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Supernovae from massive AGB stars

Arend J.T. Poelarends[1,2], Robert G. Izzard[1,3], Falk Herwig[2], Norbert Langer[1], and Alexander Heger[2,4]

[1] Sterrenkundig Instituut, Universiteit Utrecht, P.O.Box 80000, NL-3508 TA UTRECHT, The Netherlands, e-mail: a.j.t.poelarends@astro.uu.nl.
[2] Theoretical Astrophysics Group, T-6, MS B227, Los Alamos National Laboratory, Los Alamos, NM 87545, USA.
[3] Carolune Institute for Quality Astronomy, www.ciqua.org
[4] Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA.

Abstract. We present new computations of the final fate of massive AGB-stars. These stars form ONeMg cores after a phase of carbon burning and are called Super AGB stars (SAGB). Detailed stellar evolutionary models until the thermally pulsing AGB were computed using three different stellar evolution codes. The subsequent evolution was modeled by a synthetic code with different options for mass loss rate and dredge-up efficiency. We find a range of initial masses between 9.0 $M_{\odot}$ and 9.25 $M_{\odot}$ for which we expect an SAGB star to explode as an electron capture supernova. Our models allow a detailed assessment of the envelope properties of electron-capture supernova progenitors. SAGB stars with lower initial masses are the progenitors of ONeMg white dwarf, while more massive stars ignite (off-center) neon burning and follow the classical core-collapse path.

Key words. Stars: evolution – Stars: AGB – supernovae

1. Introduction

Massive AGB-stars (Super-AGB or SAGB) may end their lives either as a massive white dwarf or as an electron capture supernova. They undergo a classical AGB evolution, with subsequent burning phases including carbon burning and a thermally pulsing phase (TP-AGB). During this TP-AGB phase the core can grow until either the entire envelope is lost or the core becomes big enough – and has high enough density inside the core – to encounter electron captures on ^{20}Ne and ^{24}Mg (Miyaji et al. 1980; Miyaji & Nomoto 1987; Hashimoto et al. 1993). In this later case the core collapses and triggers a supernova. On the other hand, more massive stars (“*massive stars*”) end their lives in a classical core-collapse supernova, due to iron disintegration in their cores, before their envelope is lost. Where the transition from SAGB stars to massive stars occurs is not clear. It certainly is a function of metallicity and stellar rotation (not discussed here). But it also depends on the uncertain physics of dredge-up and convective overshooting. It is even less clear in how wide a mass range the electron capture core collapse supernovae occur. A large initial mass range for these supernovae could have significant im-

Send offprint requests to: A.J.T.Poelarends plications for supernova nucleosynthesis and chemical evolution.

Recently Qian & Wasserburg (2002, 2003) identified two distinct *r*-process components in extremely metal poor stars. One of the components they refer to as "iron free" and suggest that the origin could be SAGB stars. A possible scenario for forming the *r*-process component is described by Wheeler et al. (1998); Wanajo et al. (2003). In the end of this paper we discuss another possible scenario for *r*-process nucleosynthesis in SAGB stars.

The Crab Nebula has been identified as a possible remnant of the explosion of an $8-10\,M_\odot$ star (Nomoto 1982). Though still controversial, it is well possible that this supernova indeed was an electron capture supernova. In the 1980's Nomoto evolved a series of helium cores with different masses to study the evolution of the core, especially in the regime of electron captures (Nomoto 1987a,b). More recently, a series of detailed models were constructed by Ritossa et al. (1996); Iben et al. (1997); Garcia-Berro et al. (1997); Ritossa et al. (1999) who concluded that a $10.5\,M_\odot$ star would probably explode as an electron-capture supernova, while a $11.0\,M_\odot$ star would explode as a classical core-collapse supernova. In another recent study Eldridge & Tout (2004) put the transition from AGB to massive stars just below $10\,M_\odot$ (or just below $8\,M_\odot$ when large overshooting was considered). Siess (2006) finds the transition to massive stars around $11.0\,M_\odot$.

Due to the large envelope mass and the short interpulse time, the number of pulses needed to compute through the evolution is in the order of several thousands. For this reason no detailed calculation through the entire TP-AGB exists. Besides this, there is the uncertainty in SAGB mass loss rates, and dredge-up efficiency (Doherty, this volume; and Siess this volume). We now take a different approach and use the fact that TP-AGB stars enter a limit cycle after a brief transition phase. Based on analytic fits, we made models that incorporate the interplay between mass loss and dredge-up during the TP-AGB, and studied the dependence on the uncertain model parameters, third dredge-up efficiency and mass loss.

In this paper we present preliminary results of detailed models that cover the whole SAGB mass range - even using different stellar evolution codes that make different assumptions on the physics of the pre-AGB evolution to allow estimates on the uncertainties that result from stellar modeling. The last part of the evolution - i.e., the TP-AGB - is computed by using a synthetic model that is similar to the AGB model of Izzard et al. (2004). We calculate the final fate of the stars, determine the boundaries of the different regimes and calculate supernova rates.

2. Models

Three detailed stellar evolution codes were used to calculate the evolution up the TP-AGB or the start of Ne-burning. To identify the boundaries of the SAGB regime we used three different codes: KEPLER (Weaver et al. 1978), EVOL (Blöcker 1995; Herwig 2000, 2004), and STERN (Langer 1998; Heger et al. 2000). In addition, STERN was also used for detailed models and for calibrating the synthetic model for the the TP-AGB evolution.

The most important difference between these codes is the numerical treatment of mixing. STERN and KEPLER use the Ledoux-criterion to determine convective instability, and take into account semi-convection. KEPLER uses "fast" semi-convection, in which the semiconvective diffusion coefficient is assumes to be 1/10 of the convective diffusion coefficient; convective zones are generally bound by one zone of chemical diffusion with 1/100 the radiative diffusion coefficient, and the full nuclear reaction network is implicitly coupled to the stellar structure. In EVOL convective boundaries are determined by using the Schwarzschild criterion and mixing and burning is solved coupled together implicitly. Mixing beyond the convective boundary is formally taken into account by exponential-diffusive extra-mixing (Herwig 2000).

We calculate solar metallicity models with initial masses between $6.5\,M_\odot$ and $13\,M_\odot$ starting on the zero age main sequence and follow the evolution until completion of the second dredge-up (2DUP). We only consider non-rotating models and mass loss before the 2DUP is neglected.

Our synthetic code is based on Izzard et al. (2004) with some changes for the SAGB phase (more details in Izzard, this volume). Here we are only interested in changes in the structure of the star and do not consider the chemical evolution and nucleosynthesis. We apply either no third dredge-up ($\lambda = 0.0$) or efficient dredge-up ($\lambda = 0.5$). Three different mass loss prescriptions are used, Reimers (1975),Vassiliadis & Wood 1993 (hereafter VW93) and van Loon et al. 2005 (hereafter vL05), and assume $\eta_{Reimers} = 4$. To simplify the discussion of final fates we only use the core masses calculated with EVOL as input for the synthetic models, since the STERN core masses are too low due to the absence of rotation and the post-second dredge-up core masses of EVOL and KEPLER are in good agreement with each other.

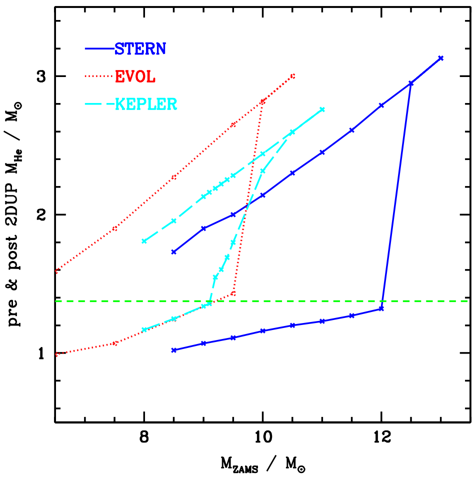

Fig. 1. Helium core masses before and at the end of the second dredge-up for different stellar evolution codes (solid line: STERN, dashed line: KEPLER, dotted line: EVOL) as a function of the initial mass. The upper lines show the maximum size of the helium core, prior to the second dredge-up and the lower lines show the size of the helium core just after the completion of the second dredge-up and prior to the onset of the TP-AGB phase. The light dashed horizontal line gives the lower limit for the final helium core mass for which the star may experience an electron-capture supernova.

3. Results

3.1. Second dredge-up

In Figure 1 we show the helium core masses just before and after the second dredge-up for the different stellar evolution codes. Stars that have a carbon-oxygen core more massive than the Chandrasekhar mass do not experience a deep second dredge-up and evolve into more advanced burning stages, eventually exploding as a classical core-collapse supernova. Stars below the critical mass experience a deep second dredge-up which decreases the size of the helium core significantly and prevents a normal core-collapse supernova.

Differences arise with respect to the critical mass for second dredge-up. Both KEPLER and EVOL have the transition around 9 $M_\odot$, STERN has it around 12.5 $M_\odot$. These differences are due to the different treatment of convection and overshooting. STERN uses the Ledoux-criterion for determining the convective boundaries and thus smaller cores (higher mass limit) result than for the Schwarzschild-criterion. Note that rotation could give significantly larger cores due to extra mixing.

Only KEPLER shows models which are in between the cases of no dredge-up and deep second dredge-up. EVOL and STERN do not show these intermediate models. This does not affect, however, the boundary between electron capture supernovae and classical supernovae; every core more massive than the Chandrasekhar mass follows the classical supernova path.

Figure 1 shows the upper boundary of the regime in which electron capture supernovae can occur. The lower boundary depends on the interplay between core growth and mass loss rate.

3.2. The SAGB-regime

Figure 2 shows the results of the TP-AGB evolution using the synthetic code and employing efficient dredge-up ($\lambda = 0.5$). Due to the

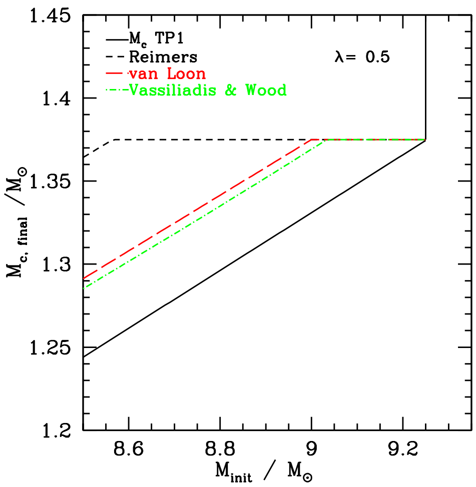

Fig. 2. Mass of the helium core at the end of the second dredge-up and at the end of the evolution as function of the initial mass for different mass loss prescriptions and for efficient dredge-up. The core sizes at the beginning of the TP-AGB phase (full drawn line) are from detailed stellar evolution models are interpolated from detailed models (c.f. Fig 1), while the other core sizes are computed with the synthetic code.

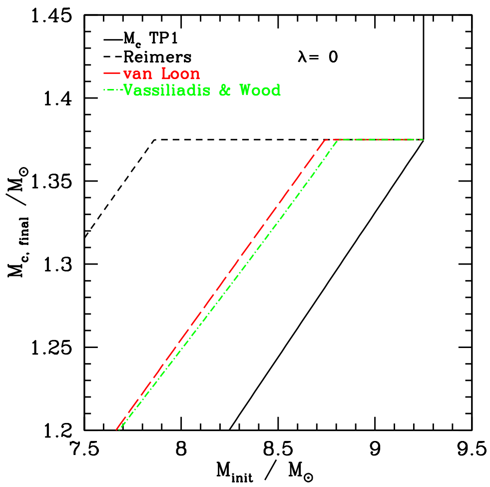

Fig. 3. Identical to Figure 2 but now for the case of no dredge-up.

mass loss, the core does not grow by more than $0.12\,M_\odot$ (Reimers) or $0.05\,M_\odot$ (VW93 and vL05). The maximum core growth varies strongly depending on the mass loss rate. As a result we find different initial mass ranges of the electron capture regime. The VW93 and vL05 rates give similar results and an electron capture supernovae mass range of $0.25\,M_\odot$ in initial mass.

Figure 3 shows the same as Figure 2 but for no dredge-up ($\lambda = 0$). In this case, the cores are able to grow much more, especially in stars with massive envelopes. Again, the maximum core growth strongly depends on the mass-loss rate. The Reimers mass loss rate allows large core growths, as high as $0.25\,M_\odot$, and gives a large initial mass regime ($\sim 1.4\,M_\odot$) for electron capture supernovae. The VW93 and vL05 rates give an electron capture channel that is only $\sim 0.45\,M_\odot$ wide. In a typical case, due to the massive envelope and the small interpulse time, the number of thermal pulses is of the order of a few thousand. Interpulse times range from ~ 50 years for the most massive stars to ~ 1000 years for the least massive SAGB stars.

3.3. Supernova number ratios

Using the inferred mass ranges from the synthetic model, we can now determine the ratio of the number of electron capture supernovae to the total number of supernovae. Table 1 gives an overview of the numbers we derive, for efficient and no dredge-up, using the Salpeter mass function.

The different mass loss rates and dredge-up efficiencies result in very different predictions. Using VW93 or vL05 mass loss rates find that electron capture supernovae comprise about 5% of all supernove, while using Reimers's mass loss recipe we obtain that up to 13% of all supernovae are electron capture supernovae in case of efficient dredge-up. For the case of no dredge-up this number increases to 20%.

3.4. Initial-final mass relation and pre-supernova properties

Figure 4 shows the initial-final mass relation for the mass range from $1.0\,M_\odot$ to $14\,M_\odot$. Background shading indicates the type of supernova or remnant. A value of $\lambda = 0.5$ for

Table 1. Mass limits and supernova number fractions for different values of the dredge-up efficiency and different mass loss prescriptions.

	$\lambda = 0.5$			$\lambda = 0$		
	$M_{\rm low}/{\rm M}_\odot$	$M_{\rm high}/{\rm M}_\odot$	%EC	$M_{\rm low}/{\rm M}_\odot$	$M_{\rm high}/{\rm M}_\odot$	%EC
Reimers	8.57	9.25	12.8	7.86	9.25	19.7
VW93	9.04	9.25	4.1	8.82	9.25	6.2
van Loon	9.00	9.25	4.9	8.76	9.25	7.1

TP-AGB dredge-up was assumed and a mass loss rate according to van Loon et al. (2005). Between 1 $M_\odot$ and 6 $M_\odot$ carbon/oxygen white dwarfs are formed.

SAGB stars result in the initial mass range from 6 $M_\odot$ to 9.25 $M_\odot$. From these stars in the range 6.0 $M_\odot$ to 9.0 $M_\odot$ make massive ONeMg white dwarfs and stars in the range 9.0 $M_\odot$ to 9.25 $M_\odot$ are progenitors of electron capture supernovae. Stars more massive than 9.25 $M_\odot$ explode as classical iron core-collapse supernovae.

To understand the supernova display and lightcurve one needs to know the structure of the star at time of explosion, in particular how much mass is left in the envelope (since we already know that they are red giant stars). For the electron capture supernovae we find a large spread in pre-SN progenitor masses. The least massive SAGB SN progenitors lose almost their entire envelope, just barely growing enough to still make an electron capture supernovae before losing the last bit of envelope, whereas the most massive SAGB SN progenitors have almost no mass loss before they explode. The effect of these different envelope masses on the resulting supernovae will have to be studied in the future and in combination with realistic models of electron capture core collapse models.

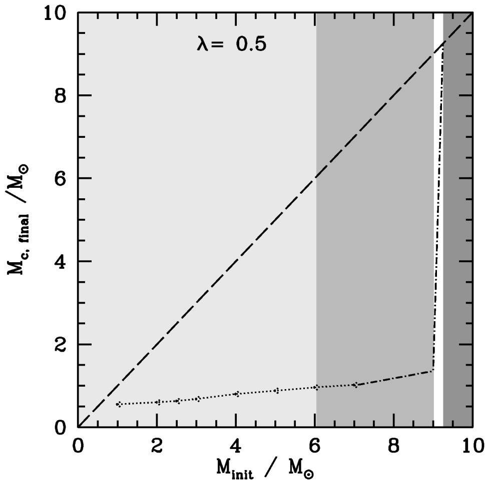

Fig. 4. Final mass of the remnant as a function of the initial mass. Different remnant regimes have different colors (light grey: CO-white dwarf, grey: ONeMg white dwarf, white: electron capture SN, dark grey: classical core collapse supernovae). Note how small the range for electron capture supernovae is compared to other mass ranges. Inside this transition zone, the remant mass varies strongly depending on how much mass is lost during the TP-AGB phase.

4. Discussion

The input of our synthetic models are the post second dredge-up core masses calculated with the EVOL code. A comparison with results from the STERN code reveals large differences in transition mass, and somewhat less in the mass range for SAGB SN stars. The resulting uncertainty in the predicted transition masses are as high as 2 $M_\odot$. These differences are due to choices that were made for and in the different codes, i.e. the absence of rotation and mass loss in the STERN models. These progenitor models and the different input physics need to be studied in detail in future work.

Some of the largest uncertainties are due to the mass loss rates. With the new empirical mass loss rate by van Loon et al. (2005), which is in good agreement with the well-known mass-loss prescription by Vassiliadis & Wood (1993), the situation may now be better than in earlier work, but due to the sensitivity of our results on that piece of input physics, a very reliable determination is required. The other big uncertainty is the dredge-up efficiency in SAGB stars, where there is large disagreement between the different studies (e.g., Ritossa et al. 1996; Doherty, this volume; Siess, this volume).

To what extend these stars may contribute to the *r*-process pattern in the universe is not clear yet, but we propose a new scenario. Like a typical AGB star, these stars have a thin helium layer just above the ONeMg-core. Due to dredge-up and mixing processes, a large fraction of neutron rich material may be present in this layer in the form of ^{13}C and ^{22}Ne. When the star explodes as an electron capture supernova, a shock wave travels through this layer and may release significant numbers of neutrons, giving rise to high neutron exposures and triggering an *r*-process.

5. Conclusion

Calculations to determine the final fate of SAGB stars have been presented. Depending on the uncertainty in the input physics, mass loss rate and dredge-up efficiency, we find possible "windows" in initial mass for essentially zero (no electron capture supernovae) to as wide as 1.4 solar masses (20 % of all supernovae are electron capture supernovae), and a best estimate of around $0.25\,M_{\odot}$. The exact mass where the transition to core collapse supernovae occurs depends strongly on the assumptions on stellar evolution (codes) in the pre-TP AGB phase. Detailed studies of the electron capture supernovae themselves are needed to determine to what extent they could contribute to the cosmic *r*-process pattern.

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