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Super–AGB yields

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Abstract. We present the first simulations of the full evolution of super-AGB stars through the entire thermally pulsing AGB phase. We analyse their structural and evolutionary properties and determine the first SAGB yields. Owing to their massive oxygen-neon core, SAGB stars suffer weak thermal pulses, have very short interpulse periods and develop very high temperatures at the base of their convective envelope leading to very efficient hot bottom burning. SAGB stars are consequently heavy manufacturers of ^{4}He, ^{13}C and ^{14}N. They are also able to inject significant amounts of ^{7}Li, ^{17}O, ^{25}Mg and ^{26,27}Al in the interstellar medium. The 3DUP mainly affects the CNO yields, especially at low metallicity. This study also reveals that changes in the temperature at the base of the convective envelope have a dramatic impact on the yields and represents another major source of uncertainty.

1. Introduction

Stars in the mass range 7-11 $M_{\odot}$ ignite carbon off-centre and after the formation of a relatively massive oxygen-neon (ONe) core, they enter the so called thermally pulsing super-AGB (TP-SAGB) phase where recurrent instabilities develop in the He-burning shell (HeBS) as in lower mass AGB stars.

The lack of simulations covering the SAGB mass range prevents us from determining the evolution of their surface chemical abundances and ultimately their yields. These data are however important for a better understanding of the galactic chemical evolution and for an observational identification of SAGB stars. This absence of yields is mainly due to the prohibitive amount of CPU time required to follow the evolution up to the complete removal of the convective envelope. In some simulations, more than 30 millions time-steps were computed, accounting for more that 4400 thermal pulses!

In this paper, we present the results of a set of models including 21 SAGB stars of various initial masses ($7 \leq M/M_{\odot} \leq 11$) and metallicities ($10^{-4} \leq Z \leq 0.04$). These models were calculated with STAREVOL (Siess 2006), using standard physics (no-extra mixing, Schwarzchild criterion) and the Vassiliadis & Wood (1993) mass-loss rate. It is important to stress that with our treatment of the convective boundaries, our models do not experience third dredge-up (3DUP) episodes. Details are given in Siess (2010).

The next section describes some general evolutionary properties of TP-SAGB stars, then in Sect. 3 we give an overview of their nucleosynthesis and in Sect. 4 we present the first SAGB yields. The paper ends with a general discussion.

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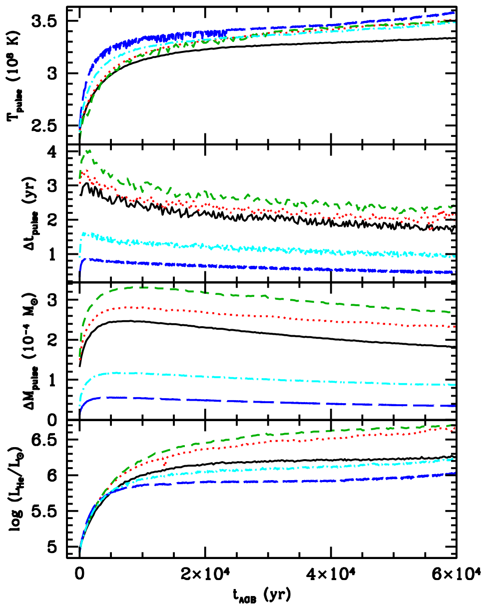

Fig. 1. Evolution of the pulse properties: maximum pulse temperature ($T_{\rm pulse}$), pulse duration ($\Delta t_{\rm pulse}$), pulse mass ($\Delta M_{\rm pulse}$), and maximum He-flash luminosity ($L_{\rm He}$) for selected TP-SAGB models. The origin of time coincides with the occurrence of the first thermal pulse. With increasing $L_{\rm He}$, the models correspond to (mass,Z,type): (9,0.001,long-dash), (8.5,0.001,dot-dash), (8,0.001, solid), (8.5,0.004,dot), and (9,0.008,short-dash).

2. The thermally pulsing super-AGB phase

After the completion of the second dredge-up (2DUP) and following carbon extinction, the core strongly contracts and the temperature at the base of the convective envelope ($T_{\rm env}$) increases rapidly from $\sim 10^7$ K to above 10^8 K. The H-burning shell (HBS) re-ignites and soon after the star develops thermal instabilities in the HeBS. After a few thousand years, the star reaches an asymptotic regime in which changes in the main properties (pulse luminosity, durations of the pulse and interpulse, ...) become smaller and more regular than at the beginning of the TP-SAGB phase.

The structure of TP-SAGB stars is very similar to that of lower-mass AGB stars: an extended convective envelope (which in the case of SAGB stars can be as massive as 10 $M_\odot$), surrounding an H- and unstable He-burning shell enclosing an inert degenerate core. The main difference is ascribed to the larger mass of the ONe core ($> 1.05\ M_\odot$) in SAGB stars. As a consequence of its higher mass, the radius of the degenerate core is also smaller ($R_{\rm core} \propto \dot{M}_{\rm core}^{-1/3}$) so the compression of the shells in the vicinity of the core is much stronger. For example, in a 10 $M_\odot$, $Z = 0.02$ model the HBS is only a few $10^{-5}\ M_\odot$ thick compared to a few $10^{-3}\ M_\odot$ in a 5 $M_\odot$ model of the same composition. This enhanced gravity leads to much higher temperatures in the HBS and at the base of the envelope.

Fig. 1 illustrates some of the properties of the thermal pulses. The first striking feature is the short duration of the convective instabilities, a few years at most, to be compared to $\sim 10 - 50$ years in a 5 $M_\odot$ model. This is partially due to the small extent of the convective instability ($\Delta M_{\rm pulse}$ is only a few $10^{-4}\ M_\odot$) and to the very high temperature at the base of the thermal pulse ($T_{\rm pulse}$) which contribute to weaken the instability. In models possessing the most massive cores, $T_{\rm pulse}$ can exceed 3.7×10^8 K leading to the efficient activation of the ^{22}Ne(α,n) neutron source and potentially to the production of s-process elements in the convective pulse. Interestingly, most of the neutrons are released during the latest (and hottest) pulses when the instability is very short-lived so in the end the irradiation may not be sufficient for an efficient nucleosynthesis. We also notice that $\Delta M_{\rm pulse}$ decreases with age and with increasing initial mass, both effects being directly linked to the core mass. Compared to their lower-mass counterparts, SAGB stars develop weaker He-shell flashes ($L_{\rm He}$ less than a few $10^6\ L_\odot$). The explanation comes from the increasing contribution of the radiation pressure ($P_{\rm rad} \propto T^4$) which enables a faster mechanical response of the structure and a faster quenching of the instability.

During the interpulse, SAGB stars experience extreme temperatures at the base of their envelope (up to 1.5×10^8 K) leading to very efficient hot bottom burning (HBB). For stars of a given core mass, $T_{\rm env}$ increases with decreasing metallicity and when the envelope mass falls below 2-3 $M_\odot$ it drops abruptly below a few 10^6 K. HBB also causes a strong departure from the classical core mass-luminosity relation. The interpulse duration ($\Delta t_{\rm inter}$) is very short in SAGB stars, a few hundred years or less (10^5 yr in a 3 $M_\odot$) and it decreases with increasing core mass. In the absence of 3DUP, the typical core growth rate is around $5 - 7 \times 10^{-7}$ $M_\odot\,{\rm yr}^{-1}$ and steadily increases along the AGB.

3. Evolution of surface abundances

The 3DUP being absent from our simulations, the only modifications to the surface abundances result from the operation of HBB. In this section, we analyse two representative and extreme configurations consisting of a 9 $M_\odot$, $Z = 0.008$ and a 8 $M_\odot$, $Z = 0.004$ model experiencing "mild" and "extreme" $T_{\rm env}$, respectively. It should also be emphasised that prior to the SAGB phase, the envelope composition was strongly enriched in ^{4}He and to a lower extent in ^{13}C and ^{14}N by the 2DUP. The presence of the dredge-out (DOUT) in the most massive models (see Gil-Pons in this volume) further exacerbates these features. It is interesting to note that after the completion of the DOUT, the star becomes carbon rich (C/O> 1).

At the time of the first thermal pulse, the CNO cycles are already very active and start to modify the envelope composition: the ^{12}C/^{13}C ratio drops to 4, ^{14}N is massively produced while ^{15}N and ^{16}O are depleted. In the "mild" temperature model where $T_{\rm env} \lesssim 120 \times 10^6$ K, ^{17}O is substantially produced. We also find that SAGB stars can become C-rich as a result of efficient O depletion. For $T_{\rm env} > 35 \times 10^6$ K, the NeNa chain is activated, leading to the destruction of ^{22}Ne and to the production of ^{23}Na mainly. When $T_{\rm env}$ exceeds $\sim 90 \times 10^6$ K, there is a strong leakage into the MgAl chain as (p,γ) reactions on ^{23}Na become faster than (p,α) reactions. The operation of the MgAl chain leads to the destruction of ^{24}Mg to the benefit of the ^{25,26}Mg and ^{26,27}Al. The production of ^{26}Al remains modest: at most SAGB stars can account for 0.3 $M_\odot$ out of the estimated galactic content of 2.8 $M_\odot$ (Siess & Arnould 2008). Above 130×10^6 K (as found in our extreme model where $T_{\rm env}$ reaches 1.5×10^8 K) the nucleosynthesis is even simpler as protons are captured by all the elements with charge $Z \leq 13$ leading to ^{28}Si production. In these conditions, all abundances involved in the CNO, NeNa and MgAl cycles reach their equilibrium abundances and slowly evolve as a consequence of the structural changes.

4. SAGB yields

Fig. 2 shows the yields for our two reference stars. They are expressed in terms of the ratio of the mass of the considered species ejected by the wind ($M_{\rm eject}$) to the mass of that species in the initial model (M_{ini}). The yield is said to be positive if $\rm M_{eject}/M_{ini} > 1$

The ^{4}He yield is largely positive because of the combined effects of a deep 2DUP and very efficient HBB. The ^{4}He surface mass fraction can reach 0.4 in some cases, making SAGB strong helium producers. The ^{7}Li can also be substantially produced by the Cameron & Fowler (1971) mechanism. This production is however inefficient in the low-metallicity models because of the higher envelope temperatures and lower mass-loss rate that prevent a massive wind ejection before ^{7}Li is destroyed when the ^{3}He supply is exhausted. With the CNO cycles operating near equilibrium, SAGB stars are naturally strong manufacturers of ^{13}C and especially of ^{14}N. The ^{17}O yield can be significant in "cool" SAGB models. Concerning the elements involved in the NeNa chains, the ^{23}Na yield depends strongly on $T_{\rm env}$. Schematically, one can expect a positive ^{23}Na yield in the least massive and/or most metal-rich SAGB stars where $T_{\rm env} \lesssim 10^8$ K. ^{24}Mg is always destroyed so its yield is negative. Concerning ^{25,26}Mg and ^{27}Al here again, their yields are mainly controlled by the value of $T_{\rm env}$. In the hottest models, there is a direct chain from Ne to Si so these yields are negative. However, in all cases, ^{26}Al is produced.

The determination of yields depends on various and largely unknown factors, and in particular on the efficiency of the 3DUP and on the treatment of convection. In order to assess these effects, we have used our postprocessing code (Siess & Arnould 2008; Siess 2010) to simulate the effects of the 3DUP by diluting, after each pulse, some of the intershell material into the envelope. As expected (Fig. 3), the dredge up of C-rich intershell matter (^{4}He:^{12}C:^{16}O = 0.66:0.31:0.02) increases the ^{12}C yields and, because this element is subsequently burnt during the interpulse, the ^{13}C, ^{14}N and ^{17}O yields are also enhanced. The injection of carbon in the envelope also boosts the production of ^{4}He because it decreases the proton lifetime against ^{12}C captures. To a lower extent we also observed an increase in the ^{22}Ne, ^{23}Na and ^{25}Mg yields when the 3DUP is accounted for. It important to realize that the *3DUP mostly impacts the SAGB yields at low metallicity*. In the more metal-rich stars, the effect of the 3DUP is weaker because these stars suffer less TP (stronger mass-loss rate) and also because the contrast between the envelope and intershell composition is not as pronounced as in metal-poor stars.

The temperature at the base of the convective envelope plays a crucial role in determining the stellar yields as it controls the efficiency of proton burning and the leakage into the MgAl chain. This value depends however on the convection theory and on the parameters of the selected theory (e.g. Ventura & D'Antona 2005). For instance, an increase in the MLT parameter α leads to deeper convection and higher $T_{\rm env}$. To get a qualitative understanding of the effect of changing $T_{\rm env}$ on the yields, we used our postprocessing code and simply scaled the envelope temperature profile allowing variations of ±10% in $T_{\rm env}$ with respect to its nominal value. With a higher temperature, proton captures are more efficient and the production of ^{13}C, ^{14}N is increased. On the other hand this leads to a stronger ^{23}Na and ^{25}Mg depletion. The effects are relatively large (a factor of a few in the yields) and affects all stars, independently of their initial composition as opposed to the 3DUP. But mass-loss and nuclear reaction rates further blur the picture. Before additional models become available, one should thus keep in mind that SAGB yields remain at the moment highly uncertain.

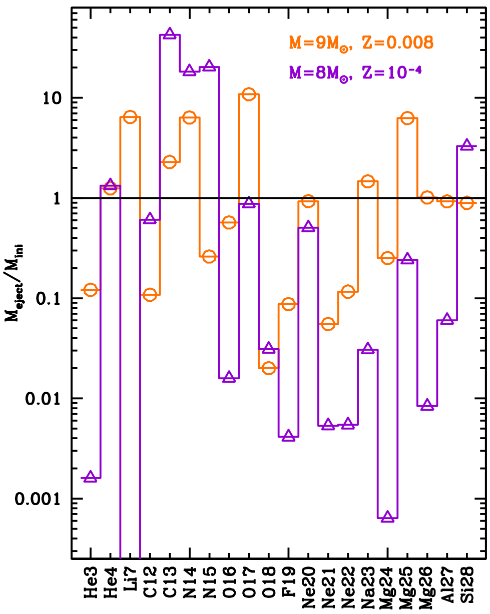

Fig. 2. Dependence of the yields on mass and metallicity. Yields are shown for a $9M_\odot$, $Z = 0.008$ (open circle) and $8M_\odot$, $Z = 10^{-4}$ (triangle). The yields are expressed in terms of the ratio of the mass of the considered species ejected by the wind ($M_{\rm eject}$) to the mass of that species in the initial model (M_{ini}).

5. Conclusion and discussion

The evolution of TP-SAGB star is very similar to that of lower mass AGB stars. The main differences stem from the presence of a more massive ONe core which compresses the inner layers producing much higher temperatures both in the burning shells and at the base of the convective envelope. Because of the higher temperatures, SAGB stars suffer weak and very short-lived thermal pulses, the interpulse durations are also considerably reduced compared to their lower mass counterparts. The SAGB yields are mainly determined by HBB, resulting in a massive production of ^{14}N, a ^{12}C/^{13}C ratio close to 4, the depletion of ^{16}O and depending on $T_{\rm env}$, the production of ^{23}Na, ^{25,26}Mg and ^{26,27}Al. In the models developing the highest $T_{\rm env}$, i.e. the most metal-poor and/or most massive stars, all the elements involved in the various proton burn-

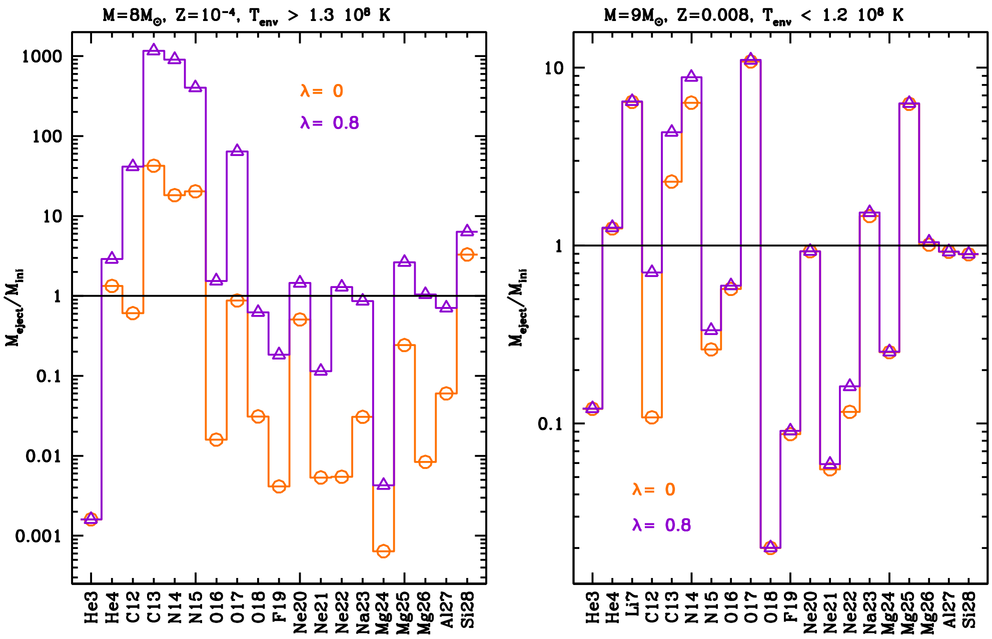

Fig. 3. Dependence of the yields on the 3DUP. The left (right) panel illustrate the effect of a high ($\lambda = 0.8$, triangle) and zero 3DUP efficiency ($\lambda = 0$, open circle) for the $8M_\odot$, $Z = 10^{-4}$ ($9M_\odot$, $Z = 0.008$) model. Units are the same as in Fig.2.

ing chains have abundances imposes by nuclear equilibrium. The NeNa and MgAl chain merge in a more compact NeSi chain where proton capture reactions proceed up to ^{28}Si where they stop. With these nucleosynthetic features, SAGB stars are strong contributors of ^{4}He, ^{14}N, ^{13}C, ^{17}O and ^{26}Al. In the models developing the lowest temperatures, they are also manufacturers of ^{25}Mg and ^{7}Li.

The impact of the 3DUP on the yields is much stronger in metal-poor stars and affects mainly ^{12,13}C, ^{14}N and to a lower extent ^{22}Ne and ^{23}Na. A change in the envelope temperature mainly affects the CNO yields and the branching into the MgAl chain, which directly impacts the ^{23}Na yield.

According to the Salpeter IMF, there are as many stars in the mass range 7-11 $M_\odot$ as massive stars with $M > 11\ M_\odot$ so one would expect SAGB stars to imprint the galactic chemical evolution (GCE). Very metal-poor stars show large ^{14}N and ^{13}C abundances and it is tempting to attribute these enrichments to SAGB stars. According to Chiappini et al. (2008) and Ekström et al. (2008), rapidly rotating massive stars provide a good explanation to the early ^{14}N galactic enrichment but these models, which omit the contribution from SAGB stars, have problems accounting for the nitrogen enrichment around [Fe/H]=-3. However, it is precisely in that metallicity range that SAGB start polluting the interstellar medium. They may contribute to solving this problem.

Large amounts of ^{4}He are released by SAGB stars in the interstellar medium. If we now imagine that some stars formed out of these ejecta, their evolution will be modified because of the lower envelope opacity caused by the higher helium content. These polluted stars will produce blue horizontal branch stars and may detach from the main sequence thus producing multiple main sequences as observed in some globular clusters (GC).

Stars in GCs show a relatively homogeneous abundance in iron-peak elements and an almost constant C+N+O but they also exhibit

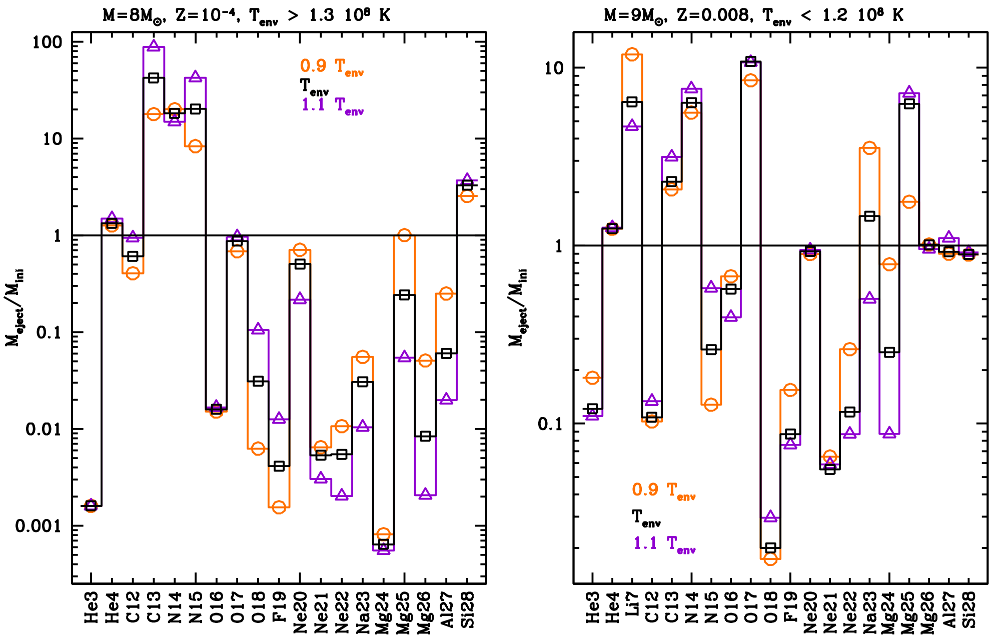

Fig. 4. Dependence of the yields on T_{env}. The left (right) panel illustrate the effect of increasing T_{env} by 10% (triangle), for the standard model (square) and decreasing T_{env} by 10% (open circle) for the $8M_\odot$, $Z = 10^{-4}$ ($9M_\odot$, $Z = 0.008$) model. Units are the same as in Fig.2.

large abundances variations in light elements characterised among others by O-Na and O-Al anti-correlations. The origin of these chemical anomalies is still debated but the evolutionary scenario seems to be the best paradigm. This scenario involves an earlier stellar population which polluted the gas out of which the GC stars currently observed were formed. Fast-rotating massive stars (Decressin et al. 2007) and massive AGB stars undergoing efficient HBB (Ventura et al. 2001) are the best candidates but the role of SAGB has not been addressed yet. Considering that SAGB stars behave similarly to the massive AGB stars, they may represent promising candidates but they also have to face the same problems and in particular to reconcile oxygen depletion with ^{23}Na production. As for massive AGB stars, it seems a fine tuning of the SAGB parameters will be required to reproduce (some of) the puzzling GC features.

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