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Lives and deaths of super-AGB stars

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Abstract. Super-AGB stars reside in the mass range ~ 6.5-11 $M_\odot$ and bridge the divide between low/intermediate-mass stars and massive stars. They are characterised by off-centre carbon ignition prior to a thermally pulsing phase which can consist of many tens to multiple thousands of thermal pulses. I will give an overview of the evolution of this class of star with particular focus on the thermally pulsing super-AGB phase. The final fate of super-AGB stars is uncertain and depends primarily on the competition between the core growth and mass-loss rates. If the stellar envelope is removed prior to the core reaching the Chandrasekhar mass, a O-Ne white dwarf will remain; otherwise the star will undergo an electron-capture supernova, leaving behind a neutron star. I describe a selection of factors which influence the mass boundary between white dwarfs and supernovae, such as composition, the efficiency of convective boundary mixing, nuclear reaction rates, the mass-loss rates, and the third dredge-up efficiency.

Key words. stars: AGB and post-AGB – stars: evolution – supernovae: general – white dwarfs– nuclear reactions, nucleosynthesis, abundances

1. Introduction

Traditionally, research in the field of single star evolution and nucleosynthesis has been divided into two main branches; one focused on low to intermediate-mass stars ~ 0.8 to 8$M_\odot$,[1] whilst the other focused on high-mass stars ≥10 $M_\odot$. The reason for this divide is because the later evolutionary stages and final fates of stars diverge greatly between these mass ranges. For stars less than about 8 $M_\odot$ after undergoing core hydrogen and helium burning they do not achieve temperatures sufficient to ignite carbon. They instead enter a thermally pulsing asymptotic giant branch (AGB) phase which consists of alternating H and He shell burning before strong stellar winds remove their envelope, and then undergo a brief planetary nebula phase before ending life as a white dwarf (e.g. review by Karakas & Lattanzio 2014). For stars more massive than about 10 $M_\odot$, after core helium burning they continue to fuse heavier elements within their cores and undergo carbon, neon, oxygen, and then silicon burning stages before undergoing a violent iron core collapse supernova (Fe-CC-SN) explosion. Depending on their initial mass they will end life as either a neutron star, or for stars more massive than about 20 $M_\odot$, as a black hole (Heger et al. 2003).

Stars in the mass range ≈ 8 to 10 $M_\odot$ bridge the divide between the high and low mass stars and are called super-AGB stars. These stars are characterised by degenerate off-centre carbon ignition prior to the thermally pulsing phase. Whilst the pioneering evolution models for the first few thermal pulses were computed over 20

[1] Mass limits for solar metallicity.

years ago (Garcia-Berro & Iben 1994) only recently have full evolutionary calculations been produced for a range of masses and metallicities (e.g. Siess 2010; Ventura et al. 2011; Gil-Pons et al. 2013; Jones et al. 2013; Doherty et al. 2014). The reason this class of star had remained relatively understudied for so long was due to both the computational difficulties of following degenerate off-centre carbon ignition, and the very large number of thermal pulses expected ranging from tens to even thousands. Another complexity in stellar calculations within this mass range is the uncertain final fates of these objects. Super-AGB stars may either end their lives as white dwarfs, or as neutron stars after undergoing an electron capture supernova (EC-SN).

Determining the boundary between stars that explode as supernovae and those that do not is a topic of vital importance in astrophysics. This mass boundary is crucial to galactic chemical evolution models because it determines the nature of the chemical pollution around this mass range. The boundary also affects the supernova rate, which determines the number of neutron stars produced and also the amount of energy released by supernovae in a given stellar population. As yet we have no observationally confirmed super-AGB stars.

Here a brief overview of the lives and deaths of super-AGB stars is given whilst for a more detailed review refer to Doherty et al. (2017).

2. Evolution until the end of carbon burning

After core H and He burning, if the CO core mass exceeds ~ 1.05 M$_\odot$, carbon will ignite. Carbon burning progresses through a multi-step process of an initial off-centre flash (or flashes) with an exterior convective region and then a flame develops which burns towards the centre. Later secondary flashes can also occur in the outer core. The primary carbon burning reactions are ^{12}C(^{12}C,p)^{23}Na, ^{12}C(^{12}C,α)^{20}Ne followed by ^{23}Na(p,α)^{20}Ne and ^{16}O(α,γ)^{20}Ne which convert the core mainly to ^{16}O, ^{20}Ne, ^{23}Na and ^{24}Mg (Siess 2007). If carbon is ignited far enough off-centre a convective flash may occur, but no subsequent flame develops. This leads to the formation of a hybrid core consisting of an CO core surrounded by a ONe shell (Doherty et al. 2010). Thermohaline mixing (Siess 2009) or convective boundary mixing at the base of the carbon burning flame (Denissenkov et al. 2013; Chen et al. 2014) may also lead to formation of hybrid CO(Ne) cores.

If nearing the end of carbon burning the ONe core reaches 1.37 M$_\odot$ (Nomoto 1987) neon is ignited. If Ne is ignited far off-centre only a few small flashes occur but no flame develops (Ritossa et al. 1999). In addition, if convective boundary mixing is applied at the base of the Ne burning flame then it may also stall on its way to the core, giving the star time to collapse as an EC-SN instead of an Fe-CC SN. This class of star are called "failed massive stars" (Jones et al. 2013). However, apart from a very narrow mass range of stars with ONe core masses ~ 1.37M$_\odot$, generally once neon is ignited it will propagate to the centre and the star will then through all further stages of burning.

During the carbon burning phase all super-AGB stars have He core masses exceeding the Chandrasekhar mass, therefore to avoid a massive star fate and reach the thermally pulsing AGB phase their core masses must be reduced. At this stage of their evolution two process can reduce the He core mass, these being second dredge-up (SDU), and dredge-out (DO) (Ritossa et al. 1999).

3. Thermally pulsing super-AGB phase

After the cessation of carbon burning a super-AGB star is composed of a massive ONe core surrounded by a CO shell, a H burning shell, and a large convective envelope. The thermally pulsing phase then begins which consists of periods of quiescent H shell burning and alternating He shell flashes (thermal pulses - TPs). Fig. 1 shows a schematic representation of two consecutive TPs during the thermal pulsing phase. With their more massive cores, both the duration of the TP, as well as the recurrence time between TPs, is much shorter in super-

AGB stars than in their lower mass counterparts. Due to this they can experience a large number of TPs, ranging from tens to multiple thousands. Two important processes are expected to be activated in super-AGB stars, these being - hot bottom burning (HBB) where the base of the convective envelope reaches high enough temperatures for nuclear burning; and third dredge-up (TDU) which occurs after a TP and involves the convective envelope penetrated though the (now extinct) H shell, mixing up He burning enriched products to the surface and also reducing the core mass. Due to efficient HBB, super-AGB stars can reach very high luminosities (M_{bol} ~ -8.2) far exceeding the classic Paczyński (1970) luminosity limit of M_{bol}=-7.1. These extreme luminosities may be the key (and only way?) to distinguish a super-AGB star from a slightly less massive AGB star. The efficiency and even occurrence of the TDU in super-AGB stars is a large unknown, with calculations finding λ^2 values ranging from 0 to > 1. Observationally, the detection of overabundances of Rb in massive AGB stars (García-Hernández et al. 2006) suggest that the TDU process is activated in those stars, however with as yet no direct observation confirmation of a super-AGB star if they undergo TDU is still unknown.

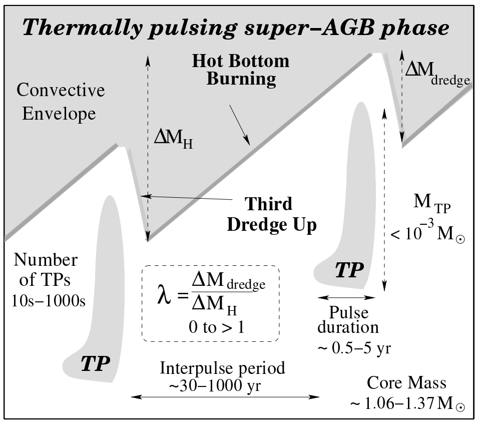

Fig. 1. Schematic Kippenhahn diagram (mass vs. time) of the thermally pulsing super-AGB phase.

4. Critical Mass limits - M_{up}, M_{mas}

The mass limits which define the super-AGB star regime are: M_{up}, the minimum mass required to ignite carbon, and M_{mas}, the minimum mass for a star to undergo all stages of nuclear burning and explode as an Fe-CC-SN. Although these mass limits have an important range of astrophysical consequences, their exact mass limits are plagued by a wide variety of large uncertainties, with a small selection of these described below.

Fig. 2 shows the M_{up} and M_{mas} values as a function of metallicity for a selection of model calculations. Clearly seen in this figure is the reduction in both mass limits with decreasing metallicity. This difference is caused by lower metallicity stars having higher central temperatures to counteract the fewer CNO seed, which results in larger He cores at the end of core H burning. Due to this, for stars of the same initial mass, lower metallicity stars will also have larger CO cores at the end of He burning which result in lower M_{up} and M_{mas} values.

The treatment of convection, in particular at convective boundaries, is one of the largest uncertainties in stellar evolution modelling. Models calculated assuming convective overshooting result in larger core masses during the core H and He burning phases than those in which the strict Schwarzschild criterion of convection is used (e.g. Bertelli et al. 1985; Siess 2007). The resulting larger CO cores for the same initial mass will lead to a reduction in the mass limits of both M_{up} and M_{mas}. This effect can be seen in Fig. 2 with the reduction of these mass limits by about 2 $M_\odot$ when comparing results from Siess (2007) without and with overshooting (small and large squares respectively).

Another important uncertainty that can impact these mass limits is the nuclear reaction rates, in particular that of ^{12}C + ^{12}C. It has been suspected that there may be an unmeasured resonance which would lead to an increase in this reaction rate (Cooper et al. 2009).

[2] Where λ is third dredge-up efficiency parameter defined as $\Delta M_{dredge}/\Delta M_H$ where ΔM_H is the increase in the core mass during the previous interpulse phase and ΔM_{dredge} is the depth of the dredge-up (see Figure 1).

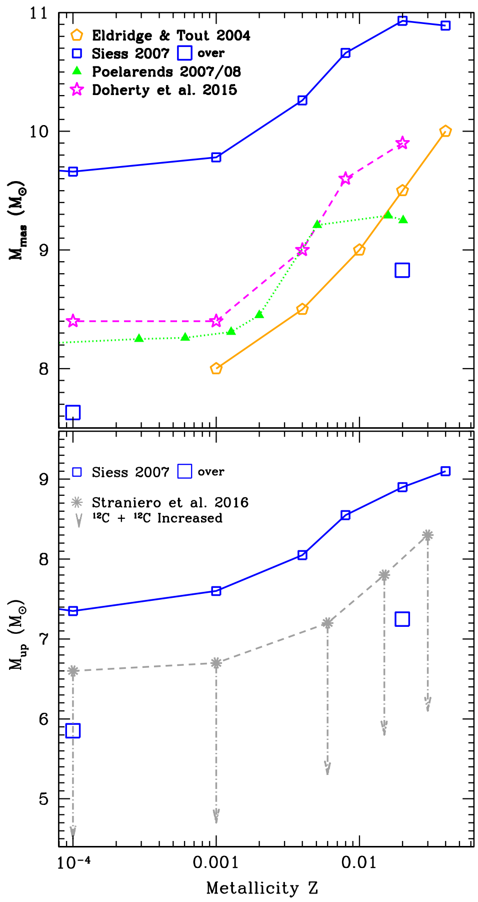

Fig. 2. M_{up} and M_{mas} values as a function of metallicity for a selection of model calculations from Eldridge & Tout (2004); Poelarends (2007); Siess (2007); Doherty et al. (2015) and Straniero et al. (2016). The effects of key uncertainties: convective overshooting and ^{12}C + ^{12}C reaction rates are also highlighted.

The impact of a faster carbon burning reaction is a lower core mass (and hence initial mass) for carbon ignition. This reduction for the M_{up} value (in this case by about 2 $M_\odot$) can be seen by the extent of the arrows in Fig. 2 which shows the results from computations by Straniero et al. (2016) using a carbon burning reaction rate modified to include a possible resonance at 1.5MeV (see also Chen et al. 2014).

5. Final fates - How do super-AGB stars end their lives?

As mentioned previously, near the end of carbon burning the He core mass is reduced to below the Chandrasekhar mass due to either SDU or a DO. From this post SDU/DO core mass the competition between the growth of the core and the mass loss from the envelope during the thermally pulsing super-AGB phase determines the stars' fate. If the core reaches $M_{EC} \approx$ 1.375 $M_\odot$ (Nomoto 1987) an EC-SN will occur leaving a neutron star[3], otherwise the envelope will be lost and an ONe white dwarf will remain. The mass limit dividing these two fates is called M_n, the minimum initial mass for creation of a neutron star.

Unfortunately both the core growth and mass loss are hampered by very large uncertainties. The effective core growth rate must take into account not only the outward movement of the H burning shell during the interpulse phase but also the (possible) reduction of the core due to repeated TDU events. The mass-loss rate for super-AGB stars, especially at low metallicity, is highly contentious. In current computations the mass-loss prescriptions of Vassiliadis & Wood (1993); Bloecker (1995) or van Loon et al. (2005) are typically used, and result in very rapid mass-loss rates of $\geq 10^{-5}$ $M_\odot$ yr^{-1}.

Fig. 3 shows the final fates results of parametric calculations from Poelarends (2007)[4] and detailed evolutionary calculations from Doherty et al. (2015). The results from Poelarends (2007) shown here include two parameterisations, both assuming efficient TDU (based on Karakas et al. 2002) and mass-loss rate from van Loon et al. (2005), however in one parameterisation (their favoured) a metallicity scaling of $\sqrt{Z/Z_\odot}$ from Kudritzki et al. (1987) is applied to the mass-loss rate. This metallicity scaling results in a reduction in the mass-loss rate at decreasing metallicity and also in this case to a reduction in

[3] Debate over the final fate of an EC-SN as either a neutron star of an ONeFe remnant has recently been reignited (e.g. Jones et al. 2016)

[4] The Z=0.02 case was presented in Poelarends et al. (2008).

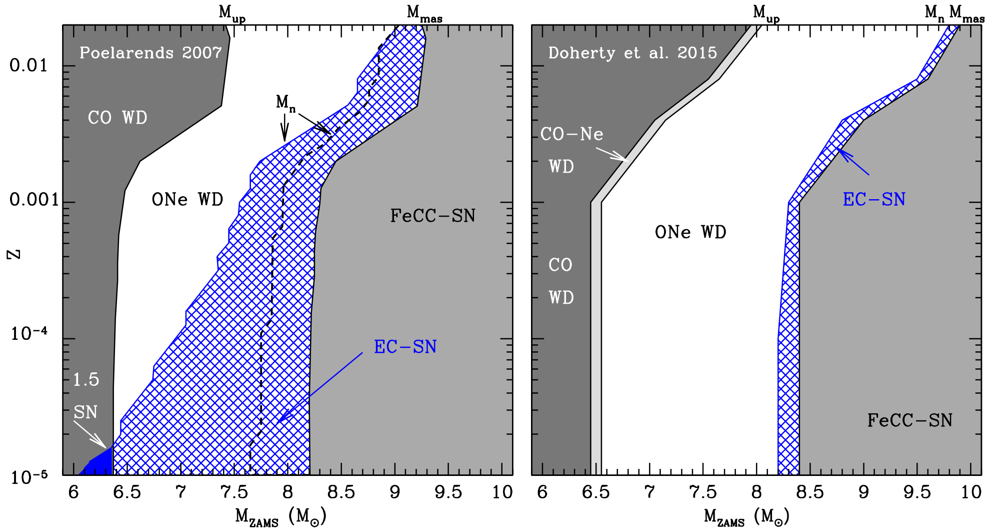

Fig. 3. Initial mass - metallicity final fates diagram for calculations from Poelarends (2007) and Doherty et al. (2015). The solid and dashed lines for $M_{\rm n}$ in the left panel represent the cases with and without a metallicity scaling upon the mass-loss rate. Modified from Doherty et al. (2017).

Table 1. Mass width of the EC-SN channel ($\Delta M_{\rm EC-SN}$ in $M_\odot$) and percentage of EC-SN to total Type II-P rate as a function of initial metallicity from the models of Poelarends (2007) and Doherty et al. (2015). For the calculations of the EC-SN contribution we assume a Kroupa et al. (1993) initial mass function and an upper mass limit for (Fe-CC-SN) Type II-P supernovae explosions at 18 $M_\odot$ (Smartt 2015).

Z	Poe07 (+Z-scaling)		D15	
	$\Delta M_{\rm EC-SN}$	%	$\Delta M_{\rm EC-SN}$	%
0.02	0.25 (0.25)	5 (5)	0.1	2
0.001	0.35 (0.75)	9 (17)	0.1	2
10^{-5}	0.55 (1.85)	13 (38)	0.2	5

the $M_{\rm n}$ value at lower metallicity. This leads to a large increase in the number of EC-SN and at the metallicity of $Z = 10^{-5}$ all super-AGB stars will explode as EC-SN and even CO cores could grow sufficiently to reach the Chandrasekhar mass and explode as Type 1.5 SN (Iben & Renzini 1983). In their case without the metallicity scaling upon the mass loss (seen as dashed $M_{\rm n}$ line in Fig. 3) whilst the mass width for EC-SN increases with decreasing metallicity it does so far less dramatically. In the models from Doherty et al. (2015) they find efficient TDU and use the mass-loss prescription from Vassiliadis & Wood (1993), which is slightly faster than that from van Loon et al. (2005). With these model assumptions they find $M_{\rm n}$ values close to $M_{\rm mas}$ with the majority of super-AGB stars ending life as ONe WDs with only a very narrow EC-SN channel.

Table. 1 provides the mass widths for the EC-SN channels, and the percentage contribution of EC-SN to the total Fe-CC-SN rate. For the models of Doherty et al. (2015) only a small fraction of the Type II-P SN will come from the EC-SN channel, whilst in the results from Poelarends (2007) with the metallicity scaled at $Z = 10^{-5}$, 38% of all Type II-P would be EC-SN. These results clearly illustrate the importance of understanding the mass-loss rate of super-AGB stars, in particularly at low metallicity.

6. Conclusions

Over the past decade large advances have been made in the computational study of super-AGB stars. There are now full evolutionary calculations of the entire thermally pulsing phase as well as nucleosynthetic and dust production yields over a wide range of masses and metallicities. The fate of (single) super-AGB stars at moderately metal-rich metallicities is now also relatively well established with the majority expected to end life as ONe white dwarfs with a fine EC-SN channel. However there are still many secrets of this mass range to be uncovered, with two of the most important questions being the fate of super-AGB stars at low metallicity and the exact mass limit between white dwarfs and supernovae. Unfortunately, the WD/SN boundary is still highly uncertain with $\sim$ 2-3 $M_\odot$ variation in the theoretical calculated limit depending on (reasonable) choices of input physics. One promising way to improve the stellar models may come from the new approach to model convection based on multidimensional simulations (e.g. 321D - Arnett et al. 2015). There are also a wide variety of observational studies from both the high- and low-mass star channels such as detailed supernova surveys and white dwarf initial-final mass relations which aim to constrain the WD/SN boundary. Contributions discussing these crucial topics can be found within this volume.

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