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Is there a chance for SNI1/2?

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The evolution of primordial stars of initial masses between 5 and 10 $M_{\odot}$ has been computed and analyzed in order to determine the nature of the remnants of massive intermediate–mass primordial stars and to check the influence of overshooting in their evolution. We have obtained the values for the limiting masses of Population III progenitor stars leading to carbon–oxygen and oxygen–neon compact cores. We have also obtained the limiting mass for which isolated primordial stars would lead to core–collapse supernovae after the end of the main central burning phases. Considering a moderate amount of overshooting, the mass thresholds at the ZAMS for the formation of carbon–oxygen and oxygen–neon degenerate cores shift to smaller values by about 2 $M_{\odot}$. As a by–product of our calculations, we have also obtained the structure and composition profiles of the resulting compact remnants. We find that the final fate of the considered stars could not be to become white dwarfs, as it is the case of objects of larger metallicity of analogous initial masses. Instead, as we show by means of a synthetic code, they might end their lives as SNI1/2.

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1. Introduction

Even though the precise limits are unknown, it has been generally accepted that single stars less massive than $\sim 10 M_{\odot}$ end their lives as white dwarfs, whereas stars whose mass in the ZAMS is larger than this limit explode as supernovae. However, recent calculations, specially those corresponding to primordial or extremely metal–poor stars are sheding doubts on the fate of intermediate–mass stars — see, for instance, Refs. [1, 2, 3, 4, 5]. The main reasons for these uncertainties are the unknowns relating the mixing of isotopes and the stellar winds during the thermally–pulsing (Super)AGB phase. Moreover, the situation is complex because both phenomena are connected.

Convection in stellar interiors still lacks a completely satisfactory treatment in one–dimensional codes mainly because it is, by its nature, a multidimensional phenomenon. The mixing parameters in the cases of stars whose metallicity is similar to the solar value can be callibrated by comparison with observations, but this is not the case for primordial and the most metal–poor stars. The physical peculiarities of these objects also make things complicated because their evolution is characterized by strong thermonuclear flashes that alter the stellar structures, the nucleosynthesis and the ongoing mixing processes [6]. The new perspectives in this sense are promising, as the results from multidimensional calculations are beginning to be introduced in the one–dimensional models [7, 8]. Therefore, it is expected that more realistic results may eventually be obtained during the next few years.

Here we explore how the peculiarities of the mixing processes and the choice of the prescription for the mass–loss rates due to stellar winds determine the fate of intermediate–mass stars of primordial composition, and we assess whether they end their lives as white dwarfs, as it is the case of solar metallicity stars of analogous masses, or as SNeI1/2 [9]. The end of the old generations of stars as white dwarfs or as supernovae would have profound consequences on the chemical evolution of the Galaxy, and might be a necessary factor to complete its understanding [10, 11]. Additionally, an accurate knowledge of how primordial and very old stars lived and died will undoubtely help us to better understand the reionization history of the Universe.

Finally, it is important to realize that the IMF of primordial and ultra–metal poor stars is the subject of an active debate. A number of calculations have pointed to the possibility that pristine hydrogen– and helium–clouds would be unable to fragmentate into the precursors of non–massive stars, and instead, primordial stars would have masses between 100 and $600 M_{\odot}$ [12]. However, other works have proposed that rotation and vibrations of HD molecules could act as efficient coolants to allow fragmentation into clouds that would form stars of low and intermediate mass [13]. In addition, accurate multidimensional simulations of the growth of instabilities of primordial clouds have been made [14, 15] which show that the primordial IMF should be a bimodal function with a main peak around $100 M_{\odot}$ and a secondary peak around $1 M_{\odot}$. Therefore, the evolution of intermediate–mass primordial stars is worth considering and has already been studied in a series of recent papers [6, 16, 17, 18].

We have organized the present work as follows. Section 2 describes the treatment of the overshooting used for the calculations and the evolution of intermediate–mass primordial stars during the main central burning stages. Section 3 considers the evolution during the early stages of the TP–(S)AGB. Section 4 is devoted to obtain hints of the final fate of our model stars by means

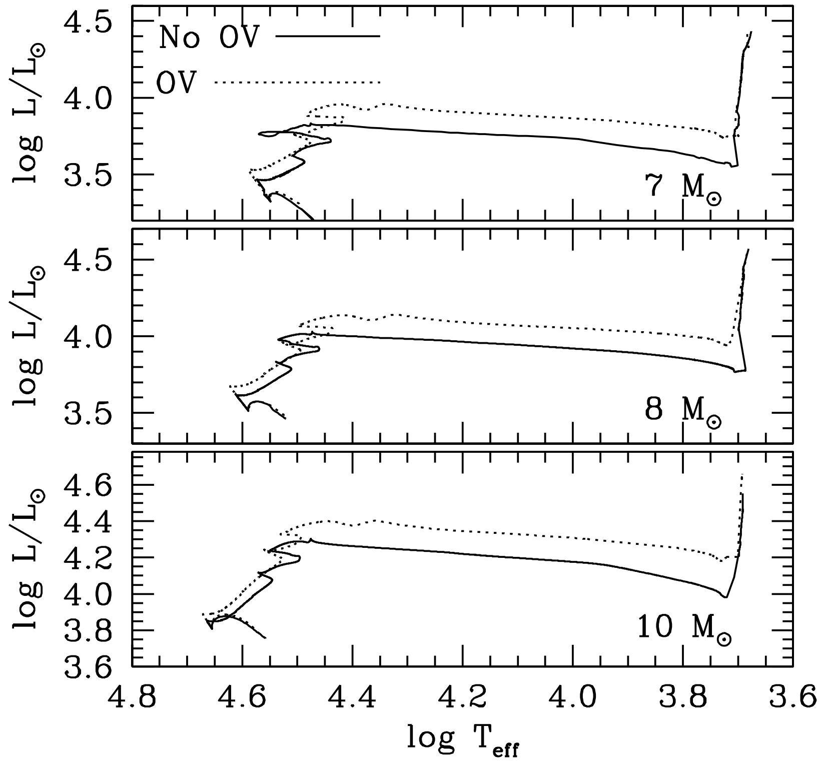

Figure 1: Evolutionary tracks in the Hertzsprung–Russell diagram of our model stars. The solid lines correspond to the case in which overshooting was disregarded, whereas the dotted lines show the evolution for the case in which overshooting was taken into account.

of a simplified synthetic code. In the last section we summarize our findings and draw the main conclusions of our work.

2. Evolution previous to the TP-(S)AGB phase

The results of the calculations presented in this work have been obtained using the evolutionary code described in Ref. [4]. We have computed evolutionary sequences of primordial stars with masses between 5 and $10 M_\odot$, with and without overshooting. In order to understand the effects that overshooting produces in this mass and metallicity ranges we have followed closely the implementation detailed in Ref. [19], which itself evolves from that explained in Ref. [1]. Therefore, convection is extended beyond the formal limits set by the Schwarzschild criterion to zones where $\nabla_{\rm rad} > \nabla_{\rm ad} - \delta$, where δ is given by

$$\delta = \frac{\delta_{\rm OV}}{2.5 + 20\zeta + 16\zeta^2} \tag{2.1}$$

being $\zeta = P_{\rm rad}/P_{\rm gas}$ and $\delta_{\rm OV}$ is equal to 0.12 [19].

The hightlights of the evolution during the main central burning stages are the following. Both the core hydrogen–burning phase and the core helium–burning phase occur at the left hand side of

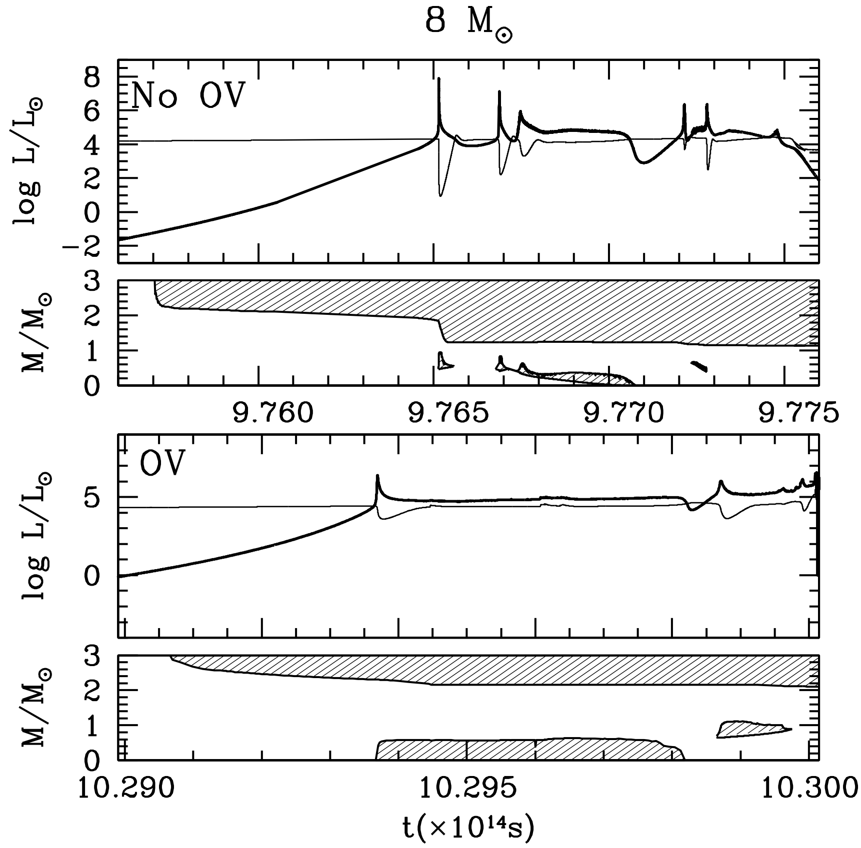

Figure 2: Temporal evolution of the main structural parameters during the bulk of the carbon burning phase for the $8\,M_{\odot}$ model computed without overshooting (upper panel) and with it (bottom panel). The shaded areas represent the evolution of the convective regions, the thick solid line depicts the evolution of the carbon burning luminosity and the thin solid line shows the helium burning luminosity.

the Hertzsprung–Russell diagram — see Figure 1. Opposite to what occurs for solar metallicity stars, in which hydrogen burning in a shell causes the expansion and cooling of the outer layers of the stars and, therefore, the excursion to the red giant branch, zero metallicity stars have such compact cores at the end of the core hydrogen burning phase that helium burning sets very shortly afterwards. Therefore, primordial stars remain at the hot part of the Hertzsprung–Russell diagram and do not climb the giant branch until helium burning sets in a shell. This general behavior is independent of the implementation of overshooting but, depending on whether we consider it or not, the time scales for core hydrogen burning increase about by about 12% and the times required for core helium burning increase by about 6% when overshooting is taken into account. The sizes of the resulting carbon–oxygen cores also increase by about 25% when overshooting is considered.

Table 1 shows the times at which core hydrogen burning is completed ($t_{\rm CHB}$) and the time for which core helium burning is completed ($t_{\rm CHeB}$) for our different model stars, both for the cases in which overshooting is neglected and when overshooting is considered. The masses of the helium core after central hydrogen burning ($M_{\rm He}$) and those of the carbon–oxygen cores after central helium burning ($M_{\rm CO}$) are also included in Table 1.

$M_{ZAMS}/M_{\odot}$	t_{CHB} ($\times 10^{14}$ s)		$M_{He}/M_{\odot}$		t_{CHeB} ($\times 10^{14}$ s)		$M_{CO}/M_{\odot}$	
	no OV	OV	no OV	OV	no OV	OV	no OV	OV
5.0	19.8838	21.2417	1.17	1.32	23.6791	24.2174	0.64	0.80
6.0	13.8396	15.3209	1.18	1.60	16.2184	17.0675	0.65	0.90
7.0	10.5091	11.8733	1.20	2.23	12.1470	12.8494	0.83	1.15
8.0	8.3796	9.4119	1.48	2.30	9.7551	10.3818	1.09	1.38
9.0	6.8994	7.7360	1.85	2.35	8.0519	8.5778	1.18	1.50
10.0	6.0116	6.7436	2.09	2.38	6.8359	7.3791	1.30	1.76

Table 1: Main nuclear burning times and core masses.

Overshooting also has effects on the threshold masses required for complete carbon burning and the development of degenerate oxygen–neon cores in intermediate–mass primordial stars. This threshold mass is $7.8\,M_{\odot}$ for the case in which no overshooting is considered, but it decreases down to about $6\,M_{\odot}$ when overshooting is taken into account. Nevertheless, carbon burning occurs in a way very similar to that of solar metallicity stars. The ignition of carbon in a partially degenerate environment causes the development of strong flashes, with associated luminosities L_C of about $10^7 L_{\odot}$, and inner convective zones that occur as a consequence of the sudden energy release and increase of temperature near the zones where the flashes occur.

Figure 2 shows the time evolution of the luminosity associated to carbon burning (thick solid lines), and helium burning (thin solid lines), as well as the evolution of convective regions (shaded areas) during the carbon burning phase of our $8\,M_{\odot}$ model stars, both without overshooting (upper panels), and with overshooting (lower panels). When overshooting is taken into account, the smaller degeneracy parameters in the stellar interior still allow the development of a carbon flash, but once degeneracy is lifted after this flash the rest of this nuclear burning stage occurs in nearly stationary conditions, opposite to the rich sequence of carbon flashes that characterizes carbon burning in the model without overshooting.

As a summary of our main results, Table 2 shows the masses and compositions of the degenerate cores resulting after the main central burning stages. Figure 3 shows the composition profiles of the cores of the $7M_{\odot}$ model star computed without overshooting (left panel) and with overshooting (right panel). It is important to realize that the model computed without overshooting is unable to develop an oxygen–neon core, whereas the model of the same initial mass computed with overshooting develops an oxygen–neon core surrounded by a carbon–oxygen layer, as previously found in other studies [4].

3. Evolution during the early TP-(S)AGB phase

Once central hydrogen, helium and, in the corresponding cases, carbon burning have been completed, helium burning remains active in a shell that surrounds the stellar core and is able to sustain a deep convective envelope. At this stage, when the helium–burning shell is at a few times $10^{-4}M_{\odot}$ from the helium–hydrogen discontinuity, hydrogen reignites in a shell and the TP-(S)AGB begins. We follow the standard nomenclature [20] and use the term TP-AGB for those stars which have CO cores, and the term TP-SAGB for those which develop ONe cores. By TP-(S)AGB we

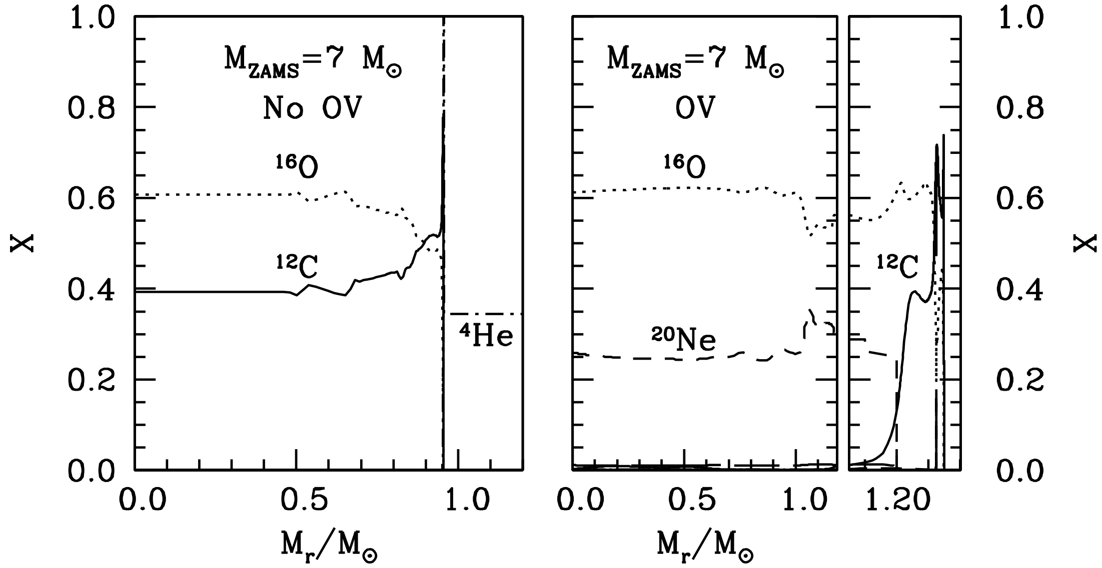

Figure 3: Left panel: composition profile of the core of the $7M_\odot$ star computed without overshooting. Right panel: same for the case computed with overshooting. In the small panel at the right there is a expanded view of the CO buffer.

$M_{ZAMS}/M_\odot$	$M_{CO}/M_\odot$	$M_{ONe}/M_\odot$	$\Delta M_{CO}/M_\odot$	X(C)/X(O)	X(Ne)/X(O)
5	0.90	—	—	0.60	—
6	0.92	—	—	0.62	—
7	0.96	—	—	0.65	—
8	—	1.11	0.025	—	0.56
9	—	1.18	0.015	—	0.47
10	—	1.33	0.010	—	0.35
5	0.94	—	—	0.60	—
6	—	1.00	0.070	—	0.50
7	—	1.20	0.200	—	0.42
8	—	1.34	0.002	—	0.36
9	—	1.36	0.008	—	0.35

Table 2: Characteristics of the cores at the end of our calculations for the model sequences computed without overshooting (top section) and with overshooting (bottom section).

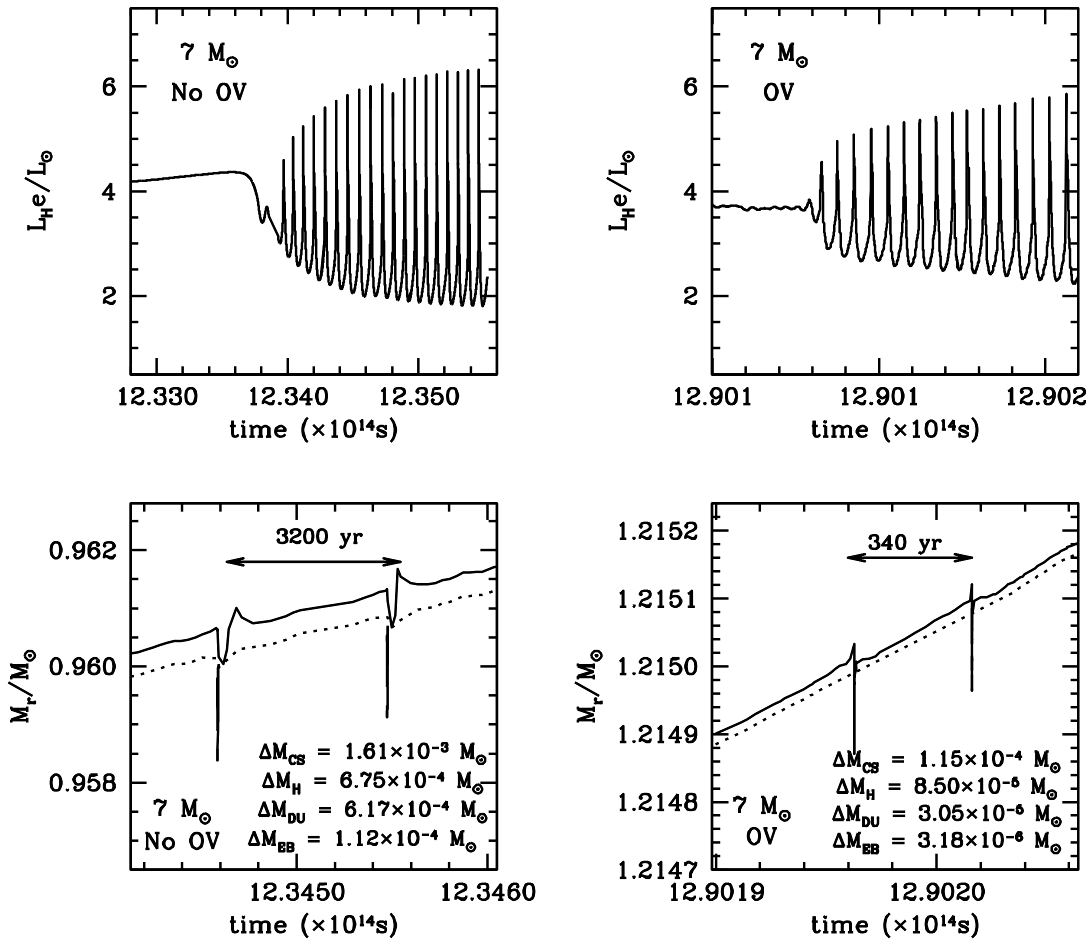

Figure 4: Upper panels: Time evolution of the helium luminosity during the early TP-(S)AGB of the $7M_{\odot}$ models computed without overshooting (left) and with overshooting (right). Lower panels: Temporal evolution of the edges of the convective shell and of the base of the convective envelope during the 8^{th} and the 9^{th} pulses of the $7M_{\odot}$ model star computed without overshooting (left panel) and the 23^{th} and 24^{th} pulses of the $7M_{\odot}$ computed with overshooting (right panel).

will mean both cases indistinctly. The TP-(S)AGB is characterized by the alternance of helium and hydrogen as main energy suppliers of the star. The hydrogen burning shell adds mass to the helium–rich layer beneath and, when a certain critical mass is reached, a helium flash develops. The associated energy release causes the formation of an inner convective shell, and the expansion and cooling of the layers above cause the switch–off of the hydrogen burning shell and the advance inwards of the base of the convective envelope. If the latter is able to reach the zones processed by helium burning, the corresponding isotopes will be dredged–up to the stellar surface. This is the so–called third dredge–up episode. When the helium flash is over, the associated inner convective zone disappears, the hydrogen burning shell recovers, the base of the convective envelope receeds, and the cycle repeats. It is important to mention at this point that the occurrence or not of the third

$M_{ZAMS}/M_\odot$	t_{core}	t_{env}^{SC}	t_{env}^{B}
5	3.0×10^6	6.2×10^9	2.6×10^8
6	1.9×10^6	2.1×10^9	1.2×10^8
7	1.2×10^6	3.1×10^8	7.7×10^6
8	1.1×10^6	4.1×10^7	6.7×10^5
9	0.7×10^6	2.9×10^7	3.4×10^5
5	9.0×10^6	4.1×10^8	6.6×10^6
6	7.2×10^5	4.3×10^7	7.0×10^5
7	5.0×10^5	6.8×10^6	4.2×10^4
8	1.7×10^5	1.2×10^7	3.1×10^5

Table 3: Timescales (in years) associated to core growth and loss of the envelope for the case in which no overshooting was taken into account (top section) and for the case in which overshooting was adopted (bottom section).

dredge–up is extremely model dependent but, at the same time, it is crucial for the determination of the final fate of primordial stars. Our model stars do not show any significant third dredge–up, as it has been also found in other recent studies [5], whereas other works on intermediate–mass primordial stars do show the effects of a third dredge–up episode [16].

In Figure 4 we show the evolution with time of the helium luminosity for our $7\,M_\odot$ computed without and with overshooting — left and right upper panels respectively. The lower panels show the evolution during two thermal pulses of the base of the convective envelope and the limits of the inner convective zones that accompany each helium flash. Relevant data, such as the values of ΔM_{CS}, the maximum mass of the convective shell, ΔM_H, the mass through which the hydrogen profile moves between pulses, ΔM_{DU}, the amount of mass dredged–up during pulse power–down and ΔM_{EB}, the mass of the outer edge of the convective shell and the base of the convective envelope, are shown on the bottom of the lower panels.

4. Probing the late stages of the intermediate–mass primordial star evolution

As already mentioned, according to our calculations the TP-(S)AGB evolution shows no signs of significant third dredge–up. Under these condition, a reasonable guess of the fate of the considered stars can be made by comparing the time required by their cores to reach the Chandrasekhar mass, t_{Ch}, with the time required by the stars to lose their envelopes, t_{env}. The values for t_{env} have been computed according to the different mass–loss prescriptions existing in the literature, both with and without a metallicity correction. This metallicity correction is usually expressed as $(Z/Z_\odot)^\alpha$, where an educated guess for α is 0.5. However, we stress that it is not clear yet whether this factor should be added or not to the standard mass–loss prescriptions when computing stellar evolution. The reason is that very metal poor stars appear naturally to be more compact and, therefore, the mass loss rates are lower than those of larger metallicity stars.

The results are shown in Table 3. As can be seen, when the prescription of Ref. [21] for the mass–loss rates is considered, t_{Ch} appears to be several orders of magnitude shorter than t_{env}. Therefore, our stars would be expected to explode as SNeI1/2. This prescription that is a modified

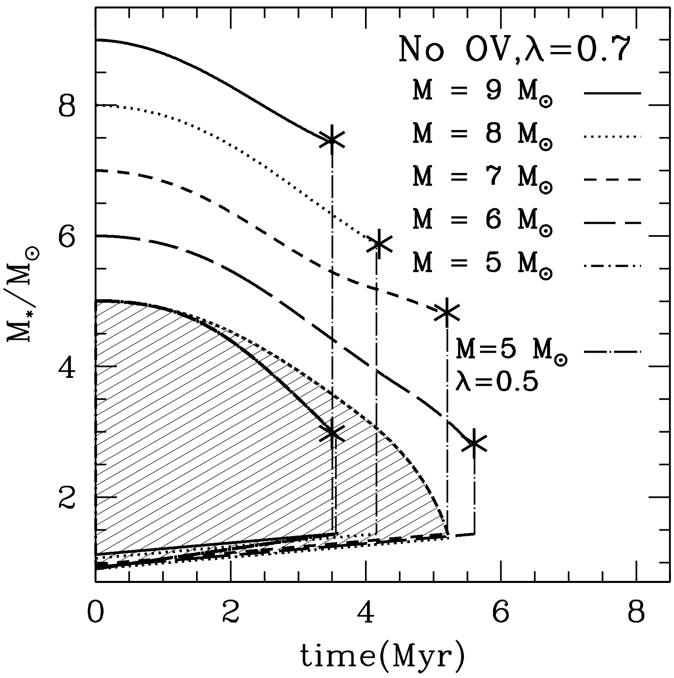

Figure 5: Possible fate of our 5, 6, 7, 8 and $9\,M_\odot$ models computed without overshooting, given a dredge–up parameter $\lambda = 0.7$. Mass–loss has been taken to account according to Ref. [22].

version of the classical Reimers law [22], is supposed to give reasonable results, even for the tip of the AGB:

$$\dot{M}_{\rm SC}(Z_\odot) = \dot{M}_{\rm R}(Z_\odot)\left(\frac{T_{\rm eff}}{4000}\right)^{3.5}\left(1+\frac{g_\odot}{4300\,g}\right) M_\odot\,{\rm yr}^{-1} \tag{4.1}$$

where $T_{\rm eff}$ is the effective temperature, g is the surface gravity, $g_\odot$ is the surface gravity of the Sun and $\dot{M}_{\rm R}$ is the Reimers mass–loss rate:

$$\dot{M}_{\rm R}(Z_\odot) = -4\times10^{-13}\eta_{\rm R}\,\frac{LR}{M}\,M_\odot\,{\rm yr}^{-1} \tag{4.2}$$

where $\eta_{\rm R}$ is a parameter such that $1/3 < \eta_{\rm R} < 3$. Another widely used mass–loss presciption is that of Ref. [23]

$$\dot{M}_{\rm B}(Z_\odot) = -4.83\times10^{-9}\frac{L^{2.7}}{{M_{\rm TP}}^{2.1}}\dot{M}_{\rm R}(Z_\odot)\,M_\odot\,{\rm yr}^{-1} \tag{4.3}$$

where $M_{\rm TP}$ is the actual mass of the considered star during the TP-(S)AGB phase and, therefore, decreases as mass is lost. Nevertheless it must be kept in mind that this prescription tends to yield consistently larger values than other generally accepted prescriptions [24, 25]. Note that even when this prescription is used, the formation of SNeI1/2 is allowed for the 5, 6 and $7\,M_\odot$ cases computed without overshooting. In any case it is important to point out that, qualitatively, our results coincide with the recent results reported in Ref. [5], where the entire TP-AGB phase was computed for primordial stars of masses $5\,M_\odot$ and $7\,M_\odot$, without overshooting.

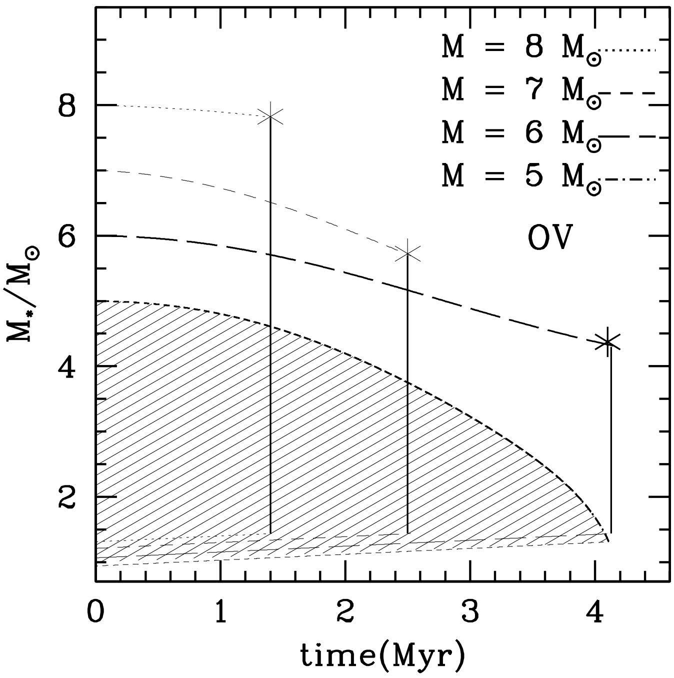

Figure 6: Possible fate of our 5, 6, 7 and $8M_\odot$ models computed with overshooting, given a dredge–up parameter $\lambda = 0.7$.

We have also contemplated the possibility that the absence of any significant third dredge–up, that supports the results of Table 3, were dependent on the physics and on the particular treatment of mixing in the convective regions implemented in the codes. To begin an early exploration of the final fate of primordial stars, we have built a toy synthetic code, following the approach of other recent works [26]. Our aim is to check the effects of changing the dredge–up efficiency:

$$\lambda = \frac{\Delta M_{\rm dredge}}{\Delta M_{\rm H}} \tag{4.4}$$

where $\Delta M_{\rm dredge}$ is the mass dredged–up from the region located between the hydrogen burning shell and the helium burning shell, and $\Delta M_{\rm H}$ is the variation of mass of the H–rich envelope due to hydrogen burning during the interpulse period [27].

We have performed a few tests with our synthetic code. As inputs to this synthetic code we have used the surface temperature and radius computed with our evolutionary code, as well as the masses and the compositions, both of the stellar cores and the envelopes. We have also adopted the Reimers mass–loss rate. To begin with, we have considered a fixed value for the dredge–up efficiency $\lambda = 0.7$, and we have computed the minimum mass required to form a SNeI1/2 — see Figure 5. In this figure those evolutionary sequences which end up forming a supernova are marked with an asterisk. Also, the lines at the bottom of the figure indicate the mass of the degenerate core, whereas the upper lines depict the evolution of the total mass of the considered stars. Note that with this relatively large value for λ, the $5M_\odot$ star becomes a white dwarf, but the $6M_\odot$ star ends up its life as a supernova. This is obviously also the case for the rest of more massive stars. When

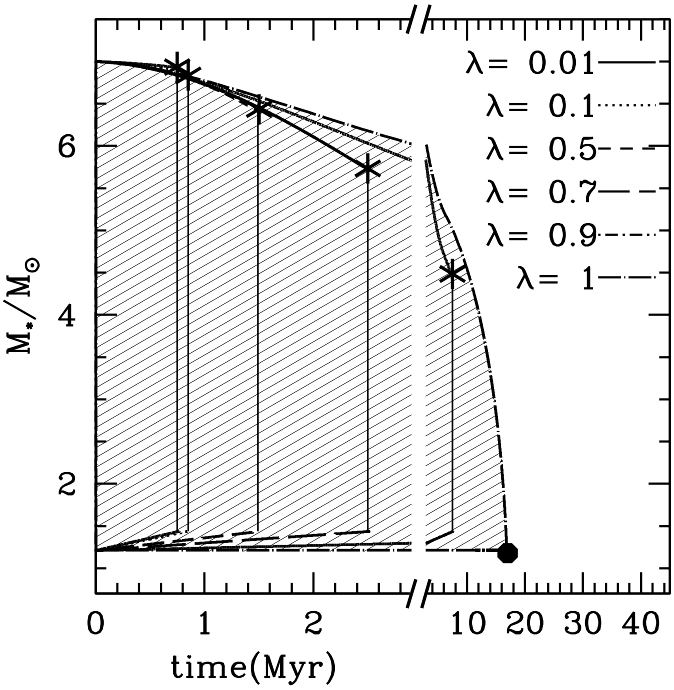

Figure 7: Possible fate of our $7 M_\odot$ model computed with overshooting, given different dredge–up parameters λ ranging from 0.01 to 0.7. Mass–loss rates have been computed according to Ref. [28].

overshooting is taken into account — see Figure 6 — the former result does not vary, and the maximum mass that allows for the formation of a white dwarf is still $5 M_\odot$. In order to probe the possible effects of the dredge–up efficiency, we have performed a second test in which we have considered a $7 M_\odot$ — see Figure 7. Note that in this case we have adopted the mass–loss rate of Ref. [28]:

$$\log \dot{M}(M_\odot\ \mathrm{yr}^{-1}) = -11.4 + 0.0125\, \{P(\mathrm{days}) - 100\,(M/M_\odot - 2.5)\} \tag{4.5}$$

$$\log P(\mathrm{days}) = -2.07 + 1.94 \log (R/R_\odot) - 0.9 \log (M/M_\odot) \tag{4.6}$$

For this case we have computed the approximate time evolution of the total stellar mass and its core mass for different values of the dredge–up efficiency ($\lambda = 0.0, 0.1, 0.5, 0.7, 0.9$ and 1.0). The case with $\lambda = 0.0$ would correspond to no third dredge–up, and that is exactly what we obtain with our evolutionary code, whereas the case $\lambda = 1.0$ would correspond to an efficiency of third dredge–up that does not allow core growth. It can be seen that in all cases except for $\lambda = 1.0$, which simply makes impossible the occurrence of SNI1/2, the stellar cores are able to reach M_{Ch} much earlier than the stellar winds are able to remove the hydrogen–rich envelopes. Therefore, these stars will end their lives as SNI1/2.

Finally, we have repeated the former test, but we have considered a prescription to describe stellar winds that yields much larger mass–loss rates [23]. Under these conditions only with the smallest values for the λ parameter efficiency can the $7 M_\odot$ star become a SNI1/2 — see Figure 8.

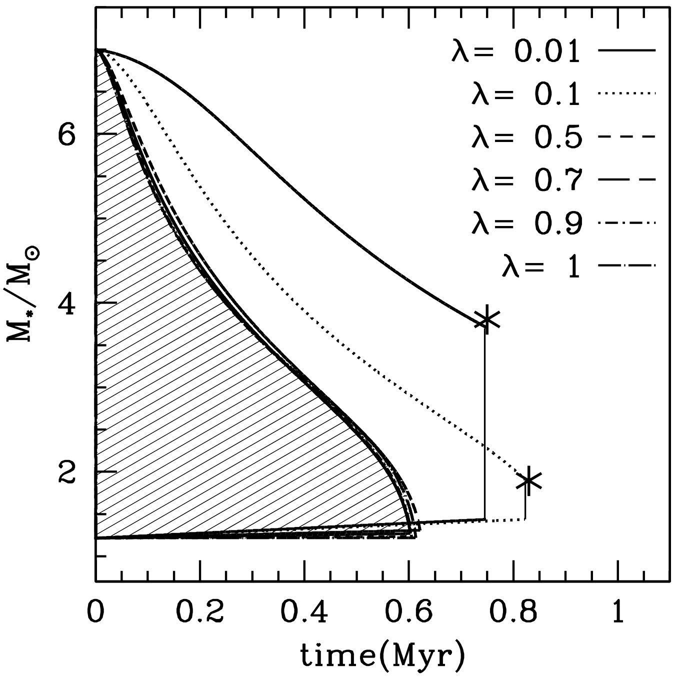

Figure 8: Possible fate of our $7\,M_{\odot}$ model computed with overshooting, given different dredge–up parameters from $\lambda = 0.01$ to 0.7. Mass–loss has been taken into account according to Ref. [23].

5. Summary and discussion

We have computed and analyzed the evolution of primordial stars of ZAMS masses between 5 and $10\,M_{\odot}$, from the main sequence, until the early stages of the TP-(S)AGB, both neglecting and taking overshooting into account. As a result, the main properties of the evolution as well as the values for the masses and composition of the resulting degenerate cores have been determined. We conclude that taking overshooting into account leads to an evolution that is similar to that of primordial objects computed without overshooting that are initially about $2\,M_{\odot}$ more massive than the considered star.

According to our calculations, our model stars do not experience a third dredge–up episode, and this result seems to be independent on overshooting. However, we stress that the treatment of mixing turns out to be crucial. In particular, other choices for the treatment of mixing or the inclusion of diffusion can possibly lead to different results. Furthermore, the uncertainties about the mixing cause uncertainities in the magnitude of the radiative winds (which are themselves one of the main unknowns in stellar evolution). We know that stars whose envelopes are very metal poor present more compact configurations and are only able to sustain relatively weak winds. If the mixing during the TP-(S)AGB of primordial or extremely metal–poor stars is negligible or very weak, the stellar envelope will remain slightly polluted, the winds induced will be small, and the stellar cores will be able to reach the Chandrasekhar mass in times that are several orders of magnitude shorter than the times required by the stars to lose their envelopes. In such cases the stars would end their lives exploding as SNI1/2. The explosion mechanism would be similar to that of a thermonuclear supernova, but they would show hydrogen in their spectra, as SNeII. But if mixing during the TP-(S)AGB, that is, the effects of the third dredge–up episode, are being underestimated in our calculations, and the pollution of the stellar envelopes are significant, the winds would be able to remove the envelope and leave almost naked degenerate cores. This has been assessed by means of a synthetic code. We have explored several mass–loss prescriptions as well as a wide range of mixing efficiencies during the third dredge–up. Depending on the magnitude of the mass–loss rates through radiative winds and on the mixing efficiency during the third dredge–up we have found that in most of the cases these stars would probably end–up their lives as SNI1/2, even when a moderately large third dredge–up efficiency is introduced.

Acknowledgments

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References

[1] Eldridge, J.J., & Tout, C.A., 2004, *MNRAS*, **353**, 87

[2] Poelarends, A.J.T., Herwig, F., Langer, N., & Heger, A., 2006, *Mem. SAI*, **77**, 846

[3] Gil–Pons, P., Gutiérrez, J., & García–Berro, E., 2007, *A&A*, **464**, 667

[4] Gil–Pons, P., Suda, T., Fujimoto, M.Y., & García–Berro, E., 2005, *A&A*, **433**, 1037

[5] Lau, H.B., Stancliffe, R.J., & Tout, C.A., 2007, *Am. Inst. Phys. Conf. Proc.*, **948**, 373

[6] Campbell et al., 2007, in *"The First Stars III"*, in press

[7] Arnett, D., 2008, in *"9th Torino Workshop"*, in press

[8] Herwig, F., 2000, *A&A*, **360**, 952

[9] Arnett, D., 1968, *A & Sp. Sci.*, **5**, 180

[10] Nomoto, K., Umeda, H., Maeda, K., & Ohkubo, T., 2003, *Nucl. Phys. A*, **718**, 277

[11] Tsujimoto, T., & Shigeyama, T., 2006, *ApJ*, **638**, L109

[12] Bromm, V., Coppi, P.S., & Larson, R.B., 2002, *ApJ*, **564**, 23

[13] Flower, D.R., *MNRAS*, **333**, 763

[14] Nakamura, F., & Umemura, M., 1999, *ApJ*, **515**, 239

[15] Nakamura, F., & Umemura, M., 2001, *ApJ*, **548**, 19

[16] Siess, L., Livio, M., & Lattanzio, J., 2002, *ApJ*, **570**, 329

[17] Chieffi, A., Domínguez, I., Limongi, M., & Straniero, O., 2001, *ApJ*, **554**, 1159

[18] Marigo, P., Girardi, C., Chiosi, C., & Wood, R., 2001, *A&A*, **371**, 152

[19] Schröder, K.P., Pols, O., & Eggleton, P.P., 1997, *MNRAS*, **285**, 696

[20] Ritossa, C., García–Berro, E., & Iben, I., 1996, *ApJ*, **460**, 489

[21] Schröder, K.P., & Cuntz, M., 2005, *ApJ*, **630**, L73

[22] Reimers, D., 1975, *Mem. Soc. R. Sci. Liège*, ser. 6, **8**, 369

[23] Blöcker, T., 1995, A&Ap **297**, 727

[24] Willson, L.A., 2000, *Ann. Rev. Astron. & Astrophys.*, **38**, 573

[25] Gallart, C., Zoccali, M. & Aparicio, A., 2005, *Annu. Rev. Astron. & Astrophys.*, **43**, 387

[26] Izzard, R.G., Tout, C.A., Karakas, A.I., & Pols, O., 2004, *MNRAS*, **350**, 407

[27] Karakas, A.I., Lattanzio, J.C, & Pols, O., 2002, *PASA*, **19**, 515

[28] Vassiliadis, E., & Wood, P., 1993, *ApJS*, **92**, 125

[29] Suda, T. et al., 2007, in *"The First Stars III"*, in press

[30] Young, P., Knierman, K.A., Rigby, J.R., & Arnett, D., 2003, *ApJ*, **595**, 1114