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The role of convection in AGB modeling

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Abstract. We present results of detailed evolutionary calculations of intermediate mass stellar models (IMS) evolved from the pre-MS phase along the whole Asymptotic Giant Branch (AGB). We show that the results obtained in terms of the chemistry of the ejecta are different from recent calculations presented by other research groups, due to the different treatment of convection. We compare models calculated with different convective models, and we discuss carefully how convection influences the results obtained and the differences found.

Key words. AGB evolution – stellar interiors

1. Introduction

The intermediate mass stars (i.e. stars with initial mass in the range $1M_{\odot} \leq M \leq 7M_{\odot}$), shortly after the end of helium burning in the central regions, experience a phase of thermal pulses (TPs). For most of the time the global energy release is supplied by a CNO burning shell; sporadically, a He-rich layer just below the CNO burning shell is activated under instability conditions (Schwartzschild & Harm 1965, 1967; Iben 1975, 1976).

Their evolution is characterized by a growing core mass, luminosity, and temperature at the base of the external convective zone, until mass loss determines a decrease of the mass of the envelope which triggers a general cooling of the structure and a later evolution as a CO white dwarf (Lattanzio & Karakas 2001).

The bottom of the envelope, being in very close proximity to the CNO layer, might in the most massive models reach temperatures sufficiently large to become a site of nucleosynthesis, in a process which is known as "Hot Bottom Burning" (HBB) (Blöcker & Schönberner 1991). It is therefore possible that the surface of these stars contains (and ejects) material which has been subject to nuclear processes.

This is the reason why these sources have been suggested as possible responsible for the chemical anomalies observed in globular clusters (GCs) stars (Carretta 2003; Gratton et al. 2001; Sneden et al. 2004), which seem to indicate that some of these latter must have formed from gas processed by nuclear reactions, with a composition which might resemble the chemistry of the ejecta of AGBs (the "self-enrichment" scenario: Cottrell & Da Costa 1981; D'Antona et al. 1983; Ventura et al. 2001; Ventura et al. 2002).

In this paper we present massive AGB models ($M \geq 3M_{\odot}$) evolved from the pre-MS phase through the whole AGB, with a metallic-

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Table 1. Chemical content of the ejecta of the FST models.

M_{ZAMS}	Y^a	$[^{12}C]^b$	$[^{14}N]$	$[^{16}O]$	$(C+N+O)^c$	$[^{23}Na]$	$[^{24}Mg]$	$^{25}Mg/^{24}Mg$	$^{26}Mg/^{24}Mg$
3.0	0.26	–0.10	1.52	0.01	3.24	1.21	0.03	0.20	0.50
3.5	0.27	–0.44	1.37	–0.19	2.18	0.75	–0.01	0.31	0.39
4.0	0.29	–0.56	1.28	–0.39	1.70	0.46	–0.28	0.98	0.73
4.5	0.32	–0.60	1.24	–0.49	1.51	0.02	–0.66	2.37	1.63
5.0	0.32	–0.70	1.13	–0.61	1.17	–0.16	–0.95	3.68	3.00
5.5	0.32	–0.80	1.04	–0.59	0.99	–0.37	–1.13	6.13	4.18
6.0	0.32	–0.82	1.01	–0.54	0.96	–0.43	–1.23	8.96	4.96
6.5	0.32	–0.81	1.01	–0.46	1.00	–0.37	–1.27	11.34	5.02

[a] Helium mass fraction.
[b] $[A] = \log(X(A)_{ej}) - \log(X(A)_{in})$.
[c] Ratio between the average (C+N+O) abundance of the ejecta and the initial (C+N+O) value.

ity typical of those GCs (like M3, M13) whose stars exhibit the aforementioned anomalies, i.e. $Z = 0.001$.

We show that the results obtained, in terms of physical behavior of the models and of the nucleosynthesis at the base of the external envelope, is strongly dependent on the treatment of convection.

We therefore compare the results obtained by assuming the full spectrum of turbulence (FST) model (Canuto & Mazzitelli 1991; Canuto et al. 1996) model for turbulent convection with the computations performed by assuming the traditional mixing length theory (MLT) model (Böhm-Vitense 1958; Vitense 1953).

The implications for the role which these stars may have played within the context of the self-enrichment scenario are discussed.

2. Physical and chemical properties of the AGB models

All the evolutions discussed in this paper have been calculated by the code ATON2.1 for stellar evolution, a detailed description of which can be found in Ventura et al. (1998), with the most recent updates given in Ventura & D'Antona (2004). For the cross-sections of the various reactions involved in the nuclear network, we used the NACRE (Angulo et al. 1999) release.

Mass loss was modeled according to the formula given in Blöcker (1995); the value of the free parameter η_R included in the above prescription is taken as $\eta_R = 0.02$, in agreement with a previous calibration of mass loss during the AGB evolution suffered by IMS made in order to fit the luminosity function of lithium-rich AGBs observed in the Large Magellanic Cloud (Ventura et al. 2000).

We use as standard models those calculated by assuming the FST model for turbulent convection. In agreeement with previous works (Ventura et al. 2001), we note a steep rise of both luminosity and temperature at the base of the envelope in all the models considered.

In terms of nucleosynthesis, we present in Table 1 the overall chemical content of the ejecta, in terms of [X/Fe]. Basically, we note the followings:

1. All the models, with the only exception of $3M_{\odot}$, deplete oxygen (see the 5th col. of tab. 1), thus indicating that an efficient CNO burning takes plase at the base of the external envelope.
2. The average C+N+O content of the ejecta is almost constant, being increased at most by a factor of about 2.
3. Sodium is produced in the less massive models, while it is eventually destroyed in the more massive stars, where the Ne-Na cycle is activated within the external convective region.

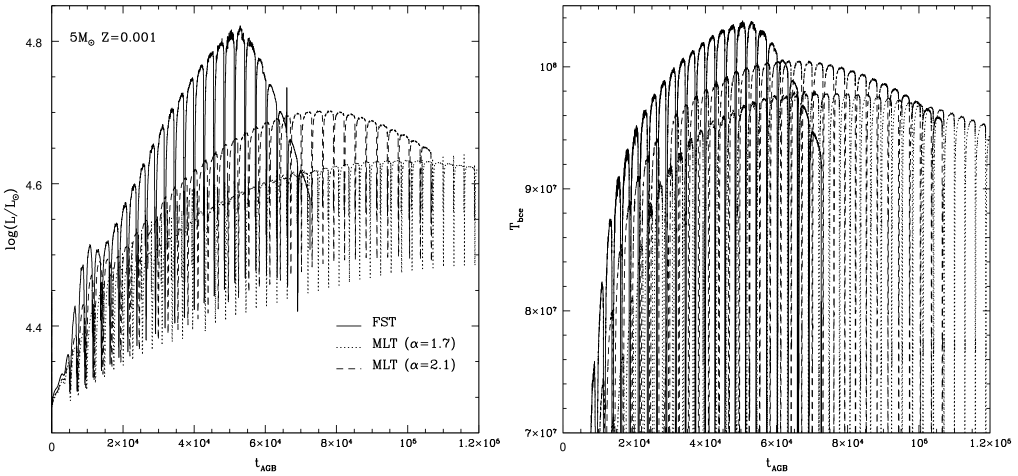

Fig. 1. Left panel: The variation with time of the luminosity of three $5M_{\odot}$ models calculated with the FST and MLT convective model: for this latter, two evolutions corresponding to two different values of the free parameter α have been calculated. Right panel: The evolution of the temperature at the bottom of the convective envelope of the same models presented in the left panel.

4. ^{24}Mg is strongly destroyed in models with mass $M \geq 5M_{\odot}$, therefore leading to high magnesium isotopic ratios ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg.

3. The role of convection

The results presented in the previous section are at odds with recent AGB computations presented by different groups (Fenner et al. 2004; Herwig 2004), which show that a strong ^{16}O depletion is possible only within the interiors of models with mass next to the limit for carbon ignition in the centre, and that the great number of dredge-up episodes makes the C+N+O abundance of the ejecta greatly in excess with respect to the initial value. More particularly, carbon is found to increase, and also sodium is produced in great quantities.

To understand the differences with respect to our findings, we focused our attention on the only macro-physics input which distinguishes our models, i.e. the treatment of convection. We recall that our code allows both the FST and the MLT models to be used in order to evaluate the temperature gradient within the instability regions.

We therefore decided to calculate for a $5M_{\odot}$ model two MLT evolutions with values of the free parameter α, respectively, of α = 1.7 (which is the standard value, necessary to reproduce the evolution of the Sun), and α = 2.1, which is the minimun value necessary within the MLT framework to achieve HBB conditions in massive AGBs (D'Antona & Mazzitelli 1996; Sackmann & Boothroyd 1991). We will refer to these models as MLT17 and MLT21, the FST model being the standard model presented in the previuos section.

We were able to verify that the evolution up to the beginning of the TPs phase are extremely similar, with the only exception of the colour of the RGB, which becomes progressively redder with the increase of the luminosity in the MLT models. The interested reader may find a detailed discussion about the influence of the convective model in the pre-AGB evolution of IMS in Ventura & Castellani (2004).

The two panels of Figure 1 show the evolution with time of luminosity and temperature

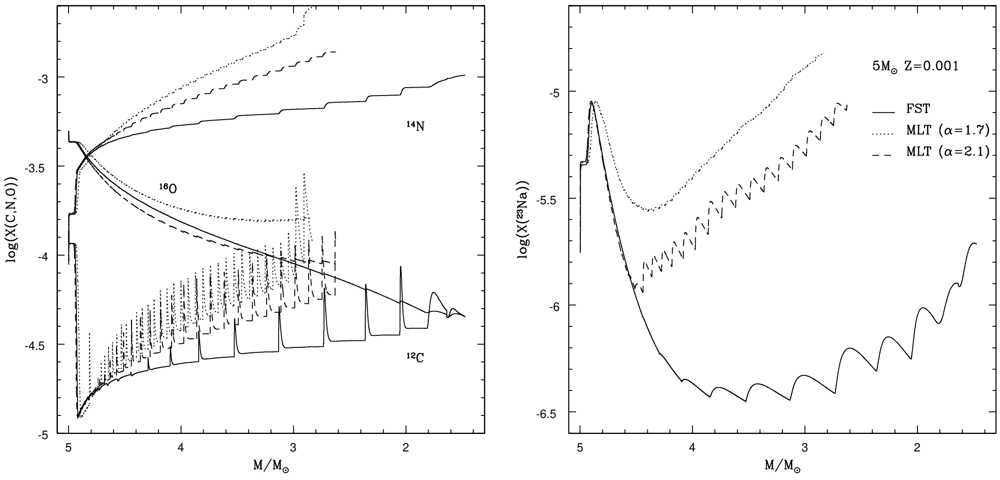

Fig. 2. Left panel: The evolution of the surface abundances of the CNO elements within the same models presented in Figure 1. Right panel: The evolution of surface sodium.

at the bottom of the convective envelope related to the evolution of the three models which we want to compare. In the FST case we note a very rapid increase of the luminosity, which is also connected to a larger temperature (see the right panel) at the bottom of the outer convective zone, which leads easily to HBB conditions.

There is a difference of almost $\sim$ 0.2 dex between the maximum luminosity reached by the FST and the MLT17 model, the MLT21 model showing an intermediate behavior.

This has relevant consequences on the mass loss rate, which has a steep dependence on the luminosity in the Blöcker (1995) formulation: the FST model loses all its envelope mass in $\sim$ 70000 yr, to be compared to $\sim$ 130000 yr (MLT21 model) and $\sim$ 200000 yr (MLT17 model). This shorter duration of the AGB evolution, in turn, determines a much smaller number of TPs (hence, of 3rd dredge-up episodes) in the FST model: *the signature of the 3rd dredge-up is much more evident in the MLT models than in the FST case*.

Before discussing the implications on the nucleosynthesis and on the chemistry of the ejecta, we stress here the important role of the treatment of convection, which, not only influences the surface chemical behavior of the models, but also the main physical properties, in terms of luminosity, mass loss rate, and AGB life-time.

The left panel of Figure 2 shows the evolution of the CNO elements; in order to have an idea of the chemical content of the ejecta, we decided to report the total mass on the abscissa, rather than time.

We see in the MLT models a greater abundance of carbon, which is efficiently dredged-up, and a larger nitrogen content; in the MLT17 model oxygen is hardly destroyed; if the evolution of this latter model were continued, we would get a larger oxygen abundance, due to the greater efficiency of the 3rd dredge-up. Our MLT models, particularly the MLT17 one, are therefore consistent with the most recent AGB computations (Fenner et al. 2004), and indicate that it is actually the treatment of convection that is mainly responsible for the differences in terms of CNO nucleosynthesis.

Turning to larger isotopes, we focus our attention on sodium, which appears to be anti-correlated with oxygen in GCs stars (Carretta 2003). The differences among the models in this case are even more relevant (see the right panel of Figure 2). In the FST case, after an early phase of production at the beginning of the AGB evolution due to ^{22}Ne burning, we find a strong sodium destruction, when the temperatures are sufficiently large to allow the activation of the Ne-Na cycle; conversely, in the MLT models, we note a sodium production, greatly in excess with respect to the initial abundance (in agreement with Fenner et al. 2004), for two reasons:

1. In the MLT models the temperatures at the bottom of the external envelope are never large enough to allow the Ne-Na cycle to be activated: therefore, surface sodium is rather preserved than destroyed.
2. In the MLT models, due to the longer duration of the whole AGB phase, we have a larger number of 3rd dredge-up episodes, which favours sodium production.

In terms of the self-enrichment scenario, the chemical content of the ejecta of the MLT models would show a C+N+O abundance in excess with respect to the initial value and a strong sodium enrichment, which is against the observational evidence: in fact, with the only exception of some giant stars in M13, the sodium excess is at most [Na/Fe]$\sim$ 0.5 (Carretta 2003), and the C+N+O abundance is approximately constant even in the most contaminated stars (e.g. Ivans et al. 1999 for M4). On the contrary the FST models do not share the same problems connected to the C+N+O abundance, the only shortcoming being the low sodium content and the high magensium isotopic ratios of the ejecta of the most massive models.

4. Conclusions

We have presented the results of detailed AGB calculations of models with masses in the range $3M_{\odot} \leq M \leq 6.5M_{\odot}$, with metallicity $Z = 0.001$.

We examined the role played by the treatment of convection, comparing models calculated with the FST and the MLT treatments; for these latter, we used two values of the free parameter connected with the choice of the mixing length, i.e. $\alpha = 1.7$ and $\alpha = 2.1$.

Our main finding is that the physical behavior of the models is strongly dependent on the convective model: in the FST case we find a rapid increase of the temperature at the base of the external envelope and of luminosity, which, in turn, favours greater mass loss rates and therefore shorter AGB life-times.

In terms of CNO nucleosynthesis, the larger temperatures in the FST model favour a strong oxygen depletion; besides, the smaller number of 3rd dredge-up episodes determines a lower carbon and nitrogen abundance, and an almost constant C+N+O abundance of the ejecta. On the other hand, in the MLT models (particularly in the model calculated with the solar-tuned value of the free parameter, $\alpha = 1.7$) the temperature never attains values large enough to trigger a strong oxygen depletion, and the C+N+O abundance is greatly in excess with respect to the initial value.

Even for the larger isotopes the differences are relevant: sodium is produced in the MLT models while it is eventually destroyed in the FST case, which is again due to the differences among the temperatures at the bottom of the outer convective zone and the AGB life-times.

Any prediction regarding the pollution of the interstellar medium due to AGBs ejecta must take into account all the uncertainties connected with the treatment of convection.

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References

Angulo C. et al., 1999, Nucl. Phys. A, 656, 3
Blöcker T., 1995, A&A, 297, 727
Blöcker T., Schönberner D., 1991, A&A, 244, L43
Böhm-Vitense E., 1958, Zs. Ap., 46, 108
Canuto V. M., Goldman I., Mazzitelli I., 1996, ApJ, 473, 570
Canuto V. M., Mazzitelli I., 1991, ApJ, 370, 295
Carretta E., 2003, Mem. S.A.It. Suppl., 3, 90
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
D'Antona F., Mazzitelli I., 1996, ApJ, 470, 1093
Fenner Y., Campbell S., Karakas A. I., Lattanzio J. C., Gibson B. K., 2004, MNRAS, 353, 789
Gratton R., Bonifacio P., Bragaglia A., et al., 2001, A&A, 369, 87
Herwig F., 2004, ApJS, in press
Iben I. Jr., 1975, ApJ, 196, 525
Iben I. J., 1976, ApJ, 208, 165
Ivans I. I., Sneden C., Kraft R. P., et al., 1999, AJ, 118, 1273
Lattanzio J. C., Karakas A. I., 2001, M.S.A.It., 72, 255
Sackmann I. -J., Boothroyd A. I., 1991, ApJ, 366, 529
Schwarzschild M., Harm R., 1965, ApJ, 142, 855
Schwarzschild M., Harm R., 1967, A&A, 145, 486
Sneden C., Kraft R. P., Guhathakurta P., Peterson R. C., Fulbright J. P., 2004, AJ, 127, 2162
Ventura P., Castellani M., 2004, A&A, in press
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., D'Antona F., 2004, A&A, submitted
Ventura P., Zeppieri A., D'Antona F., Mazzitelli I., 1998, A&A, 334, 953
Vitense E., 1953, Zs. Ap., 32, 135