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The Chemical Imprint of Super-AGB Stars

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Abstract. The evolution and nucleosynthesis of stars in the mass range $\sim 7 - 11\,M_\odot$ is reviewed. The main evolutionary features can be summarized as follows: off-center carbon ignition followed by the propagation of a flame to the center, formation of a neon-oxygen core and subsequent development of recurrent instabilities in the helium burning shell during the so-called thermally pulsing super-AGB (SAGB) phase. Our analysis of the pulse properties and nucleosynthesis show that owing to large dilution factors, the surface modifications induced by third dredge-up episodes are weak. The chemical imprint of SAGB stars mainly results from the action of hot-bottom burning, namely a large production of ^{13}C, ^{14}N, ^{25}Mg, ^{26}Al and potentially of ^{23}Na. We also briefly describe how the mass range where SAGB stars lie depends on the metallicity.

1. Introduction

Super-AGB (SAGB) stars are those that are sufficiently massive to ignite carbon but not massive enough to activate neon photodissociation. The minimum initial mass for a SAGB star is usually referred to as $M_{\rm up}$ and varies as a function of initial composition and internal mixing processes. Typical values for $M_{\rm up}$ range from $5 - 7$ up to ~ 9 M$_\odot$ (Siess & Pumo 2007). On the other hand, stars with initial mass larger than $M_{\rm mas}$ proceed through all nuclear burning stages and end their lives as iron-core-collapse supernovae. SAGB stars are thus confined to a very narrow mass range between $M_{\rm up}$ and $M_{\rm mas}$ and make the transition between intermediate mass stars that leave a CO white dwarf and the massive stars that produce a neutron star or a black hole.

Previous studies of massive AGB stars mostly focused on the carbon burning phase (Garcia-Berro et al. 1997; Siess 2006a) or on the explosive stage of the evolution of massive neon-oxygen (NeO) cores that enter the electron capture regime (e.g. Miyaja et al. 1980; Nomoto 1984, 1987). Thus little is known about the thermally pulsing super-AGB phase and associated nucleosynthesis. Whether these stars are the site of the *s*- or even the *r*-process is still not clearly established. But a major issue concerns their yields. Depending on poorly constrained physical parameters such as mass loss or core overshooting, SAGB stars can in principle cover a relatively large mass range between 5 and $11\,M_\odot$ and therefore play a significant role in the chemical evolution of galaxies.

In this paper, we review the evolutionary features of SAGB stars, concentrating on the carbon burning and thermally pulsing super-AGB phase. In § 3 we describe their nucleosynthesis, and in the last section we discuss the range of initial masses where SAGB stars lie.

2. Evolutionary Features of Massive AGB Stars

In this section, the evolution of super-AGB stars will be described through a detailed analysis of a 10.5 $M_\odot$ star of solar metallicity.

2.1. Pre-Carbon Evolution

The evolution of massive AGB stars prior to carbon ignition is very similar to that of intermediate mass stars. During the pre-main sequence phase, the structure contracts and the star moves along the Hayashi line toward lower luminosities. As the central temperature (T_c) increases, a radiative core develops, and when T_c reaches $\sim 10^7$ K, H ignites. On the ZAMS, nuclear energy is generated in a convective core mainly via the CNO cycle. It is worth noting that in these stars H burning is not restricted to the convective core but actually proceeds slightly outward (Figure 1). When H is exhausted, convection disappears at the center and core contraction resumes while the envelope expands

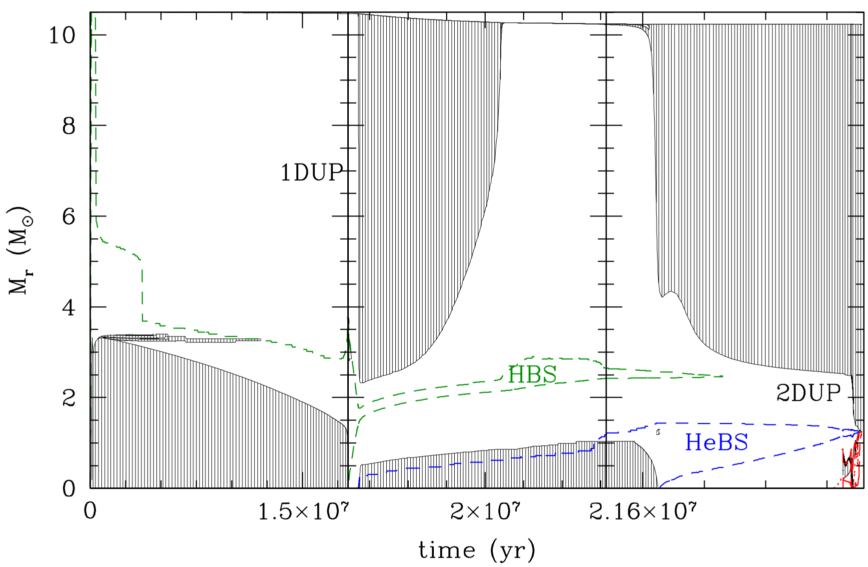

Figure 1. Kippenhahn diagram of a $Z = 0.02$, $M = 10.50$ $M_\odot$ star up to carbon ignition. The hatched areas represent the convective zones, and the dashed lines delineate the nuclearly active H-burning (HBS) and helium-burning (HeBS) shells.

and deepens. At its maximum inward extent, the convective zone has reached the H-burning shell (HBS) and brings to the surface the ashes of proton burning during the so-called first dredge-up (Fig. 1). The star then climbs the red giant branch until He ignites at the center when $T_c \approx 10^8$ K. It should be emphasized that the presence of semi-convective layers above the convective core makes the modeling of central He-burning very sensitive to the numerics and physical input (see Straniero et al. 2003). The result is that large variations of core masses can be observed between different sets of models with important consequences for the subsequent evolution (§ 4).

2.2. Carbon Burning Phase

At central He-exhaustion, core contraction resumes and as the neutrino emission rises, the peak temperature ($T_{\rm max}$) moves outward. In low and intermediate mass stars, the increase in $T_{\rm max}$ ceases when core contraction is put to a halt by the re-ignition of the HBS. In SAGB stars owing to their larger core mass, $T_{\rm max}$ reaches $\sim 7 \times 10^8$ K and carbon ignites off-center in partially degenerate matter. As energy is deposited by the $^{12}\mathrm{C} + ^{12}\mathrm{C}$ reactions the temperature increases but the mechanical response is delayed by the partial degeneracy. Therefore heat accumulates at the ignition point and the temperature gradient increases, leading to the development of a convective flash. The luminosity associated with this instability can be as large as 10^7 L$_\odot$ in the (more degenerate) lower-mass SAGB stars, and in our 10.5 M$_\odot$ models it reaches $\sim 2.5 \times 10^6$ L$_\odot$ (Figure 2). The energy released during carbon ignition is first absorbed to lift the degeneracy and then mostly converted into mechanical work. The large expansion that ensues is then responsible for the quenching of the instability as the temperature drops in the nuclearly active region. Thereafter core contraction resumes and the temperature starts to increase again in the central regions. The peak temperature moves inward and carbon burning is re-activated deeper in the star. However, the ignition conditions are now different: the degeneracy is lower ($\eta = 1$ compared to 2–3 during the flash) and when the secondary convection zone appears it grows in a region that was previously occupied by the flash. Less fuel is available to power the instability and a smaller expansion ensues, allowing for the development of a stable convective flame. In a thin radiative zone a few kilometers wide located just below the convective flame, most of the nuclear energy is produced. There, in the so-called precursor flame, the luminosity profile is negative, indicating that energy flows inward. The precursor flame pre-heats

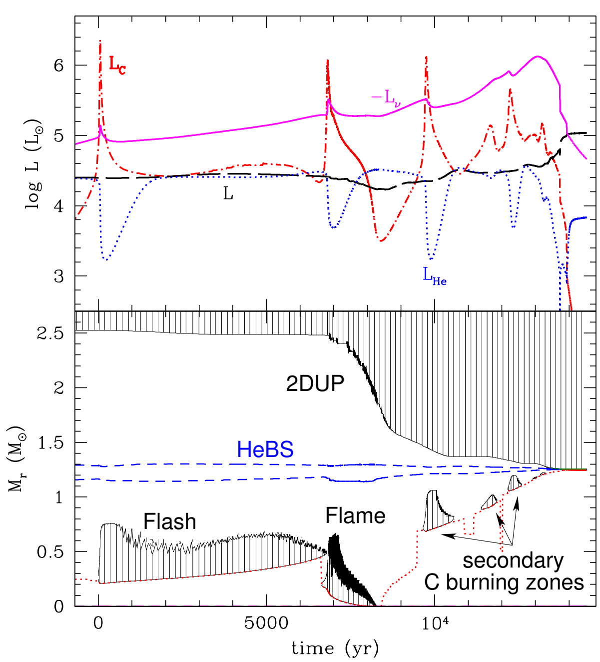

Figure 2. (*Lower panel*): Kippenhahn diagram of a $Z = 0.02$, $M = 10.50$ M$_\odot$ star during the carbon burning phase. The origin of time has been shifted to the beginning of the carbon flash. The dashed lines delineate the HeBS and the dotted line, the locus of maximum nuclear energy production by C burning. (*Upper panel*): Energetics of the carbon burning phase. The neutrino (L_ν, *solid line*), He ($L_{\rm He}$, *dotted line*), carbon ($L_{\rm C}$, *dotted-dashed line*) and surface (L, *long-dashed line*) luminosities are shown. During this phase the HBS is extinguished.

the material ahead of the convective flame, modifies the temperature gradient and allows the convective zone to move inward, engulfing at the same time the ashes of C burning.

When the flame reaches the center (after ~ 8000 yr in our $10.5\,M_\odot$ model), convection disappears and carbon burning proceeds radiatively around the newly formed neon-oxygen core. As can be seen from Fig. 2, secondary convective zones can eventually develop at the re-ignition of carbon pockets. During this phase, carbon burning is powered by $^{12}C(^{12}C,\alpha)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$ reactions followed in third place by $^{16}O(\alpha,\gamma)^{20}Ne$ (Siess 2006a). As a result, at the beginning of the SAGB phase, the core is mainly made of ^{16}O (55–60% by mass) and ^{20}Ne (29–32%) with some traces of ^{23}Na (5–6%) and ^{24}Mg (3%).

2.3. The Second Dredge-Up in Massive AGB Stars

The second dredge-up is an important event in the evolution of SAGB stars not only because it modifies the surface composition but also because it has the potential of hampering the formation of a supernova by reducing the size of the H-depleted core. Depending on the initial stellar mass, the second dredge-up (2DUP) can take place before, during (as for the $10.5\,M_\odot$ model) or after carbon burning (see Garcia-Berro et al. 1997 for details). The occurrence of this deep mixing event is simply related to evolutionary timescales. Lower mass stars evolve more slowly and the envelope has enough time to deepen before carbon ignites. Massive stars, on the other hand, avoid the 2DUP and evolve through all nuclear burning stages. An interesting evolutionary feature taking place in the upper mass range of the SAGB stars is the occurrence of the so-called dredge-out phenomenon (Iben et al. 1997; Siess & Pumo 2006). As illustrated in Figure 3, near the end of carbon burning a convective zone develops in the He-burning shell (HeBS). The instability grows in mass and eventually reaches the H-rich envelope where it merges. The consequences of this event are important since

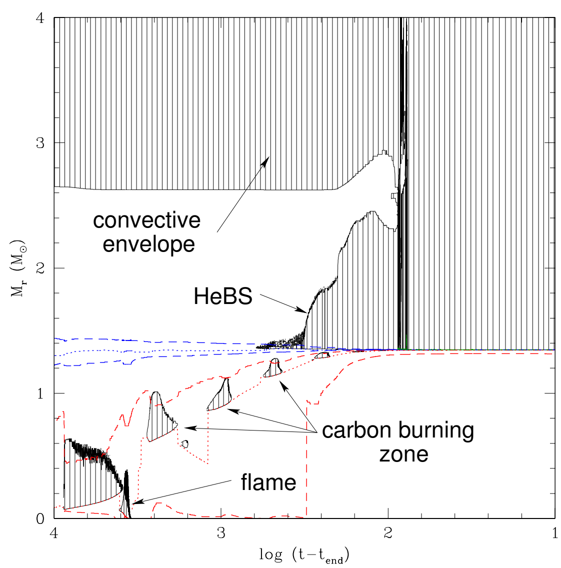

Figure 3. The dredge-out phenomenon taking place in a $10.8\ M_\odot$ star of solar composition. During this event, the convective zone that develops in the helium burning shell (HeBS) grows in mass and merges with the envelope.

it produces a strong surface enhancement of ^{12}C and ^{4}He and decreases the H-depleted core mass below the Chandrasekhar mass limit.

2.4. The Thermally Pulsing SAGB Phase

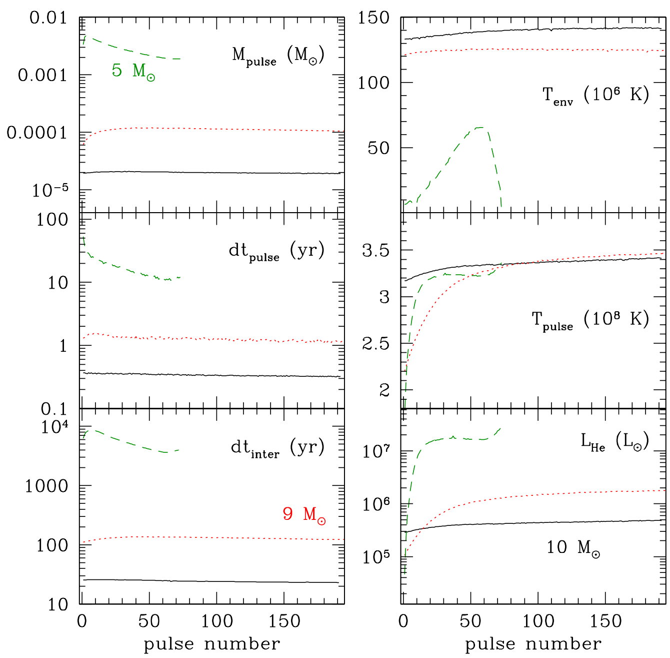

Figure 4. Selected properties of the thermally pulsing phase of a 5 (*dashed line*), 9 (*dotted line*) and 10 $M_\odot$ (*solid line*) star as a function of pulse number for stars with a metallicity $Z = 0.004$. The quantities shown are the pulse mass ($M_{\rm pulse}$) and duration (${\rm dt}_{\rm pulse}$), interpulse period (${\rm dt}_{\rm inter}$), maximum He luminosity during the pulse ($L_{\rm He}$), maximum pulse temperature ($T_{\rm pulse}$) and mean interpulse temperature at the base of the envelope ($T_6^{\rm env}$ in units of 10^6 K).

After completion of the second dredge-up, if the NeO core mass is less than $1.37\,M_\odot$ (Nomoto 1984), the star enters the thermally pulsing SAGB (TP–SAGB) phase. Similarly to standard AGB stars, the evolution along the asymptotic giant branch is characterized by the occurrence of recurrent thermal instabilities in the HeBS. However, the properties of the pulses (Figure 4) are quite different from those of intermediate mass AGB stars. First, they are much weaker in terms of He-generated luminosity. Values are typically one or two orders of magnitude smaller than in standard AGB stars and range between 10^6 and $10^7\,L_\odot$. This feature is attributed to the higher pulse temperature which lowers the degeneracy and makes the contribution of the radiation pressure to the total pressure larger than in standard AGB stars (Siess 2006b). As a result, when the instability develops, the temperature increase is rapidly quenched by the fast mechanical response of the structure, since $P_{\rm rad} \propto T^4$. Second, the pulse frequency is much shorter. This is a logical expectation since larger core masses lead to shorter pulse and interpulse durations. Quantitatively, the interpulse period decreases from $\sim$4000 yr at $5\,M_\odot$ to 100 yr at $9\,M_\odot$ and to only 20 yr at $10\,M_\odot$! These numbers imply that $\sim 500 - 1000$ pulses may occur before the envelope is lost. It is worth noticing that the pulse mass is also very small in SAGB stars. It accounts at most for $10^{-4}\,M_\odot$ which is very small compared to the envelope mass ($\sim 10\,M_\odot$). Finally, SAGB stars can develop extremely high temperatures at the base of their convective envelope that approach 150×10^6 K. The nucleosynthetic consequences of the induced hot-bottom burning (HBB) will be presented in the next section.

In summary, because of their larger core mass, SAGB stars develop smaller and weaker thermal pulses, which repeat more rapidly than in standard AGB stars. The gravitational pull of the NeO core increases the compressional effects leading to higher temperatures at the base of both pulse and envelope.

Concerning the occurrence of third dredge-up (3DUP) episodes, it is now clearly established that some kind of extra mixing at the base of the convective envelope must be included in the stellar modeling to trigger this phenomenon. It should however be stressed that because of the relative weakness of the thermal pulses in SAGB stars, the HBS shell is never extinguished, and this may hinder the penetration of the envelope into the deep layers occupied by the pulse. Our simulations indicates that in the absence of mixing, the 3DUP is absent, but when a diffusive treatment of overshooting is implemented, we find that after a few instabilities the 3DUP develops. Stars with extra-mixing and 3DUP tend to develop stronger thermal pulses, have longer interpulse periods and also a lower envelope temperature. It will turn out that these structural effects have more impact on the yields than the envelope pollution by the 3DUP episodes.

3. Surface Chemical Evolution and Nucleosynthesis

Prior to the TP–SAGB phase, the surface composition is modified by the first and second dredge-ups. In both cases the envelope reaches the HBS and brings to the surface the products of the CNO cycle leading to a surface enrichment in ^{3,4}He, ^{14}N, ^{13}C and to a decrease in H, ^{12}C and O mainly. As far as the chemical composition is concerned, the effects of the 1DUP on SAGB stars are indistinguishable from those on intermediate mass stars. Concerning the 2DUP, differences can be noticeable particularly for the most massive SAGB stars where the envelope reaches the top of the HeBS, leading to an increase in ^{4}He, ^{12}C and also in ^{26}Al. Concerning core He burning, the central temperature remains too low for the activation of the ^{22}Ne(α,n) reactions and no convective *s*-process nucleosynthesis is expected during this phase, contrary to the case of massive stars. The main products of carbon burning (^{16}O, ^{20}Ne, ^{23}Na and ^{24}Mg) will remain in the core and will not affect the surface composition, provided of course that the electron capture SN channel is avoided.

3.1. Hot-Bottom Burning

The main modifications to the surface composition take place during the TP–SAGB phase as a consequence of HBB. As previously stressed, SAGB stars develop very high temperatures at the base of their envelope allowing for the activation of all proton-burning modes, the CNO cycle and the NeNa and MgAl chains. The effects on the surface abundances are illustrated in Figure 5. The operation of the CNO cycle leads to the production ^{14}N at the expense of ^{12}C and, for the temperatures considered, the ^{12}C/^{13}C ratio settles to its equilibrium value of ~ 4. ^{4}He is produced but the effects on the surface composition are weak, except that ^{3}He is strongly depleted. The activation of the NeNa chain leads to the production of ^{22}Ne which is then converted into ^{23}Na. As can be seen from Fig. 5, at high temperatures ($T_6^{\rm env} \gtrsim 100$) there is an important leakage to the MgAl chain by the ^{23}Na(p,γ) reaction and the abundance of ^{23}Na decreases below its initial early-AGB value. Above $T_6^{\rm env} \gtrsim 70$, ^{24}Mg is also efficiently

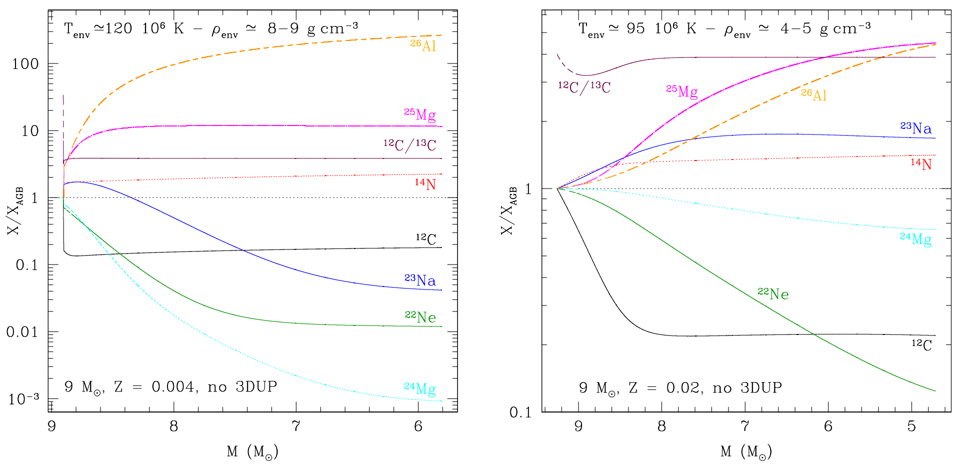

Figure 5. Evolution of the surface mass fraction of selected nuclei as a function of stellar mass for two SAGB models characterized by different values of the temperature at the base of their convective envelope ($T_6^{\rm env}$). The abundances have been normalized to their values at the beginning of the TP–SAGB phase. Note the differences in the y-scale.

destroyed by proton captures (Arnould et al. 1999) which contributes to the large production of ^{25}Mg and, after another (p,γ) reaction, of ^{26}Al. The lifetime of ^{26}Al (7.05×10^5 yr) is on the order of or longer than the SAGB lifetime, and given the slowness of the ^{26}Al(p,γ) reaction, only a small amount of ^{27}Al can be produced, allowing for the building up of this element.

In summary, during their TP–SAGB, stars in the mass range $\sim 7 - 11\,{\rm M}_\odot$ will produce a considerable amount of ^{14}N, slightly increase their ^{4}He content, significantly enrich their envelope in ^{25}Mg and ^{26}Al, destroy most of their ^{3}He, and potentially produce ^{23}Na.

3.2. Yields and the Effects of the 3DUP

Inside the thermal pulses, a unique nucleosynthesis takes place as a result of the ingestion of the ashes of H-burning in a region of high temperature where helium burning proceeds (see Forestini & Charbonnel 1997 for details).

The very high temperatures found at the base of the convective pulses enable the activation of the ^{22}Ne(α,n) neutron source. However, considering the relatively short duration of the convective instability (~ 1 yr), the neutron irradiation may remain relatively small and the convective *s*-process moderate. The released neutrons participate in the production of the Mg isotopes through (α,n) and (α,γ) reactions on ^{22}Ne made previously by two α-captures on the ingested ^{14}N. The composition left after the thermal pulse is substantially different from that of the envelope and aside from ^{12}C and ^{16}O, it is characterized among other things by a relatively high abundance of ^{22}Ne and Mg isotopes.

In SAGB stars, the ratio of the pulse mass to the envelope mass is typically a hundred times smaller than in intermediate mass SAGB stars. The impact of the 3DUP on the surface abundances will therefore be much smaller. To estimate more quantitatively this effect we have developed a very simple synthetic

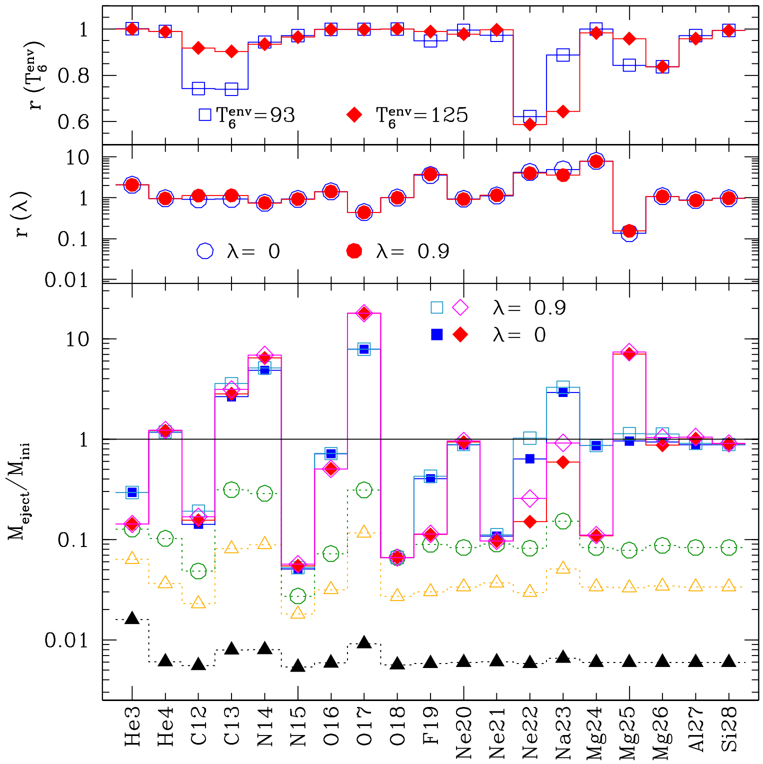

Figure 6. *Bottom*: Yields in terms of the ratio of the final ejected mass ($M_{\rm eject}[T_6^{\rm env}, \lambda]$) to the initial mass of the selected elements at different epochs of the evolution of a $9\,{\rm M}_\odot$ star at $Z = 0.04$. The final values (*squares* and *diamonds*) result from synthetic calculations (see text). The *filled* and *open triangles* indicate the mass ejected at the time of first and second DUP, respectively. The *open circles* refer to the time of the first thermal pulse. The *squares* and *diamonds* correspond to synthetic calculations with envelope temperatures $T_6^{\rm env} = 93$ and $T_6^{\rm env} = 125$, respectively. *Open* and *filled squares/diamonds* refer to models with $\lambda = 0.9$ and with $\lambda = 0$, respectively. *Middle*: Ratio of the final ejected masses of the models with the high and low $T_6^{\rm env}$ for $\lambda = 0$ (*open circles*) and $\lambda = 0.9$ (*filled circles*). $r(\lambda) = M_{\rm eject}[125, \lambda]/M_{\rm eject}[93, \lambda]$. *Top*: Ratio of the final ejected masses of the models with and without 3DUP for $T_6^{\rm env} = 93$ (*open squares*) and $T_6^{\rm env} = 125$ (*filled diamonds*). $r(T_6^{\rm env}) = M_{\rm eject}[T_6^{\rm env}, 0.9]/M_{\rm eject}[T_6^{\rm env}, 0]$. The data up to the first thermal pulse come from the full computation of a $9\,{\rm M}_\odot$, $Z = 0.04$ stellar model. The parameters for the synthetic models are: ${\rm dt_{inter}} = 250\,{\rm yr}$, $\dot{M}_{\rm core} = 6 \times 10^{-7}\,{\rm M_\odot yr^{-1}}$ and $\dot{M}_{\rm loss} = 10^{-4}\,{\rm M_\odot yr^{-1}}$.

AGB evolution code which assumes (*i*) that the temperature at the base of the envelope remains constant, (*ii*) that the characteristics of the pulse, i.e. composition, mass and interpulse period do not change during the evolution, (*iii*) that the 3DUP efficiency (parameter λ) remains fixed, and (*iv*) that the mass loss and core growth rates are also constant (see Marigo in this volume for accurate synthetic modeling). With these assumptions, we can compute the evolution of the envelope composition taking into account mass loss, pollution by the 3DUP episodes and nuclear burning by HBB.

Although this model is highly simplified and may not be very accurate, it illustrates the overall small impact of the 3DUP on the yields (compare the open and filled squares/diamonds in Figure 6). The synthetic calculations indicate that the effects of the 3DUP are weak and account for at most a 40% change (top panel). The differences mainly concern ^{12}C and as a result of HBB ^{13}C, ^{22}Ne and its by-product ^{23}Na as well as ^{25}Mg. This study also reveals that the yields are much more sensitive to the temperature at the base of the convective envelope than to the 3DUP pollution. In particular we see from the middle panel of Fig. 6 that changing $T_6^{\rm env}$ for a given λ can change the final amount of ejected mass by almost an order of magnitude. The most affected elements are those entering the NeNa and MgAl chains and particularly ^{26}Al, the production of which by ^{25}Mg(p,γ) is boosted as the temperature increases. But 3DUP and envelope temperature are not completely disconnected. Indeed, the deepening of the convective envelope in the pulse region modifies the stellar structure. Our computations including diffusive overshooting show that when the 3DUP is present, the temperature at the base of the convective envelope is $\sim$ 10–15 % lower.

In conclusion, it is safe to say that the presence of 3DUP episodes in SAGB stars will not substantially affect the yields. However, the structural effects induced by the 3DUP (mainly associated with the decrease in $T_6^{\rm env}$) may have severe consequences on the ejected composition.

4. Conclusion and Discussion

Assuming a Salpeter initial mass function, stars in the mass range $\sim 7-11.5$ M$_\odot$ account for a substantial fraction of the overall stellar population. In fact, there are as many SAGB stars in this mass interval as massive stars with $M \geq 11.5$ M$_\odot$ which emphasizes the important role they may play in the chemical evolution of galaxies. Our study reveals that SAGB stars are important providers of ^{4}He, ^{13}C, ^{14}N, but they can also produce a large amount of ^{22}Ne, ^{23}Na, ^{25}Mg and ^{26}Al. This latter element is particularly interesting since its observations by γ-ray observations gives an instantaneous snapshot the nucleosynthetic activities in the region under scrutiny and could be used as a tracer of the SAGB population. When trying to be more quantitative, we enter the realm of uncertainty. Contrary to the "standard" AGB, the yields of SAGB appear not to be very sensitive to the 3DUP phenomenon, which is somehow good news, but they critically depend on the temperature at the base of the convective envelope which is unfortunately highly dependent on the treatment of convection (Ventura & D'Antona 2005). Galactic chemical evolution models also need knowledge of the mass range covered by SAGB stars. As introduced, SAGB stars lie between $M_{\rm up}$ and $M_{\rm mas}$ but in this mass interval another evolutionary path can be taken. If during the TP-SAGB phase the core grows beyond 1.37 M$_\odot$ (Nomoto 1984), electron capture reactions are initiated and the induced core collapse leads to the formation of a neutron star. The minimum initial mass for a star to undergo electron-capture supernova (EC-SN), referred to as $M_{\rm n}$, strongly depends on the mass loss and core growth rates which are not very well constrained (Siess & Pumo 2007). This is particularly prejudicial because the contribution of SAGB stars to the galactic chemical evolution depends on the outcome of their evolution: a NeO white dwarf with the expulsion of an envelope processed by HBB,

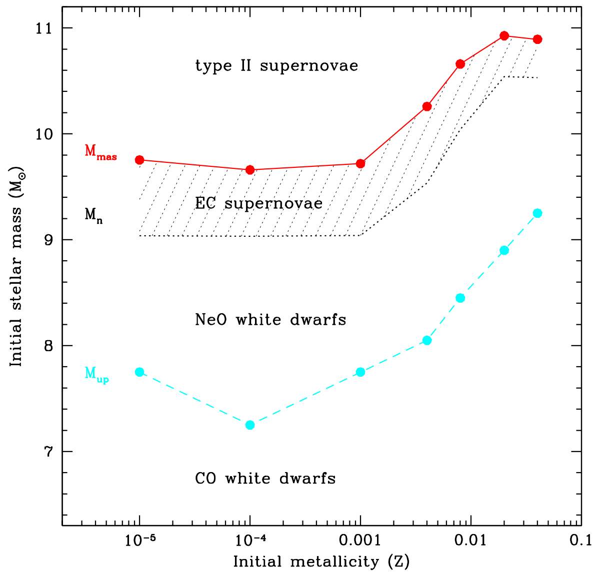

Figure 7. Mass transitions for models without core overshooting as a function of initial metallicity. Stars with initial mass less than $M_{\rm up}$ will not ignite carbon and will leave a CO white dwarf. Between $M_{\rm up}$ and $M_{\rm n}$, the remnant is a NeO WD. Inside the shaded area, depending on the adopted values for the core growth and mass-loss rates, the SAGB star can evolve toward electron capture supernovae. Stars with mass larger than $M_{\rm mas}$ behave as massive stars and end their life as iron core collapse SN (see also Pumo & Siess in this volume).

or a supernova-type explosion. It should be emphasized that the presence of extra-mixing strongly affects the value of these different transition masses. Our simulations including overshooting at the edge of the He core show that all the masses can be shifted downward by $\sim 1.5-2\,{\rm M}_\odot$, thus affecting the number and mass distribution of SAGB stars. Figure 7 shows the dependence of $M_{\rm up}$, $M_{\rm n}$ and $M_{\rm mas}$ on initial composition. Aside from the fact that, because of opacity effects, the mass transitions decrease with metallicity (except at very low Z), it is worth noting that the EC-SN channel exists and is highly dependent on the stellar parameters. Anyhow, this evolutionary path remains limited to a very narrow mass range of less than $1\,{\rm M}_\odot$ width.

In conclusion, the mass interval occupied by SAGB stars is critically dependent on physical parameters such as mass loss and the presence of 3DUP or extra-mixing, and the quest of stellar yields for the SAGB stars will require the exploration of a large parameter space.

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Discussion

Cristallo: Which mass-loss rates are you using in your models?

Siess: Vassiliadis & Wood (ApJ 413, 641, 1993).

Schönberner: What is the luminosity of these super-AGB stars, and how does the luminosity compare with the core-mass–luminosity relation?

Siess: Super-AGB stars have a surface luminosity ranging between 20 000 and 70 000 $L_\odot$, which is significantly higher than intermediate mass AGB stars ($\lesssim$ 30 000 $L_\odot$). Concerning the core-mass–luminosity relation, because of efficient HBB, this relation will certainly not be satisfied for SAGB stars.

Wood: Do the thermal pulses affect the surface luminosity, especially toward the end when there is not much envelope mass left on the star?

Siess: Thermal pulses, although relatively weak, do affect the surface radius. After inspection of the models, I report that a variation of $\sim 7 - 10\,\%$ in radius is observed. The amplitude grows as the envelope mass decreases.

Busso: You have quite a substantial amount of ^{26}Al. Why don't you check if SAGB stars have any effect on the galactic distribution of ^{26}Al?

Siess: ^{26}Al is indeed an interesting radioactive nucleus. I will certainly pay attention to that element. These are preliminary results; this type of modeling is rather lengthy.

Tosi: It is very important for chemical evolution models to have accurate yields for the 7–11 $M_\odot$ range. Which other sets of yields for other masses will yours be more compatible with?

Siess: I would go for the Karakas and Lattanzio yields. The physics of our codes is becoming very comparable and they are the most complete to date.

"A fish of about that size", Lionel Siess