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Exploring the divisions and overlap between AGB and super-AGB stars and supernovae

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Abstract. We discuss the mass ranges over which we find AGB and super-AGB stars. The most massive super-AGB stars are candidate progenitors for type II core-collapse SNe. We discuss the two supernovae, SN1980K and SN2003gd that provide some restrictions on the upper mass limit of super-AGB stars.

Key words. AGB Stars – Super-AGB Stars – Supernovae.

1. Introduction

The primary factors that affect the evolution of a stars are initial mass, initial metallicity, mass-loss, duplicity and extra mixing above and beyond that from convection described by mixing-length theory. The interplay between these factors determines the evolutionary path taken and whether a star gives rise to a supernova (SN) or produces a white dwarf. These factors are linked. A more massive star experiences more mass loss, as does a star with initially higher metallicity.

We have been studying these factors to determine their effect on the population of SNe progenitors (Eldridge & Tout 2004b; Eldridge 2004). By using observations of SN types and Wolf-Rayet (WR) ratios we have been able compare a number of mass-loss prescriptions and decide on a best fitting prescription. One interesting aspect of our work is the nature of the lowest-mass stars that explode as SNe. Ritossa, Garcia-Berro & Iben (1999) suggested that these would be super-AGB stars which are similar in structure to AGB stars but have oxygen/neon (ONe) cores rather than carbon/oxygen (CO) cores.

In this paper we give details of the mass ranges over which we find the different courses of evolution, AGB, super-AGB and SN. We also discuss observational evidence from SNe on super-AGB evolution and the lowest mass for a SN to occur. We find that the nature of the lowest mass SN progenitors may provide a tight constraint on convection in stellar interiors.

2. The Mass Ranges of AGB Evolution

AGB stars result from two courses of evolution. For lower masses the helium burning shell catches up with the hydrogen burning shell. While for more massive AGB stars (above 3 $M_{\odot}$), the convective envelope penetrates down to the CO core at second dredge

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up. Both cases put the hydrogen and helium burning shells in close proximity, an unstable arrangement that leads to thermal pulses rather than steady shell burning. Furthermore, because the hydrogen burning shell is now at a higher temperature near the helium burning shell, hydrogen burning occurs at a much greater rate and the luminosity of the star rises by a factor of at least 10.

Most AGB stars have CO cores and do not ignite carbon there. These go on to form CO White Dwarfs as the envelope is removed by a stellar wind during the thermally pulsing phase. If the envelope is not removed these stars would eventually approach the Chandrasekhar mass ($M_{\rm Ch}$) and carbon would ignite in the centre leading to a thermonuclear SNe. The resultant SNe would have observational characteristics of type Ia SNe with a type II mask. They are often referred to as a type $1\frac{1}{2}$ (Iben & Renzini 1983).

However stars above about $7\,M_\odot$ experience carbon burning (Garcia-Berro & Iben 1994). The lowest-mass stars in this range ignite carbon in a shell around the more degenerate central regions. This shell slowly burns inwards, raising the degeneracy as it goes. In more massive stars carbon ignites in the core and then burns outwards in brief shell flashes rather than in a steady burning shell. This is due to the mild degeneracy of the CO core when the burning reaction takes place. Carbon burning leaves an ONe core and the star becomes a super-AGB star. The carbon burning continues outwards until it reaches the base of the helium burning shell at which point it extinguishes. However the hydrogen and helium shells can still continue to burn outwards until $M_{\rm Ch}$ is reached. At this point the core collapses but now there is no carbon to ignite and prevent collapse. Densities can be reached of around $9.6 < \log_{10}(\rho/{\rm g\,cm^{-3}}) < 9.8$ at which electron capture on to ^{24}Mg can occur. This accelerates the core collapse and formation of a neutron star in a type II SN. The only difference to other SNe is that the core collapse is via electron capture rather than iron photodisintegration.

Our work uses the Cambridge stellar evolution code written by Eggleton (1971) and most recently updated by Pols et al. (1995) and Eldridge & Tout (2004a). We include convective overshooting as described by Schröder, Pols & Eggleton (1997). Because of new nuclear reactions rates and opacity tables the mass ranges for different behaviour are shifted relative to previous studies. We list the ranges when we include convective overshooting ($M_{\rm OS}$) and when we remove it ($M_{\rm noOS}$). The behaviour is as follows.

- $M_{\rm noOS} \leq 7\,M_\odot$, $M_{\rm OS} \leq 5\,M_\odot$ – stars undergo second dredge-up and thermal pulses with a central CO core. They lose their envelopes and leave CO white dwarfs before before their cores reach $M_{\rm Ch}$.
- $M_{\rm noOS} \approx 8\,M_\odot$, $6\,M_\odot \leq M_{\rm OS} \leq 7\,M_\odot$ – during or after second dredge-up carbon ignites in a shell because the core is degenerate and has a temperature inversion caused by neutrino losses. The star then undergoes thermal pulses with an ONe core. Because the core mass after dredge-up is far from $M_{\rm Ch}$ we assume these stars lose their envelopes and form ONe white dwarfs. These are super-AGB stars.
- $M_{\rm noOS} \approx 9\,M_\odot$, $M_{\rm OS} \approx 7.5\,M_\odot$ – carbon ignites before second dredge-up, in a shell if the centre is degenerate. Thus at dredge-up there is a growing ONe core. If this can reach $M_{\rm Ch}$ before the envelope is lost then the star undergoes a SN. The outcome depends on the nature of the thermal pulses and the core mass after dredge-up. Only those with cores close to $1.38\,M_\odot$ undergo SNe.
- $M_{\rm noOS} \approx 10\,M_\odot$, $M_{\rm OS} \approx 8\,M_\odot$ – the CO core is greater than $M_{\rm Ch}$ before dredge-up. However shell carbon burning, enhanced by a thin neon burning shell in the most massive stars of this type, drives a convection zone that reduces the size of the CO core to $M_{\rm Ch}$ so dredge-up can occur. This CO material is mixed with the envelope and increases the CO abundance at the surface during second dredge-up. After dredge-up the star has an ONe core of $M_{\rm Ch}$ which progresses to a SN by electron capture on to ^{24}Mg. These are extreme super-AGB stars.

- $M_{\rm noOS} \geq 11\,M_\odot$, $M_{\rm OS} \geq 9\,M_\odot$ – the helium core or CO core masses are too great for dredge-up to occur. The limiting mass for the helium core is $3\,M_\odot$ and for the CO core $1.5\,M_\odot$. Nuclear burning in these stars progresses until it cannot support the core and a SN explosion ensues.

If super-AGB stars do undergo SN then the luminosity of the lowest-mass SN progenitors depends upon the occurrence of second dredge-up in the late stages of evolution (Smartt et al. 2002). In the mass range of interest second dredge-up can increase the final luminosity from $\log_{10}(L/L_\odot) < 4.6$ to $\log_{10}(L/L_\odot) > 5.2$. Therefore these stars, if they occur in nature, should provide a large population of luminous red giant progenitors. The more massive models increase in luminosity 100 to 10 yr before the SN. This is because, before second dredge-up, the stars have more massive cores. This leads to denser cores after second dredge-up with less time required to achieve the densities for electron capture. We take this to occur at a central density of $\log_{10}(\rho/{\rm g\,cm^{-3}}) = 9.8$ (Miyaji et al. 1980; Nomoto 1987). We define this as the point when the SN explodes.

Most super-AGB stars probably do not undergo SNe. They lose their envelopes and form ONe white dwarfs before core collapse can occur. Their much higher luminosities enhance mass loss and, in our models, it can take 100,000 yr or longer for the burning shells to advance and for the core to reach the conditions for core collapse if the core is smaller than $1.38\,M_\odot$. To lose their envelopes during this time a mass-loss rate of only $< 10^{-4}\,M_\odot\,{\rm yr^{-1}}$ is required and this is not unreasonable for a luminous red giant. Also if the helium-burning shell is unstable and thermal pulses do occur the burning shell advances more slowly and there is even more time for mass loss.

However there are a class of stars, extreme super-AGB stars, that have CO cores greater than $M_{\rm Ch}$ when second dredge-up occurs. Figure 1 shows an example of such a star at solar metallicity and without convective overshooting. An intershell convective region forms and reduces the CO core mass before the convective envelope penetrates into this region when it mixes helium-burning products to the surface of the star. Whether these stars exist or some process prevents second dredge-up is unknown. Only evidence from observations of SN progenitors will show whether these stars occur in nature.

Eventually the star becomes too massive for second dredge-up to occur before core collapse either by electron capture or photodisintigration after the formation of an iron core. However this change over in behaviour and absence of second dredge-up provides a sharp change in the luminosity of SN progenitors.

3. SN Observations

There are two SNe that provide evidence for the upper mass for super-AGB evolution and that super-AGB may undergo SNe. An important question to ask is what type of SN would a super-AGB stars give rise to? Extreme super-AGB stars undergo second dredge-up only just before the SN and so have little time to lose their envelopes. They probably give rise to type IIP SN. Between these and the stars that have time to loose their envelopes in a wind there is a range of super-AGB stars that would lose a large fraction but not all of their envelope and will give rise to a IIL SN.

In our calculations we do not see any thermal pulses. However we do use low resolution models in this case. This only affects the stars that have CO core masses less than $M_{\rm Ch}$. The super-AGB stars that we assume explode as SNe have cores that collapse very soon after second dredge-up. No further burning needs to take place for the SN to occur.

First we consider SN1980K, a type IIL SN, that could have had a super-AGB progenitor. IIL SN progenitors have lost most of their hydrogen envelopes so they cannot sustain a plateau phase in their light curve. Most progenitors are thought to evolve from massive single stars that have lost a large fraction of their original envelopes, either in winds or by a binary interaction. SN1980K's progenitor was not observed in pre-SN data but a limit could be placed on its initial mass of less than

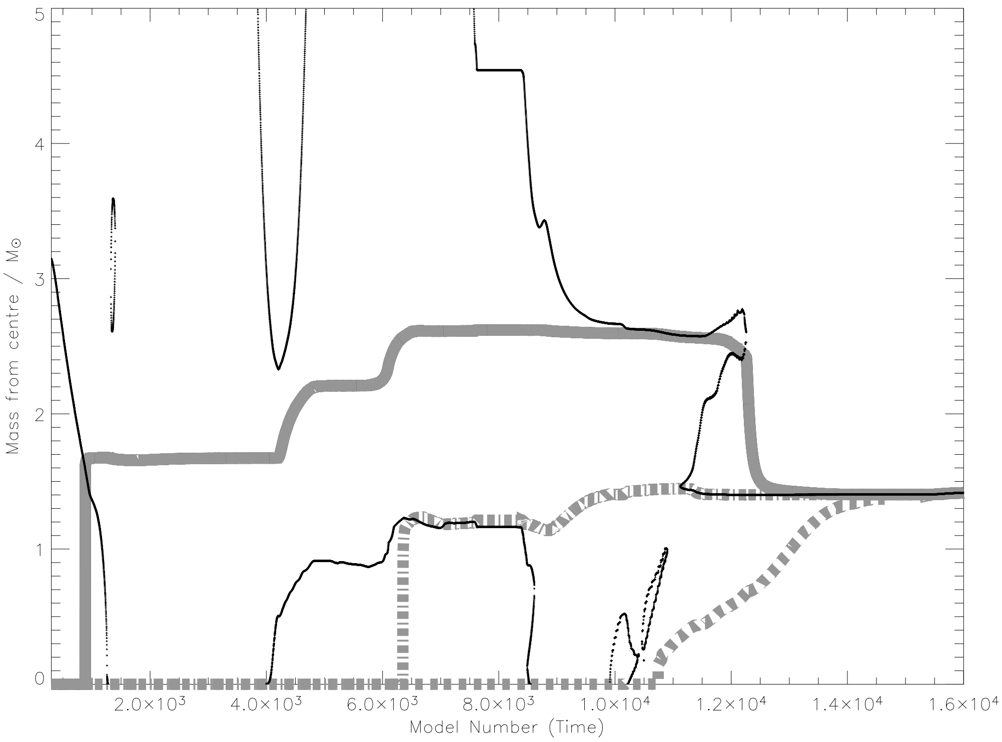

Fig. 1. Evolution of the structure of a 10 $M_{\odot}$ star. The thin black lines show the convective regions while the thick grey lines represent the burning shells. The solid grey line is the hydrogen-burning shell, the dash-dotted line the helium-burning shell and the dashed line the carbon-burning shell. Notice the formation of the convection zone between the hydrogen and helium burning shell at around model 11,000 that reduces the mass of the CO core before second dredge-up.

20 $M_{\odot}$ (Smartt et al. 2003). With the models of Eldridge & Tout (2004b) we can rule out a massive single star as progenitor so it is most likely that the progenitor was in a binary system.

However it has been suggested by Swartz, Wheeler & Harkness (1991) that super-AGB stars might give rise to IIL SNe. This agrees with the mass limit from pre-SN observations and there is another observation that provides further evidence. Montes et al. (1998) deduced the mass-loss history from radio observations. There was an increase in mass loss 10,000 yr before the SN. This is the same period of time a 7.5 $M_{\odot}$ model with overshooting experiences between second dredge-up and SN. The mass loss during this time would reduce the envelope to the small amount required for a IIL SN. So, though there are more likely alternatives from binary evolution, if we hope to find super-AGB progenitors, we must look at both IIP and IIL SNe.

The other SN to consider is SN2003gd. It is the only red giant progenitor observed with a pre-SN luminosity of $\log_{10}(L/L_{\odot}) = 4.3 \pm 0.3$. If we match this against our models, solid curve in Figure 2 we can see that they only just agree with the upper error bar. We know that the progenitor did not go through second dredge-up because the pre-SN observations were taken less than one year before the SN and our models in this range undergo second dredge-up 10 to 100 yr before the SN. The dashed curve in Figure 2 is what we would

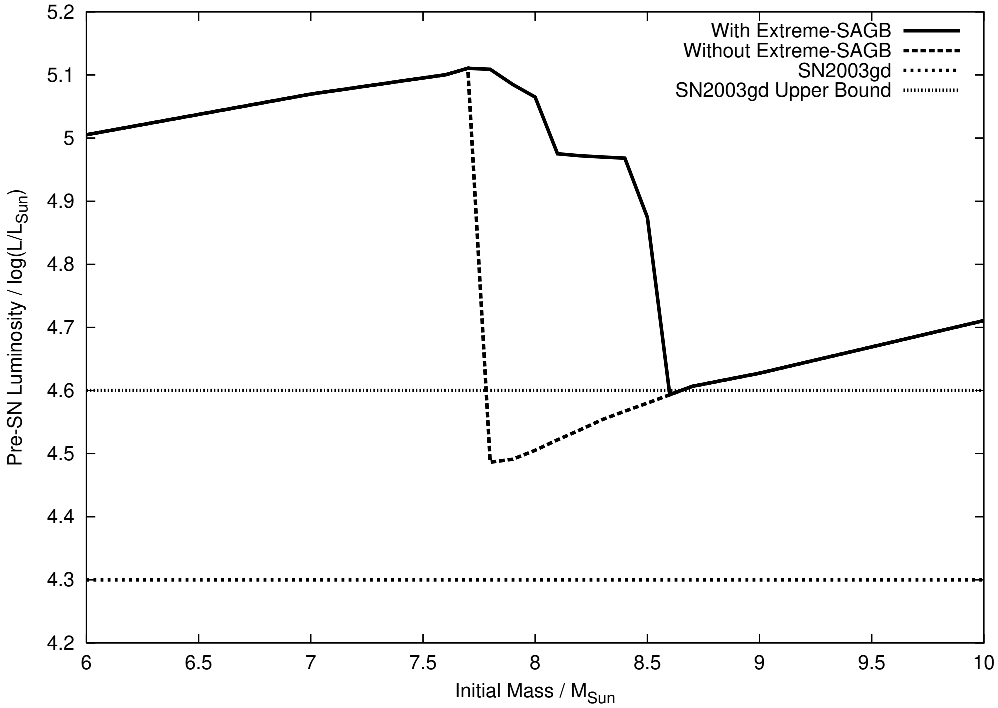

Fig. 2. The luminosity of SNe progenitors. The solid line includes the extreme SAGB stars while the dashed line does not. The horizontal lines are the observed luminosity of the progenitor of 2003gd and its upper error bar.

expect the luminosity of SN progenitors to be if second dredge-up were not to occur once the CO core is greater than $M_{\rm Ch}$ so that no extreme super-AGB stars would exist. These agree slightly better with SN2003gd so we might need to prevent second dredge-up in these stars.

A simple way to prevent dredge up would be to restrict convection at the base of the envelope so that dredge up does not occur and the core collapses before this. Other possible variables that are likely to have an effect are the ^{12}C+α $\rightarrow$ ^{16}O reaction rate and neutrino cooling rates. Convection itself is very uncertain and models are simple. In future we can refine our theory and use observations of SN progenitors similar to that of SN2003gd to provide a limit on the nature of convection in stellar interiors.

4. Future Work

Our future plans include exploring the effect of convection on lowest-mass SN progenitors and looking for low-luminosity progenitors in models of binary stars.

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