P.L., & Da Costa, G.S. 1981, ApJ, 245, 79

D'Antona, F., Gratton, R., & Chieffi, A. 1983, Mem.S.A.It., 54, 173

Denissenkov, P.A., & Herwig, F. 2003, ApJ, 590, L99

Fenner, Y., Campbell, S., Karakas, A.I., Lattanzio, J.C., & Gibson, B.K. 2004, MNRAS, 353, 789

Gratton, R. et al. 2001, A&A, 369, 87

Gratton, R., Sneden, C., & Carretta, E. 2004, ARA&A, 42, 385

Ivans, I.I. et al. 1999, AJ, 118, 1273

Ramirez, S., & Cohen, J.G. 2002, AJ, 123, 3277

Ramirez, S., & Cohen, J.G. 2002, AJ, 125, 224

Smith, G.H., Shetrone, M.D., Bell, R.A., Churchill, C.W., & Briley, M.M. 1996, AJ, 112, 1511

Sneden, C., Kraft, R.P., Guhathakurta, P., Peterson, R.C., & Fulbright, J.P. 2004. AJ, 127, 2162

Vassiliadis, E., & Wood, P.R. 1993, ApJ, 413, 641

Ventura, P., & Castellani, M. 2005, A&A, 430, 1035

Ventura, P., D'Antona, F., & Mazzitelli, I. 2000, A&A, 363, 605

Ventura, P., D'Antona, F., Mazzitelli, I. & Gratton, R. 2001, ApJ, 550, L65

Ventura, P., D'Antona, F., & Mazzitelli, I. 2002, A&A, 393, 215

Ventura, P., Zeppieri, A., D'Antona, F., & Mazzitelli, I. 1998, A&A, 334, 953

Ventura, P., & D'Antona, F. 2005a, A&A, 431, 279

Ventura, P., & D'Antona, F. 2005b, A&A, 439, 1075

Vitense, E. 1953, Zs.Ap., 32, 135

Yong, D., Grundahl, F., Nissen, P.E., & Shetrone, M.D., 2003, A&A, 402, 985