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Evolutionary properties of $\sim 7 - 13\mathrm{M}_\odot$ stars and the associated nucleosynthesis

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Abstract. In the light of new evolutionary computations (Siess & Pumo 2006), we review the evolutionary properties of $\sim 7 - 13M_\odot$ stars and their correlated nucleosynthesis, pointing particular attention on the role of initial composition, initial mass and core overshooting. Moreover, based on these computations, the effects of initial composition and core overshooting on the values of M_{up} (critical initial mass above which C-burning ignites) and M_{mas} (minimum initial mass for the completion of all the nuclear burning phases) are presented. The impact of our results in relation to different astrophysical issues is also briefly discussed.

Key words. Stars: evolution - Stars: interiors - Stars: AGB - nucleosynthesis - abundances

1. Introduction

It is well known that the evolution and the fate of the stars are primarily determined by their initial stellar mass and to a second extent by other parameters such as chemical composition, mass loss rate, rotation or internal mixing processes. Independently of these "secondary" parameters, stars can be loosely classified into different groups according to their initial mass and, in this simplistic picture, critical masses emerge that set the transition among the various groups (e.g. Maeder & Meynet 1989). Roughly speaking we can consider three categories of stars according to their initial mass. The first two categories are the so-called low- and intermediate-mass stars which are not able to ignite carbon, being less massive than M_{up} ($\sim$ 7 to $9M_\odot$) defined as the minimum initial mass for the carbon ignition. The third category is formed by the so-called massive stars that are more massive than M_{mas} ($\sim$ 11 to $13M_\odot$) defined as the minimum initial mass for the completion of all the nuclear burning phases (e.g. Chiosi et al. 1992; Woosley et al. 2002). In this scenario the class of stars with initial mass between M_{up} and M_{mas} is missing. These stars, referred to as Super-AGB (SAGB) stars, have a very peculiar evolution and nucleosynthesis, filling the gap between intermediate-mass stars and massive stars (e.g. Pumo & Siess 2007). In fact, SAGB stars are massive enough to ignite carbon but, being unable to evolve through all nuclear burning stages, they end their life either forming a neon-oxygen white dwarf (NeO WD) or going through an electron-capture supernova (EC SN) becoming a neutron star, if electron-capture reactions are efficiently activated (e.g. Ritosa et al. 1999). Although SAGB stars are of very special interest in stellar physics both

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because they are at the crossroad of different evolutionary paths and because they exhibit remarkable structural evolution and correlated nucleosynthesis, full stellar evolution models including updated input physics and detailed reactions network are not yet available for SAGB stars and there are still open questions and uncertainties concerning their evolution (e.g. Herwig 2005; Siess & Pumo 2006). In particular the "boundaries" M_{up} and M_{mas} of the SAGB stars are quantitatively not well defined. The advanced evolution (post-He-burning phases and final fate) of SAGB stars has not been studied in sufficient detail, so what fraction of these stars evolve into each of the two "final" channels (NeO WD or EC SN) and consequently the mass M_N making the transition between the two fates are unclear questions. Moreover the nucleosynthesis correlated to the SAGB stars evolution has not been intensively investigated and little is known about the production of s-nuclei during the post-C-burning evolution (Ritosa et al. 1999) and about the possibility (e.g. Wanajo et al. 2003) or not (Kitaura et al. 2006) of r-process nucleosynthesis during the EC SN event. In this paper we address some of the above mentioned issues, focusing on the role of initial composition, mass loss and convective overshooting on the advanced evolution of SAGB stars. Emphasis is also placed upon the values of M_{up} and M_{mas}.

2. Stellar evolution code and models

Our study is based on the analysis of two grids of stellar models described in Siess & Pumo (2006). The main features of these evolutionary sequences are summarised in the following: (*i*) starting from the pre-main sequence, all the models have been calculated by the code STAREVOL in the version described in Siess (2006) with the differences reported in Siess & Pumo (2006); (*ii*) the first grid consists of 70 stellar models without overshooting having initial masses (M_{ini}) between 7 and $13M_{\odot}$ with 5 different values of the initial metallicity (Z) in the range 10^{-5} to 0.04; (*iii*) the second grid consists of 20 stellar models with overshooting having $5 \leq M_{ini}/M_{\odot} \leq 10.5$ for $Z = 10^{-4}$ and 0.02.

3. Results and discussion

3.1. Evolution prior to carbon ignition

Prior to carbon ignition, the evolution of SAGB stars is similar to the one of intermediate-mass stars. In fact, for any set of models having a given Z, we find that the core H- and He-burning take place in a convective core, the mass of which increases with M_{ini}, whereas the duration of the two burning phases is a decreasing function of M_{ini}. As for the core composition, the nucleosynthesis processes lead primarily to the production of ^{12}C and ^{16}O. Given the "primary" nature of the ^{12}C, we find that its mass fraction ranges between $\sim$ 0.2 and 0.4 regardless of Z, and it seems to be a trend with both M_{ini} and mixing treatmet (fixed Z), according to which the ^{12}C mass fraction decreases as both M_{ini} increases and the overshooting is inserted in the evolutionary computations. Moreover the ^{12}C mass fraction is anti-correlated to the ^{16}O mass fraction, because of the major efficiency of the $^{12}C(\alpha,\gamma)^{16}O$ reaction, due to the higher core temperature when both M_{ini} increases and the overshooting is inserted in the models, that leads to an increase of ^{16}O at the expense of ^{12}C.

All our models with $Z > 0.001$ experience the first dredge-up phenomenon (1DUP) after the central hydrogen exhaustion. During this phase, the SAGB stars evolve to the red giant region (RGB) in the HR diagram, burning hydrogen in a shell above the contracting core, composed essentially of ^{4}He (central mass fraction $\sim$ 0.96-0.99). Our SAGB models with $Z \leq 0.001$ (regardless of mixing treatment) ignite the core He-burning before they ever reach the RGB, and thus experience no 1DUP. For models where the 1DUP takes place, the modifications of the surface composition are similar to those affecting intermediate-mass stars: the hydrogen mass fraction decreases to the benefit of ^{4}He; ^{12}C and ^{16}O are depleted; while ^{17}O, ^{13}C and ^{14}N are increased, leading to a decreasing of the ratio $^{12}C/^{13}C$ from $\sim$ 90 to 20. Moreover, the surface enrichments of

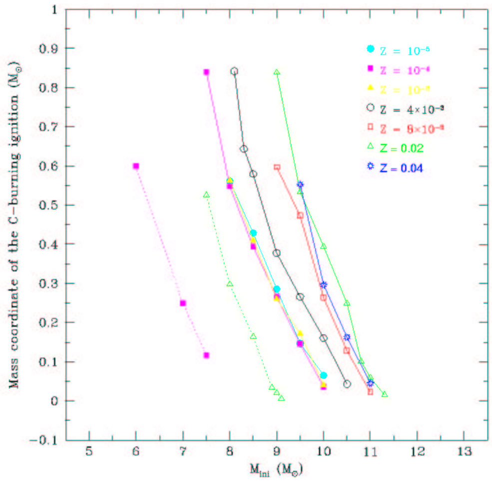

Fig. 1. Location of the off-centre carbon ignition for models with a given Z as a function of M_{ini}. The dotted lines refer to models with overshooting.

Table 1. M_{up} and M_{mas} values as a function of Z, for the models without (upper panel) and with (lower panel) overshooting respectively.

Z	M_{up} [$M_{\odot}$]	M_{mas} [$M_{\odot}$]
0.00001	7.75	9.75
0.0001	7.25	9.66
0.001	7.75	9.72
0.004	8.05	10.26
0.008	8.45	10.66
0.02	8.90	10.93
0.04	9.25	10.89
0.0001	5.75	7.63
0.02	7.25	8.83

^{23}Na, ^{21}Ne and ^{26}Mg, concomitant to a decrease of ^{22}Ne and ^{25}Mg, witness the activation of the NeNa and MgAl chains during the H-burning phase in the internal stellar layers reached by 1DUP (see Pumo 2006,for details). Concerning the second dredge-up phenomenon (2DUP), we find that all our models experience it, but the exact features of such event (deepest extent of convective envelope and chemical signatures) highly depend on M_{ini} for a given Z and mixing treatment (see Pumo 2006,for details). Moreover in some of our SAGB models (e.g. $9.5M_{\odot}$ models with $Z = 10^{-5}$, 10^{-4} and 10^{-3}, $10M_{\odot}$ models with $Z = 0.008$, $10.8M_{\odot}$ model with $Z = 0.004$, $10.8M_{\odot}$ model with $Z = 0.02$ and $7.5M_{\odot}$ model with overshooting having $Z = 10^{-4}$) the 2DUP is replaced by the so-called dredge-out phenomenon (Iben et al. 1997).

3.2. M_{up} and the C-burning phase

After central He exhaustion, the temperature maximum moves outward due to neutrino energy losses, and carbon ignites off-centre in condition of partial degeneracy when the peak temperature reaches $\sim 6.5-7\cdot10^{8}K$. The mass coordinate of carbon ignition (Fig. 1) is a decreasing function of M_{ini} for a given mixing treatment and/or Z; but it increases with Z for a given mixing treatment and/or M_{ini}, the only exceptions being for $Z = 10^{-5}$ and 0.04. In particular, the behaviour of the $Z = 10^{-5}$ models is linked to the fact that, when $Z \lesssim 10^{-4}$, the contribution of metals to the opacity is vanishing and the H and He cores are less massive (Cassisi & Castellani 1993), so the mass coordinate of carbon ignition decreases when passing from $Z = 10^{-5}$ to $Z = 10^{-4}$. The exception of the most massive $Z = 0.04$ models ($M_{ini} \geq 10M_{\odot}$) is related to the variation of the helium (Y) content as Z changes. Indeed Y passes from ~ 0.25 to only ~ 0.27 for Z lying between 10^{-5} to 0.02, but it increases to ~ 0.30 at $Z = 0.04$. Such a important variation leads to an increase in the H core (Bono et al. 2000) and consequently in the He core, which may cause carbon to ignite closer to the centre for the most massive $Z = 0.04$ models compared to the $Z = 0.02$ models.

Using the mean between the M_{ini} value of the least massive model which ignites carbon and the one of the most massive model which does not ignite, we have evaluated M_{up} as a function of Z. Our results show (Table 1) that M_{up} decreases when moving from $Z = 0.04$ to 10^{-4} and increases at lower Z. This behaviour is linked to the fact that, decreasing Z, the opacity decreases leading to a more massive core during the central H-burning, which in turn causes an increase of the core at the end of He-burning phase and consequently a lower M_{up} value; but for $Z \lesssim 10^{-4}$, as explained previously, the H and He cores are less massive, so M_{up} reverses its trend starting to increase. Once carbon is ignited, the evolution proceeds in two steps (see also Siess 2006): first a carbon convective flash which induces a structural readjustment leading to a temporary quenching of the convective instability, and then the development of a convective flame that propagates to the stellar centre, transforming the core into a degenerate NeO mixture whose mass and exact composition affect the final fate of the SAGB stars (see for details Pumo 2006 and Pumo et al. 2007 in this volume).

3.3. M_{mas} and final comments

Using a procedure based on the fact that stars with NeO core mass $\gtrsim 1,37 M_\odot$ at the end of C-burning phase evolve through all nuclear burning stages (Nomoto 1984), we have estimated M_{mas} as a function of Z. Due to the opacity effects previously mentioned, the behaviour of M_{mas} with Z is similar to the one of M_{up}, but it presents a maximum value around $Z = 0.02$ (Table 1). Comparing the values of M_{up}, M_N (see Pumo et al. 2007 in this volume) and M_{mas} for a given Z and mixing treatment, we obtain that only the most massive SAGB stars become neutron stars after the EC SN event, while the less massive ones end their life as NeO WDs. The existence of both "final channels" has important consequences in relation to different astrophysical issues. In fact our results, showing the existence of NeO WDs as end-products of SAGB stars evolution, reinforce the idea that massive white dwarfs could be the result of the evolution of single stars (see also Gil-Pons et al. 2005). Such an idea could explain in a very natural way the so-called neon-novae as well as the high mass secondary peak of the white dwarf mass distribution, without resorting to scenarios involving the merging of two CO WDs in a binary system, confirming the hypothesis by Weidemann (2000). Besides our study, demonstrating that the supernova-channel for SAGB stars is possible, renews the problem of clarifying the origin of the so-called sub-luminous Type II-P SNe. In fact neither of the two suggested models to explain this type of SNe (collapse of progenitor with NeO core or with iron core surrounded by extended envelope) can a priory be excluded from a theoretical point of view, reinforcing the idea that one might be able to distinguish between this two scenarios on the basis of careful spectroscopic observations, as suggested by Kitaura et al. (2006). Furthermore, the existence of both final channels and the variation of M_{up}, M_N and M_{mas} with Z and mixing treatment have to be taken into account in galactic chemical evolution modelling, since the main "ingredients" of such modelling are directly related both to these final channels and to these transition masses.

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