An Explosive End to Intermediate-Mass Zero-Metallicity Stars and Early Universe Nucleosynthesis

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Abstract. We use the Cambridge stellar evolution code STARS to model the evolution of $5\,M_\odot$ and $7\,M_\odot$ zero-metallicity stars. With enhanced resolution at the hydrogen and helium burning shells in the AGB phases we are able to model the entire thermally pulsing asymptotic giant branch (TP-AGB) phase. The helium luminosities of the thermal pulses are significantly lower than in higher metallicity stars so there is no third dredge-up. The envelope is enriched in nitrogen by hot-bottom burning of carbon that was previously mixed in during second dredge-up. There is no *s*-process enrichment owing to the lack of third dredge-up. The thermal pulses grow weaker as the core mass increases and they eventually cease. From then on the star enters a quiescent burning phase which lasts until carbon ignites at the centre of the star when the CO core mass is $1.36\,M_\odot$. With such a high degeneracy and a core mass so close to the Chandrasekhar mass, we expect these stars to explode as type 1.5 supernovae, very similar to Type Ia supernovae but inside a hydrogen rich envelope.

Keywords: stars: abundances – stars: AGB and post-AGB – stars: evolution – supernovae: general
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1. INTRODUCTION

The idea of a type 1.5 supernova or type I$\frac{1}{2}$ supernova is not new. Such supernova occur if a star's degenerate carbon/oxygen core grows up to near the Chandrasekhar mass before it loses its envelope. This possibility was suggested, for instance, by Arnett (1969), Iben & Renzini (1983), Willson (2000) and more recently by Zijlstra (2004). As the core mass approaches $1.38\,M_\odot$, carbon ignites and the thermal runaway in degenerate material cannot be delayed long enough to prevent an explosion from disrupting the entire star. Because the exploding star is a red supergiant with hydrogen-rich envelope, its spectrum and early light curve should closely resemble that of a supernova of type II. However, a substantial amount of radioactive Ni and Co is liberated by the exploding core thus producing a late exponential luminosity decline which could look like a type Ia supernova (Iben & Renzini 1983).

Lower metallicity stars have weaker stellar winds and thus their degenerate cores are able to grow to near the Chandrasekhar mass and carbon ignition can lead to thermonuclear runaway and explosion. The mass-loss rate of low-metallicity AGB objects is uncertain but it is highly probable that it is lower than at solar metallicity. A faster core growth rate also increases the possibility of supernova Type 1.5. Gil-Pons, Gutiérrez & García-Berro (2007) also reached the similar conclusion that supernovae of Type 1.5 are inevitable in the evolution of zero-metallicity stars between $5\,M_\odot$ and $7\,M_\odot$ based on estimates of the mass-loss rate and core-growth rate. However, they did not compute the full evolution and estimated the two rates from the first few pulses. In this paper, we describe the full computation of $5\,M_\odot$ and $7\,M_\odot$ models and shows that carbon ignition at the degenerate core does occur.

2. THE STARS CODE

We use the Cambridge stellar evolution code STARS to model the evolution of primordial intermediate-mass stars. It was originally written by Eggleton (1971) and has been updated by many authors such as Pols et al. (1995). Eldridge & Tout (2004) updated the opacity tables to use the latest OPAL calculations (Iglesias & Rogers 1996) and these new tables also account for changes in opacity with variations in the carbon and oxygen abundances. We use their zero-metallicity opacities in this work (Eldridge, private communication based upon calculations by Ferguson et al. (2005)). We do not use any prescription of overshooting in this work.

3. EARLY EVOLUTIONARY PHASES OF THE $7\,M_\odot$ MODEL

The evolution of our $7\,M_\odot$ zero-metallicity star differs significantly from higher metallicity stars because of the absence of carbon, nitrogen and oxygen. Hydrogen cannot be burned through the CNO cycle so it is burned via the proton-proton chain only. This chain is much less temperature dependent so zero-metallicity stars are considerably hotter than their higher metallicity counterparts and their main-sequence lifetimes are much shorter. At the start of the main sequence, a convective core is driven by the pp-chain. The core ceases to be convective while hydrogen is still abundant. The temperature rises and becomes hot enough that carbon is produced by the triple-α reaction before hydrogen is exhausted. Because carbon is present in a hydrogen-rich region, the CNO cycle can now take place and drive a convective region in the core again.

4. LATE AGB PHASES OF THE $7\,M_\odot$ MODEL

We have modelled the evolution of the $7\,M_\odot$ model through its entire thermally pulsing (TP) phase. There are 590 thermal pulses in 1.1×10^5 yr. The interpulse period is about 700 yr for the first few pulses and decreases to about 100 yr at the end of the TP phase. The core mass is $1.04\,M_\odot$ when the first thermal pulse starts. The maximum helium luminosity of our model never exceeds $10^{5.5}\,L_\odot$. The pulses are too weak to lead to any third dredge-up, in agreement with the work of Gil-Pons et al. (2007) (see Figure 1).

The issue of third dredge-up in AGB stars has been a contentious one for some time. It has been postulated that third dredge-up only happens in stars above a certain critical metallicity (Komiya et al. 2007). While our models agree with the work of Gil-Pons, Gutiérrez & García-Berro (2007) who find that third dredge-up is absent, both Chieffi et al. (2001) and Siess et al. (2002) find that third dredge-up does occur in their zero-metallicity intermediate mass AGB stars. Chieffi et al. (2001) treated the convective boundaries according to the prescription of Herwig et al. (1997) who use a mixing scheme so efficient that the composition discontinuity between the two burning shells is smoothed out. This seems to indicate the efficiency of third dredge-up depends on the treatment of convection and the inclusion of extra-mixing mechanisms such as convective overshooting. However, Gil-Pons, Gutiérrez & García-Berro (2007) find that the total amount of mass dredged-up is very small even when overshooting is included. Prescriptions that overshoot into the processed core generally raise the metallicity and make the behaviour more like that of stars of higher metallicity that do undergo deep third dredge-up (Stancliffe, Tout & Pols 2004; Stancliffe, Izzard & Tout 2005). For example, in recent models of super-AGB stars, Doherty & Lattanzio (2006) find that a $9.5\,M_{\odot}$ has a dredge-up efficiency of 0.7. Dredge-up efficiency is defined by the ratio of the amount of H-exhausted intershell matter mixed into the envelope to the amount of core growth during the interpulse period. However, Siess & Pumo (2006) find no third dredge-up. As they highlighted, the occurrence (or not) of third dredge-up depends sensitively on how one treats the convective boundaries, as well as whether one includes additional mixing mechanisms. The STARS code uses an arithmetic scheme for determining the diffusion coefficient for the mixing. It has typically given deeper dredge-up than found in other codes (Stancliffe, Tout & Pols 2004; Stancliffe, Izzard & Tout 2005) so it is significant that we find no dredge-up in these models when others do. It may be that we do not find third dredge-up because we do not apply extensive extra-mixing and we shall investigate this in future work.

Because helium burning already proceeds at a relatively high rate in the hotter burning shells during the interpulse period, the jump in helium luminosity during pulses is small compared to their higher metallicity counterparts. Later pulses are weaker and they cease altogether when the core mass reaches $1.1\,M_{\odot}$ (see Figure 2). The star then enters a quiescent evolutionary phase for about 1.8×10^{5} yr while the hydrogen and helium burning shells grow outward without any thermal pulses. The star reaches carbon ignition after 2.9×10^{5} yr.

We have also evolved a $5\,M_{\odot}$ model. The evolution is very similar to that of the $7\,M_{\odot}$ star. When thermal pulses begin when the core mass is only $0.92\,M_{\odot}$ and pulses cease when the core has grown to $1.05\,M_{\odot}$. Like the $7\,M_{\odot}$ star, it also enters a quiescent phase until carbon ignites degenerately in the core centre when the core mass reaches $1.36\,M_{\odot}$. The total time from the onset of thermal pulses to the onset of carbon ignition is 1.2×10^{6} yr, much longer than the $7\,M_{\odot}$ star because the whole thermally-pulsing AGB phase lasts much longer.

5. SUPERNOVAE TYPE 1.5 AND NUCLEOSYNTHESIS

Carbon ignition occurs at the centre under degenerate conditions when the core mass reaches $1.36\,M_{\odot}$. We plot a carbon ignition curve in Figure 3. It shows that the core ignites carbon degenerately at the centre before any other part of the star. In particular, the burning shell is not hot enough. The subsequent thermonuclear runaway (similar to a type Ia supernova) releases sufficient energy to blow the whole star apart.

The envelope is enriched in nitrogen by hot-bottom burning of carbon that was previously mixed in during second dredge-up. There is no *s*-process enrichment owing to the lack of third dredge-up. Despite the envelope, we would expect the explosion

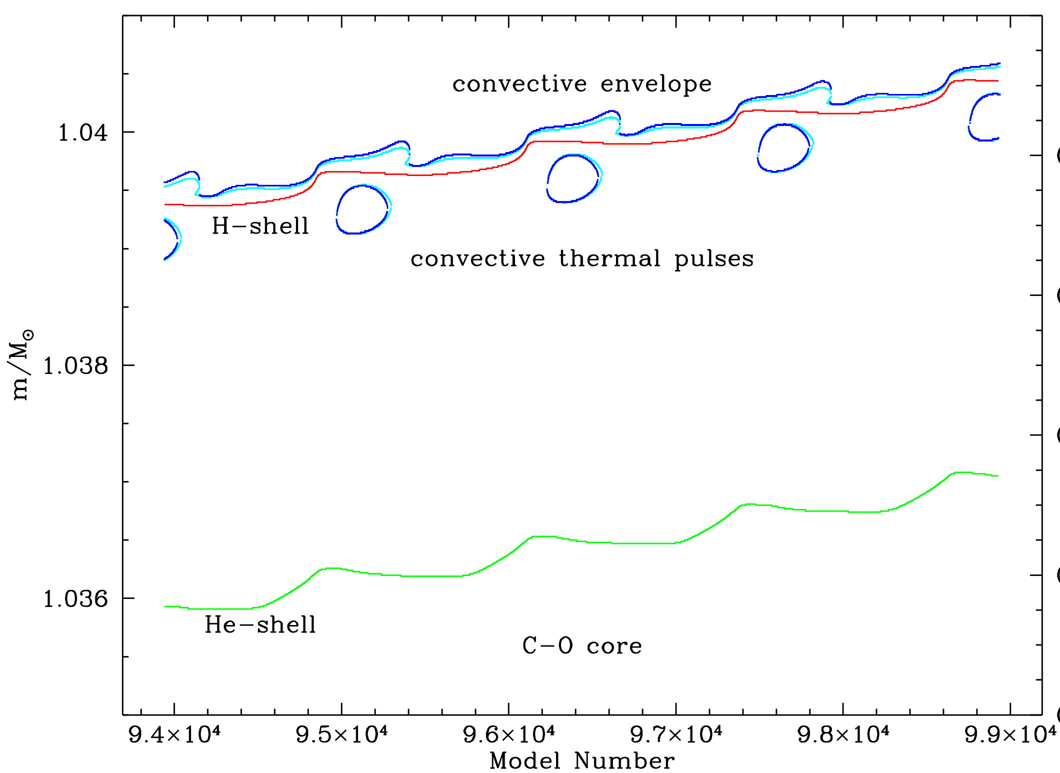

FIGURE 1. The internal structure of our $7\,M_\odot$ model close to the burning shells and its evolution. Model number increases monotonically with time but models are concentrated where changes are faster. The smoothest lines are the hydrogen and helium burning shells and the other lines convective boundaries. The helium core grows mostly during the thermal pulses when the burning drives an intershell convective zone. Hydrogen burning proceeds between the pulses. Though the convective envelope does deepen after each pulse they are too weak for third dredge-up.

mechanism of this star to be very similar to a Type Ia supernovae so we can estimate the nucleosynthetic yield from the exploding core depending on the explosion progress.

In both scenarios the two biggest yields are silicon and iron. The ^{28}Si yield is $0.142-0.272\,M_\odot$ and ^{56}Fe is $0.587-0.695\times10^{-1}\,M_\odot$. Such stars are important for the iron contribution in the early Universe. On the other hand, if the star is in binary system, the envelope may be lost before the ignition of carbon and the composition of material ejected can be very different if the supernovae can be avoided (Lau, Stancliffe & Tout 2007).

In the above estimates, we have ignored the nucleosynthesis that may take place in the envelope during the explosion. Unlike a Type Ia supernovae which does not have a hydrogen-rich envelope, this star could produce extra nucleosynthesis during its explosion just as a Type II supernova does when a shock wave sweeps through the envelope.

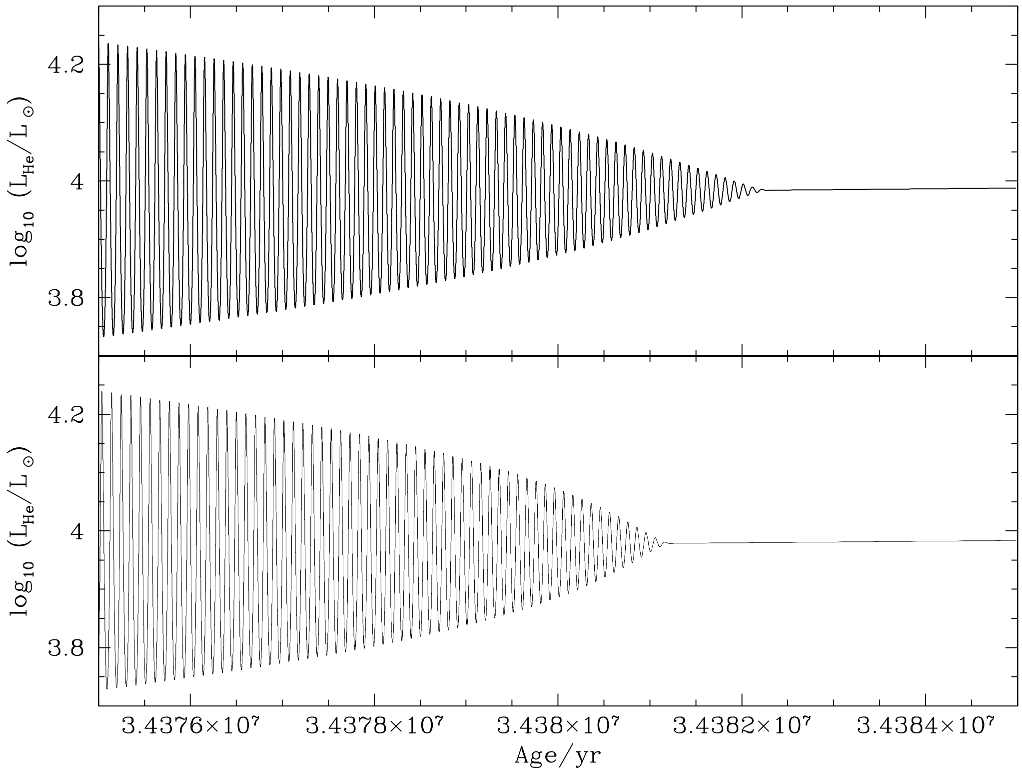

FIGURE 2. The end of the thermal pulses in the $7\,M_\odot$ star model. The pulses get weaker and eventually stop as indicated by the variation of helium luminosity. Top: Model without mass loss. Bottom: Model with Remiers' mass loss. The difference between the two models is very small.

TABLE 1. Nucleosynthesic yield of CNO from our $7.0\,M_\odot$ model. The total yield is the sum of the yield from the envelope and from the explosion. The explosive yield is from Iwamoto et al. (1999) and the yield depends the explosion mechanism. We can see that the main yield of carbon and oxygen is from the explosion while more nitrogen is obtained if the explosion mechanism is delayed detonation.

	$Y_{^{12}\mathrm{C}}/M_\odot$	$Y_{^{14}\mathrm{N}}/M_\odot$	$Y_{^{16}\mathrm{O}}/M_\odot$
Yield from Envelope	3.3×10^{-6}	1.6×10^{-5}	1.9×10^{-7}
Yield from explosion			
Deflagration	5.1×10^{-2}	3.3×10^{-8}	1.3×10^{-1}
Delayed Detonation	10^{-2}	10^{-4}	7×10^{-2}

6. MASS-LOSS TIMESCALE AND THE FATE OF THE STARS

We have also evolved the $5\,M_\odot$ and $7\,M_\odot$ models with Reimers' mass loss. The evolution is almost identical to that without mass loss. For example, for the $7\,M_\odot$ model, the minor

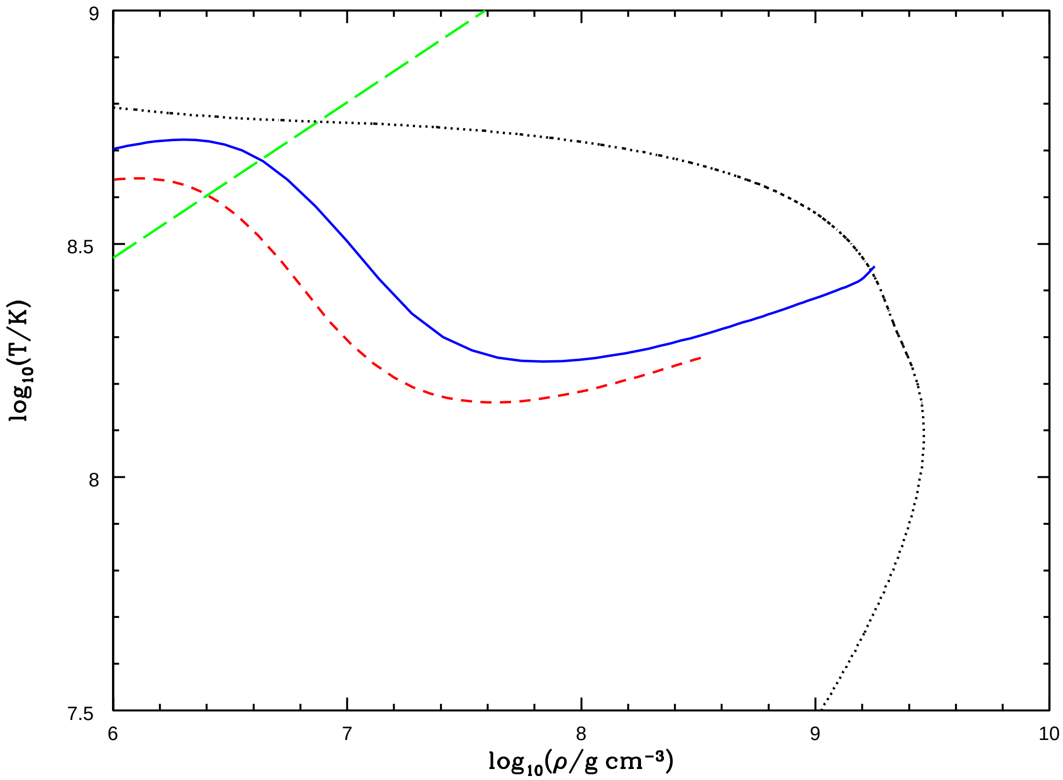

FIGURE 3. The interior of the $7.0\,M_\odot$ model. The dotted line indicates where carbon burning produces energy faster than it is lost via neutrinos. Above and to the right-hand side we have the right conditions for carbon ignition to drive a thermonuclear runaway. We add the internal structure profile with the core at the highest density and the burning shell at the highest temperature. The dashed line is at a slightly earlier time and the solid line is at the end of the evolution. Carbon ignites degenerately at the centre before the burning shell is hot enough to ignite carbon. The long dashed line at the top left hand corner is the boundary between non-degenerate and degenerate regions which are to its right.

difference is that the thermal pulses stop about 1,000 yr earlier and the helium luminosity is generally lower but by less than 25% (see Figure 2). The Reimers' mass-loss rate (Kudritzki & Reimers 1978) is

$$\dot{M}_{\mathrm{R}} = -4.0\times10^{-13}\eta\,\frac{(L/\mathrm{L}_\odot)(R/\mathrm{R}_\odot)}{(M/\mathrm{M}_\odot)}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}, \tag{1}$$

where L is the luminosity of the star, M its mass and R its radius. We use $\eta = 1$ which is likely to overestimate the mass loss in low metallicity stars. The total mass lost from the star since the first thermal pulse is then about $1.0\,\mathrm{M}_\odot$ and the average mass-loss rate is $3.4\times10^{-6}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. We have also estimated the mass-loss rate caused by the onset of radial pulsations (Vassiliadis & Wood 1993) and find it to be much lower than that of Reimers' prescription. For the $5\,\mathrm{M}_\odot$ star, the total mass lost is $1.4\,\mathrm{M}_\odot$ with an average mass loss rate of $1.1\times10^{6}\,\mathrm{M}_\odot\mathrm{yr}^{-1}$.

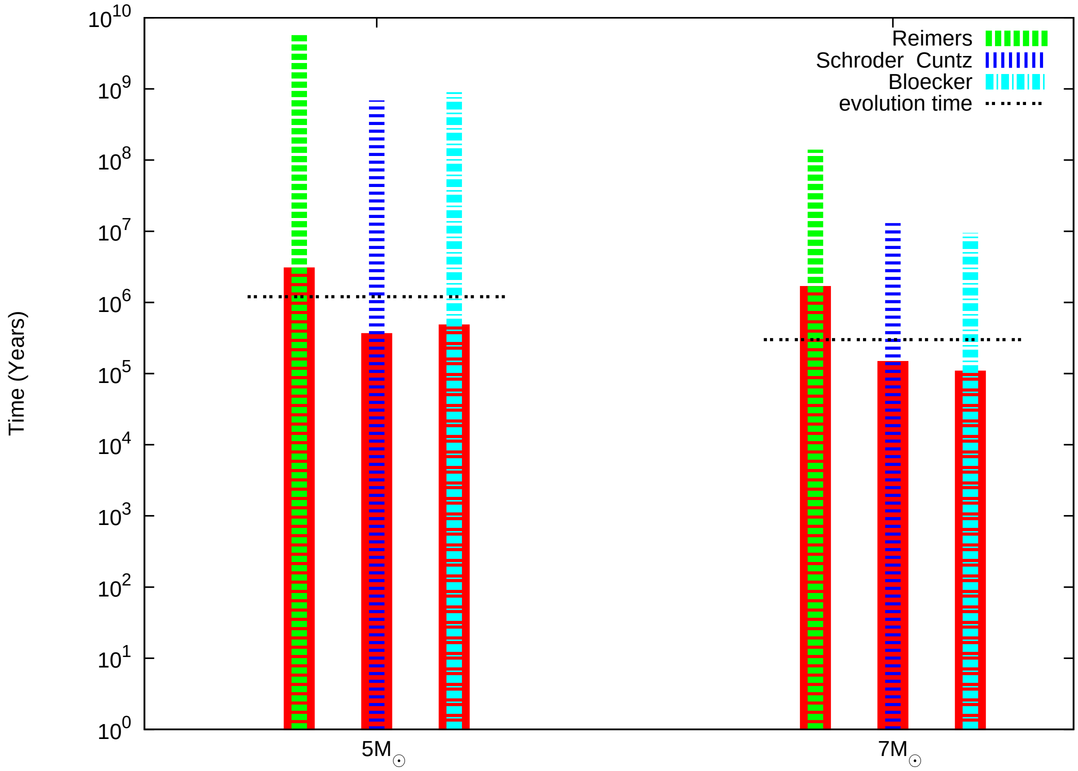

FIGURE 4. Timescales to lose the envelope using different mass-loss rates compared with the actual evolution time. The solid bars are when no metallicity scaling is used while the broken bars give the longer timescales involved when the mass loss scaling $\dot{M}(Z) = \dot{M}(Z_\odot)(\frac{Z}{Z_\odot})^{0.5}$ is applied. It shows that only a small scaling is needed for the mass-loss timescales to be greater than the evolution time.

The Reimers' rate was originally calibrated with M supergiants and so has no observational support for AGB stars so we briefly consider other mass-loss prescriptions such those of Schröder & Cuntz (2005) and Blöcker (1995) and apply the commonly used scaling

$$\dot{M}(Z) = \dot{M}(Z_\odot)\left(\frac{Z}{Z_\odot}\right)^{0.5}, \tag{2}$$

where $\dot{M}(Z_\odot)$ is the mass-loss rate for solar metallicity and Z is the surface metallicity.

We plot the evolution time and mass-loss timescale with and without scaling in Figure 4. The timescales for the star to lose its envelope are all significantly longer than the actual time the star takes to evolve up to the point of carbon ignition with the scaling. Even without scaling, the timescales are similar to or slightly shorter than the evolution time so even a weak scaling with a much higher surface metallicity means that the star does not lose its envelope before exploding. We can be fairly confident that carbon ignition and the following supernova does occur.

7. CONCLUSION

We have shown that the fate of high-mass AGB primordial stars is to ignite carbon degenerately at their centres and explode as supernovae with behaviour similar to a Type Ia but with a hydrogen-rich envelope because the mass-loss rate is low for these stars. For the $7\,M_{\odot}$ star, the critical average mass-loss rate is $1.9 \times 10^{5}\,M_{\odot}yr^{-1}$ while for the $5\,M_{\odot}$ it is $3.0 \times 10^{6}\,M_{\odot}yr^{-1}$. So far there is no observational support for any of the proposed mass-loss rates at low metallicity. In order to be certain that these stars explode, we require the mass-loss rates to be less than about one-third of the expected solar rates. Because of the low surface metallicity of these objects, the mass-loss rates should be low enough unless the surface metallity of the stars is substantially increased by extra mixing or the mass-loss metallicity scaling is very wrong.

We have also shown that for extremely metal poor stars, the strength of thermal pulses is weak and there is a lack of third dredge-up. Eventually the thermal pulses disappear and the core growth rate is much faster. This is important for a supernova type 1.5 to occur because the core can grow much faster than the time it takes for star to lose its envelope. The lack of third dredge-up also has important implications for the contribution of AGB stars to the chemistry of the early Universe, particularly for *s*-process isotopes which we are not produced without it. Further models of the TP-AGB phases of very low metallicity stars are necessary to determine the lowest metallicity at which third dredge-up begins.

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