THE SUPERNOVA CHANNEL OF SUPER-AGB STARS

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ABSTRACT

We study the late evolution of solar metallicity stars in the transition region between white dwarf formation and core collapse. This includes the super–asymptotic giant branch (super-AGB, SAGB) stars, which ignite carbon burning and form an oxygen-neon (ONe) core. SAGB star cores may grow to the Chandrasekhar mass because of continued H- and He-shell burning, ending as core-collapse supernovae. From stellar evolution models we find that the initial mass range for SAGB evolution is 7.5–9.25 M⊙. We perform calculations with three different stellar evolution codes to judge the robustness of our results. The mass range significantly depends on the treatment of semiconvective mixing and convective overshooting. To consider the effect of a large number of thermal pulses, as expected in SAGB stars, we construct synthetic SAGB models that are calibrated through stellar evolution simulations. The synthetic model enables us to compute the evolution of the main properties of SAGB stars from the onset of thermal pulses until the core reaches the Chandrasekhar mass or is uncovered by the stellar wind. Thereby, we differentiate the stellar initial mass ranges that produce ONe WDs from that leading to electron-capture SNe. The latter is found to be 9.0–9.25 M⊙ for our fiducial model, implying that electron-capture SNe would constitute about 4% of all SNe in the local universe. The error in this determination due to uncertainties in the third dredge-up efficiency and AGB mass-loss rate could lead to about a doubling of the number of electron-capture SNe, which provides a firm upper limit to their contribution to all supernovae of ∼20%.

Subject headings: stars: AGB and post-AGB — stars: evolution — stars: neutron — supernovae: general

Online material: color figures

1. INTRODUCTION

It is well known that, for a given initial chemical composition, it is the initial stellar mass that essentially determines the final fate of a star: lower masses produce white dwarfs, higher masses neutron stars and supernovae. The late evolution phases of stars in the transition region between white dwarfs and neutron stars are numerically difficult to model, and the relevant physics is not yet fully understood. This mass range is therefore often omitted in stellar evolution calculations. This is unsatisfactory because the uncertain initial mass region for this evolution is 7–12 M⊙, implying that as much as half of all supernovae may originate from this transition region.

Of particular interest in this context is the evolution of so-called super–asymptotic giant branch (SAGB) stars, which ignite carbon nonexplosively but also undergo thermal pulse episodes (Ritossa et al. 1996, 1999; Iben et al. 1997; Garcia-Berro et al. 1997; Siess 2006). These stars may end their lives either as massive ONe white dwarfs (Nomoto 1984) or as electron-capture supernovae (ECSNe), where the core collapse is triggered by electron captures before Ne ignition (Wheeler et al. 1998; Wanajo et al. 2003). Stars of larger initial mass ignite hydrostatic neon burning, form an iron core, and lead to classical core-collapse supernovae (CCSNe).

The upper mass limit of SAGB stars is affected by the second dredge-up, which may occur after core He exhaustion, and which drastically reduces the mass of the helium core. At this point and throughout the following early SAGB phase carbon burning transforms the CO core into an ONe core (Nomoto 1987; Ritossa et al. 1996, 1999; Iben et al. 1997; Garcia-Berro et al. 1997; Siess 2006). The degenerate core is surrounded by the He and H shell sources, which eventually produce thermal pulses due to the instability of the helium shell source (Yoon et al. 2004).

In this situation, the mass of the H-free core continues to grow. If the core mass reaches the Chandrasekhar mass of 1.375 M⊙, the core will collapse triggered by electron captures on 24Mg and 20Ne, and the star will become an ECSN (Miyaji et al. 1980; Miyaji & Nomoto 1987; Hashimoto et al. 1993). Recent studies by Ritossa et al. (1996, 1999), Garcia-Berro et al. (1997), Iben et al. (1997), and Siess (2006) have shown that the mass fraction of 24Mg in the ONe core is smaller than previously thought, which diminishes the role of electron captures on 24Mg. While Gutiérrez et al. (2005) found that unburnt carbon in the degenerate ONe core could trigger an explosion at densities of ∼10⁹ g cm⁻³, we disregard this possibility further on since its observational implications are not worked out, and therefore this scenario cannot yet be confronted with supernova observations.

The initial mass range for core collapse after SAGB evolution depends on the effective core growth and mass loss of the SAGB star. Larger mass-loss rates lead to a shorter duration of the SAGB phase. For very high SAGB mass loss, there is no time for any significant core growth, and the initial mass range for ECSNe will be very small. On the other hand, the core growth rate in SAGB stars depends on the hydrogen shell burning and thus on two crucial factors, hot bottom burning (Sackmann &
Boothroyd 1991; Ventura et al. 2005) and the efficiency of the third dredge-up.

Previous studies of SAGB stars have concentrated on the evolution of the stellar cores (Nomoto 1984, 1987). According to these models, stars with helium cores between 2.0 and 2.5 \(M_\odot\) form ONe cores and explode as ECSNe, leaving a neutron star less massive than 1.3 \(M_\odot\). Ritossa et al. (1996, 1999), Iben et al. (1997), and Garcia-Berro et al. (1997) studied the evolution of complete SAGB stellar models in detail. They describe SAGB thermal pulses, as well as an outward mixing event that they called dredge-out, in which the convective envelope connects to a convection zone on top of the helium-burning layer. Siess (2006), who studied the effects of the carbon flame and of thermonuclear reactions on the structure of the ONe core, finds similar results.

Thermal pulses in AGB evolutionary models require high numerical resolution, in both time and space. The interpulse period decreases with increasing core mass to eventually only a few years for the most massive AGB star. In order to follow the evolution of SAGB stars with very high core masses, orders of magnitude more thermal pulses (up to ten thousands) have to be computed compared to low-mass AGB stars, which experience only tens of thermal pulses. For this reason, no detailed stellar evolution calculations through the entire super-TP-AGB phase exist. Ritossa et al. (1999) attempted to characterize stars that would end as ECSNe. Based on the assumption of a constant SAGB mass-loss rate of \(10^{-4} M_\odot\) yr\(^{-1}\), they speculated that out of their set of four calculated models (9, 10, 10.5, and 11 \(M_\odot\)) only the 11 \(M_\odot\) model would explode as an ECSN. The other models would lose all their envelope before the core has grown enough, and their final fate would be an ONe white dwarf. Eldridge & Tout (2004b) determine a minimum mass for supernova explosion around 7 \(M_\odot\) (with overshooting), or around 9 \(M_\odot\) (without overshooting), again without being able to calculate the stellar evolution models through the final phases.

Models of SAGB evolution suffer from two dominant sources of uncertainty: mass loss and the efficiency of the third dredge-up. To explore these uncertainties would require to compute several model grids, which is not feasible at this time. We therefore take a different approach and use the fact that TP-AGB stars, after a brief transition phase, reach a quasi-steady state in which the important structural quantities evolve in a simple and predictable way as a function of time. This approach of synthetic AGB modeling has already been successfully used for low-mass and massive AGB stars (Renzini & Voli 1981; Iben & Renzini 1983; Marigo et al. 1996).

In the following, we first describe the detailed stellar evolution models (§ 2) and identify the initial mass range for SAGB stars by calculating the pre-AGB evolution phase up to the end of the second dredge-up and possibly C ignition, using three different stellar evolution codes (§ 3). Next, we describe our SAGB stellar evolution models (§ 4) and our synthetic SAGB evolution model (§ 5). We present our results in § 6 and concluding remarks in § 7.

2. NUMERICAL METHODS

We use three different stellar evolution codes to calculate the evolution of solar metallicity stars up to the end of the second dredge-up, or to Ne ignition. We used the codes STERN (Langer 1998; Heger et al. 2000), EVOL (Böcker 1995; Herwig 2000), and KEPLER (Weaver et al. 1978; Heger et al. 2000). All three codes use the OPAL opacities (Iglesias & Rogers 1996) and are equipped with up-to-date input physics, including a nuclear network with all relevant thermonuclear reactions.

For our investigation, the most relevant difference between the codes concerns the treatment of convective and semiconvective mixing. As seen below, these affect the He core mass after central He burning, and thereby the fate of the stellar model. STERN and KEPLER use the Ledoux criterion to determine convective instability and take semiconvection into account. In KEPLER the treatment of semiconvection leads to rather fast mixing. Specifically, it is approximated as a diffusive process with a diffusion coefficient that is 10% of the radiative diffusion coefficient. Typically, this leads to a 1000 times shorter mixing timescale as for the default value of Langer et al. (1983) as used in STERN (\(\alpha_{\text{sem}} = 0.01\)). No modification to the temperature gradient is assumed; i.e., the radiative temperature gradient is used. In addition, in KEPLER convection zones are extended by one extra grid point where fast mixing is assumed, to mimic convective overshooting. In the EVOL code, convective boundaries are determined by the Schwarzschild criterion, and semiconvection is not treated as a separate mixing process. Mixing beyond convective boundaries is treated by adopting an exponential decaying diffusion coefficient (Herwig et al. 1997; Herwig 2000). Such mixing may be induced by convective overshooting (Freytag et al. 1996), or internal gravity waves (Denissenkov & Tout 2003), or a combination of both (Young et al. 2005). For the pre-AGB evolution, the overshoot parameter in EVOL has been set to \(f = 0.016\), which was shown by Herwig (2000) to reproduce the observed main-sequence width in the H–R diagram of young open clusters. Effectively, the strength of mixing in KEPLER lies in between that of STERN (slow semiconvective mixing) and that of EVOL (Schwarzschild criterion for convection is similar to very fast mixing in semiconvective regions).

The EVOL code has previously been used to study low-mass (e.g., Herwig & Austin 2004) and massive AGB stars (Herwig 2004a, 2004b). KEPLER has in the past been applied to study massive stars (Woosley et al. 2002) but has not previously been used for AGB simulations. STERN has been used for low-mass AGB stars (Langer et al. 1999; Herwig et al. 2003; Siess et al. 2004), as well as for massive stars (Heger et al. 2000; Heger & Langer 2000).

3. PRE-AGB EVOLUTION AND THE INITIAL MASS RANGE FOR SAGB STARS

In order to identify the processes that lead to SAGB star formation, we calculate stellar evolution sequences with initial masses between 6.5 and 13 \(M_\odot\), starting from the zero-age main sequence until the completion of the second dredge-up or Ne ignition (Table 1). Up to the end of the second dredge-up, no mass loss is taken into account. The initial metallicity of our models is \(Z = 0.02\). The effects of rotation or magnetic fields are not taken into account.

3.1. H and He Core Burning

The evolution of stars toward the SAGB has been studied previously (Ritossa et al. 1996, 1999; Iben et al. 1997; Garcia-Berro et al. 1997; Siess 2006), and our simulations qualitatively confirm these results, although quantitative differences occur. In our STERN models, a consequence of including semiconvection is that during core helium burning, a semiconvective layer limits the mixing between the inner helium burning core and the outer convective core, which still grows in mass (see also Fig. 1 below). This decreases the lifetime of the core helium burning phase because the available amount of helium is reduced, and this leads to smaller helium and CO core masses compared to models that use the Schwarzschild criterion for convection.
our fiducial SAGB evolution properties (mass loss, dredge-up, as described in about the end of the simulation, and the final fate of the sequence according to second dredge-up, the helium core mass after the second dredge-up, information EVOL, and K is KEPLER), the initial mass, the helium core mass prior to the

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start the thermal pulse cycle.

The dependence of the late evolutionary phases, including the second dredge-up, on the initial mass is illustrated in the Kippenhahn diagrams of three sequences computed with the

STERN code shown in Figure 1. All models evolved through core H and core He burning. In the 5.0 $M_\odot$ models, the hydrogen burning terminates, and the second dredge-up reduces the helium core mass by about 0.2 $M_\odot$. When the helium shell source gets close to the bottom of the convective envelope, hydrogen reignites, and the thermal pulse cycle starts. For the 11.5 $M_\odot$ model, central hydrogen and helium burning is followed by off-center carbon ignition. During the carbon-burning phase the size of the helium core is reduced by a deep second dredge-up, after which the core becomes degenerate and thermal pulses develop. In the 16.0 $M_\odot$ case, convective core H and He burning is followed by core C burning, and no second dredge-up occurs. Ne ignites hydrostatically, and subsequent burning will lead to the formation of an iron core.

In accord with previous work (Ritossa et al. 1996, 1999; Iben et al. 1997; Garcia-Berro et al. 1997; Siess 2006), the second dredge-up reduces the helium core mass to values below the Chandrasekhar mass in our EVOL and STERN models. This leads to a clear definition of the upper mass limit of SAGB stars, which defines the lower limit of SAGB stars. They find for models without overshooting a value of $M_{\text{up}}$ of $5-7 M_\odot$, while a moderate amount of overshooting reduces this by $1 M_\odot$. In our models we find $M_{\text{up}} = 7.5 M_\odot$ (EVOL/KEPLER), while our STERN models, without any overshooting, give $M_{\text{up}} = 9.0 M_\odot$. We discuss these differences in the next paragraph.

### 3.2. The Second Dredge-up

The second dredge-up is a key difference between SAGB stars and massive stars that encounter Fe core collapse. After core He exhaustion, the core resumes contraction while the envelope expands. As the star evolves up the AGB, the envelope convection deepens and eventually penetrates into the H-free core. Only due to this mixing event is the H-free core mass sufficiently reduced so that an electron-degenerate core can form, which then cools and prevents Ne from igniting. If the core mass after the second dredge-up is smaller than the Chandrasekhar mass, an electron-degenerate core will form and the He and H shells will eventually start the thermal pulse cycle.

The dependence of the late evolutionary phases, including the second dredge-up, on the initial mass is illustrated in the Kippenhahn diagrams of three sequences computed with the

| Model | $M_i$ ($M_\odot$) | Pre-2DU ($M_\odot$) | Post-2DU ($M_\odot$) | Comments | Fate |
|-------|-----------------|-------------------|-------------------|---------|------|
| S5.0  | 5.0             | 0.91              | 0.84              | 14 TP   | CO WD |
| S8.5  | 8.5             | 1.73              | 1.02              | 10 TP   | CO WD |
| S9    | 9               | 1.90              | 1.07              | 30 TP   | One WD|
| S9.5  | 9.5             | 2.00              | 1.11              | One WD |
| S10   | 10              | 2.14              | 1.16              | 55 TP   | One WD|
| S10.5 | 10.5            | 2.30              | 1.20              | One WD |
| S11   | 11              | 2.45              | 1.23              | One WD |
| S11.5 | 11.5            | 2.61              | 1.27              | One WD |
| S12   | 12              | 2.79              | 1.32              | One WD |
| S12.5 | 12.5            | 2.95              | 2.95              | One WD |
| S13.0 | 13              | 3.13              | 3.13              | Ne ignition | CCSN |
| S16.0 | 16              | 4.33              | 4.33              | Ne ignition | CCSN |
| E6.5  | 6.5             | 1.59              | 0.99              | CO WD  |
| E7.5  | 7.5             | 1.90              | 1.07              | One WD |
| E8.5  | 8.5             | 2.27              | 1.24              | One WD |
| E9.5  | 9.5             | 2.65              | 1.43              | CCSN   |
| E10.0 | 10.0            | 2.82              | 2.82              | Dredge-out | CCSN |
| E10.5 | 10.5            | 3.00              | 3.00              | Ne ignition | CCSN |
| E0099 | 9.0             | 2.15              | 1.17              | $f_{\text{core}} = 0.004$ |
| K8.5  | 8.0             | 1.808             | 1.168             | One WD |
| K9    | 9.0             | 2.130             | 1.338             | One WD |
| K9.1  | 9.1             | 2.161             | 1.357             | CCSN   |
| K9.2  | 9.2             | 2.190             | 1.548             | Ne ignition | CCSN |
| K9.3  | 9.3             | 2.221             | 1.603             | Ne ignition | CCSN |
| K9.4  | 9.4             | 2.253             | 1.690             | Ne ignition | CCSN |
| K9.5  | 9.5             | 2.283             | 1.799             | Ne ignition | CCSN |
| K10   | 10.0            | 2.439             | 2.315             | Ne ignition | CCSN |
| K10.5 | 10.5            | 2.598             | 2.566             | Ne ignition | CCSN |
| K11   | 11.0            | 2.759             | 2.759             | Ne ignition | CCSN |

Note.—The columns give the model identifier (S means STERN, E is EVOL, and K is KEPLER), the initial mass, the helium core mass prior to the second dredge-up, the helium core mass after the second dredge-up, information about the end of the simulation, and the final fate of the sequence according to our fiducial SAGB evolution properties (mass loss, dredge-up, as described in § 6.4).
Helium cores with masses in between 1.4 and 2.8 $M_\odot$ have a size of the helium core just after the completion of the second dredge-up and prior to the onset of the TP-AGB. The horizontal dashed line gives the lower limit for the final helium core mass for which the star may experience an ECSN. [See the electronic edition of the Journal for a color version of this figure.]

Figure 2.—Helium core masses for stars of various initial masses, as obtained using different stellar evolution codes (solid line: STERN; dashed line: KEPLER; dotted line: EVOL). The upper part of the line shows the maximum size of the helium core, prior to the second dredge-up. The lower part shows the size of the helium core after the completion of the second dredge-up and prior to the onset of the TP-AGB. The horizontal dashed line gives the lower limit for the final helium core mass for which the star may experience an ECSN. [See the electronic edition of the Journal for a color version of this figure.]

With very small time steps until the code was not able to calculate further. Therefore, it remains unclear whether this semi-convective layer dissolves and on what timescale. If it would, the helium core masses would be reduced to just below the Chandrasekhar mass. If the semi-convective layer remains for the rest of the evolution of the star, it would allow Ne to ignite in the core and eventually lead to Fe core collapse supernovae. This renders the upper mass limit for SAGB stars according to the STERN models somewhat ambiguous in the range 12–12.5 $M_\odot$.

In the EVOL models, the convective core overshooting was calibrated by the observed width of the main sequence. However, stars rotate, and the STERN code usually takes this into account. The effect of rotation also widens the main sequence, and in this way STERN models with rotation can reproduce the observed main-sequence width as well. (Heger & Langer 2000). In this study we compute nonrotating models with STERN, in order to avoid the complex question of how rotational mixing affects SAGB properties.

4. THE TP-SAGB STELLAR EVOLUTION MODELS

4.1. Thermal Pulses and Hot Bottom Burning

Double shell burning of H and He on degenerate cores leads to periodic thermonuclear instabilities. These He shell flashes or thermal pulses are an important site for nucleosynthesis in AGB stars and cause mixing of the intershell region and, by way of the third dredge-up, mixing of processed material to the surface (Iben & Renzini 1983; Busso et al. 1999; Herwig 2005). Thermal pulses of SAGB stars are similar to thermal pulses of CO core AGB stars (Ritossa et al. 1996). In order to obtain quantitative information on these SAGB thermal pulse cycles, we calculate such model sequences for several initial masses (Table 1).

As in massive AGB stars, most of the luminosity is produced by hot bottom burning. During hot bottom burning, hydrogen is transported convectively into the H shell, and H-burning ashes are transported out of the shell into the envelope. In the more massive SAGB stars this hot bottom burning starts immediately after the completion of the second dredge-up and can proceed at very high temperatures. In our STERN models we obtain values of $1.0 \times 10^5$ K ($10 M_\odot$ with $M_\odot = 1.16 M_\odot$ after 30 thermal pulses) and $1.1 \times 10^5$ K ($11.5 M_\odot$ with $M_\odot = 1.27 M_\odot$ already at the first thermal pulse). The EVOL models show a similar trend with the 9.0 $M_\odot$ model (E0099), reaching temperatures at the bottom of the convective envelope of $1.13 \times 10^5$ K after the 12th pulse.

Hot bottom burning could be stronger (or weaker) than in our calculations, e.g., due to convective overshooting at the bottom of the convective envelope, or due to a larger (or smaller) convective efficiency than assumed in most mixing length theories based stellar evolution calculations. In that case, the accretion of He on the core may be so much reduced that the core does not grow, or only very slowly. We have performed some test calculations with enhanced convective extra mixing during the hot bottom phase. These tests show so far a stationary H shell, which
slowly processes its envelope, and no core growth, which results probably in a massive ONe white dwarf. Whether this theoretical possibility is occurring in real stars is not clear because the physics of a convective boundary inside the H shell is poorly known.

SAGB stars show an He peak luminosity during thermal pulses of around log \((L/L_\odot)\) ~ 6 (Fig. 3), which is significantly lower than obtained in massive AGB stars that reach luminosities up to log \((L/L_\odot)\) ~ 8. This may explain why the third dredge-up is less efficient in terms of the dredge-up parameter \(\lambda\) (see § 4.2).

Extending the trend seen from low-mass to massive AGB stars, SAGB stars have smaller intershell masses (in the STERN 9 \(M_\odot\) model of \(7 \times 10^{-4} \ M_\odot\) at a core mass of \(1.06 \ M_\odot\)), and the interpulse time is also lower, ranging from 50 yr for the 11.5 \(M_\odot\) SAGB star with core mass of \(1.27 \ M_\odot\) to 1000 yr for an SAGB star with a mass of 9.0 \(M_\odot\).

### 4.2. Efficiency of the Third Dredge-up

The growth of the core during the TP-SAGB may be decreased by the dredge-up of material after a thermal pulse. The efficiency of the dredge-up \(\text{DUP}\) is expressed through the dredge-up parameter \(\lambda = \Delta M_H / \Delta M_{\text{DUP}}\), where \(\Delta M_H\) is the core mass increase due to H burning during the interpulse phase and \(\Delta M_{\text{DUP}}\) is the mass that is dredged up by the convective envelope.

In the models calculated with STERN we did not observe any dredge-up. This result is consistent with results for nonrotating low-mass AGB stars (Siess et al. 2004) from the same code that are also calculated using the Ledoux criterion for convection. Ritossa et al. (1996) and Siess & Pumo (2006) find a similar result. The recent models of Doherty & Lattanzio (2006) find very efficient dredge-up, e.g., \(\lambda \approx 0.7\) for a 9.5 \(M_\odot\) model. Observations clearly require a third dredge-up in low-mass and massive AGB stars, since we see its result in terms of carbon and s-process enrichment in real AGB stars. However, the efficiency of the third dredge-up in massive and SAGB stars is not constrained observationally, partly probably because of the high dilution factor in the massive envelope.

In order to get an idea about the efficiency of the third dredge-up in SAGB stars and the robustness of our and previous results, we studied the behavior of the thermal pulses also with the EVOL code. We calculated a 9 \(M_\odot\) model (E0099) until the 12th pulse. This model was computed with a 4 times smaller factor for the overshooting than the other EVOL models (\(f_{\text{over}} = 0.004\)) until the TP-AGB. This gives the star a smaller core than the regular models. On the TP-AGB a value of \(f_{\text{over}} = 0.008\) was used. The first thermal pulse starts after the completion of the second dredge-up, when the bottom of the convective envelope is at \(m_1 = 1.17 \ M_\odot\). The surface luminosity after 12 pulses is log \((L/L_\odot)\) = 5.07, the maximum helium luminosity during the 12th pulse is log \((L_{\text{He}}/L_\odot)\) = 6.17, and the duration of the interpulse period is \(\sim 500\) yr.

After the eighth pulse, the ensuing mixing has the characteristics of a “hot” dredge-up, first described for massive low-metallicity AGB stars by Herwig (2004a) and also found by Chieffi et al. (2001) for \(Z = 0\) models. Any small amount of mixing of protons into the hot \(^{12}\text{C}\)-rich layers, performed here by diffusive exponential overshooting, leads to violent H burning, which increases the convective instability. Like a flame, this corrosive hydrogen burning enforces the penetration of the convective envelope into the intershell (see Fig. 4). For this situation, we find efficient dredge-up (\(\lambda \approx 0.5\)); i.e., half of the interpulse core growth is dredged up, reducing the average pulse cycle core growth rate. Unfortunately, the hot dredge-up phenomenon adds another source of uncertainty to dredge-up predictions as the dredge-up efficiency is extremely sensitive to the overshooting or extramixing efficiency at the bottom of the convective boundary.

### 5. THE SAGB POPULATION SYNTHESIS MODEL

Mass loss and the dredge-up are the two most important but also most uncertain processes that determine the final evolution of SAGB stars. Here we employ a simplified synthetic model that allows us to estimate the effect of different assumptions concerning these two processes on the initial mass range for ECSNe.

#### 5.1. A Simple Estimate

We start with a simple back-of-the-envelope estimate: Stars that have, after carbon burning, a helium core mass larger than the Chandrasekhar mass \(M_{\text{Ch}}\) explode as CCSNe. The Chandrasekhar mass of a cold iron core is \(M_{\text{Ch eff}} = 1.375 \ M_\odot\) (Sugimoto & Nomoto 1980; Nomoto 1981). In order to form an ECSN, the core mass has to grow from the mass at the beginning of the TP-AGB, \(M_{\text{P}}(2\text{DUP})\), to the Chandrasekhar mass by

\[
\Delta M_c = M_{\text{Ch}} - M_{\text{P}}(2\text{DUP}) .
\]  

This value depends strongly on the initial mass, as Figure 5 shows.
Whether the core is able to grow by this amount depends only on the mass of the envelope, the core growth rate, and the mass-loss rate. Given these quantities, \( \Delta M_{\text{c, max}} \) is the maximum mass that the core can grow.

The core growth rate due to nuclear burning is \( dM_c/dt \). Due to the third dredge-up, the value for the core growth rate can decrease. We correct for this by introducing a factor \( 1 - \lambda \). The timescale on which the envelope of the star will be lost is

\[
\tau_{\text{env}} = \frac{M_{\text{env}}}{dM/dt_{\text{env}}},
\]

and, multiplied by the core growth rate, this gives the maximum value that the core can grow. This gives an approximate relation for the growth of the core during the TP-SAGB phase,

\[
\Delta M_{\text{c, max}} = \frac{M_{\text{env}}}{dM/dt_{\text{env}}} (1 - \lambda) dM_c/dt.
\]

For a typical, but constant, core growth rate of \( \dot{M}_c = 5 \times 10^{-7} M_\odot \text{yr}^{-1} \) and an envelope mass of \( M_{\text{env}} = 10 M_\odot \), Figure 6 shows \( \Delta M_{\text{c, max}} \) as a function of the mass-loss rate, for two different values of \( \lambda \) (no dredge-up and \( \lambda = 0.9 \)).

Figure 5 shows that in order to have an initial mass range for ECSNe of, for example, \( 1 M_\odot \), the core growth during the SAGB phase must be of the order 0.1–0.2 \( M_\odot \). Figure 6 shows that if SAGB mass loss is larger than \( \approx 10^{-6} M_\odot \text{yr}^{-1} \), such a core growth cannot be achieved, even for inefficient third dredge-up. For mass-loss rates below \( \approx 10^{-6} M_\odot \text{yr}^{-1} \), however, a core growth of a few times \( 10^{-1} M_\odot \) is predicted even if \( \lambda = 0.9 \). Compared with the empirical mass-loss rates derived by van Loon et al. (2005, hereafter vL05; cf. Table 2), it is clear that the initial mass range for ECSNe is sensitive to the third dredge-up.

### 5.2. Synthetic SAGB Evolution

A quantitative estimate of the initial mass range for ECSNe can be obtained through a synthetic model for the TP-AGB phase, similar to that of Izzard et al. (2004, hereafter I04) for AGB stars, which is based on detailed AGB models from Karakas (Karakas et al. 2002). The extension to SAGB stars is made by fitting the TP-AGB evolution of detailed stellar evolution models (STERN) presented above, specifically over the mass range between 7 and 11.5 \( M_\odot \) in initial mass.

Based on the SAGB STERN evolution sequences with up to 30 thermal pulses, we derive fits for luminosity, radius, and \( Q \)-factor (see § 5.2.3), as functions of the core mass \( (M_c) \), the envelope mass \( (M_{\text{env}}) \), and as secondary parameters the metallicity \( (Z) \) and the envelope hydrogen abundance \( (X_H) \). Since the SAGB evolution models have entered into a quasi-steady state regime, these fits are good approximations for the subsequent evolution of SAGB stars during the TP-AGB in mass (total, core, and envelope), luminosity, and radius.

We then use these analytic expressions as the basis for our synthetic TP-SAGB model. As starting values for our synthetic SAGB calculation we use total mass, core mass, and envelope hydrogen abundance after the second dredge-up. First, the luminosity is calculated from the initial core and envelope mass; then the radius is calculated, which is a function of the previously calculated luminosity and the envelope mass; and finally, the core growth is calculated and integrated over a time step \( dt \).

From these quantities, the effective temperature, mass-loss rate, the resulting new mass of the envelope, and the new mass of the core are calculated. The new core mass and envelope mass are used as input for the next time step.

In the following subsections we describe the basic outline of our synthetic model (for details we refer to I04).

#### 5.2.1. Luminosity and Radius

We follow I04 and model the luminosity with two terms, one that contains a core mass–luminosity relation (CMLR) and one

| Source                  | Type               | Rate \((M_\odot \text{yr}^{-1})\) |
|-------------------------|--------------------|----------------------------------|
| Reimers \((\eta = 1)\)  | Red giants         | \(\sim 5 \times 10^{-6}\)       |
| Reimers \((\eta = 4)\)  | Red giants         | \(\sim 2 \times 10^{-5}\)       |
| Schröder & Cuntz        | Supergiants        | \(\sim 1 \times 10^{-7}\)       |
| Van Loon                | AGB/RSG            | \(\sim 3 \times 10^{-7}\)       |
| Blöcker                 | AGB                | \(\sim 6 \times 10^{-4}\)       |
| Vassiliadis & Wood      | AGB                | \(\sim 4 \times 10^{-4}\)       |
term due to hot bottom burning. The total luminosity of the star can now be written as (see their eq. [29])

\[ L = f_t (f_r L_{\text{CMLR}} + L_{\text{env}}) L_\odot, \]

where \( L_{\text{CMLR}} \) is the core mass–luminosity relation given by

\[ L_{\text{CMLR}} = 3.7311 \times 10^4 \max \left( \frac{M_e}{M_\odot} - 0.52629, 0 \right) \times \left( \frac{2.7812 - \frac{M_e}{M_\odot}}{1.2 \left( \frac{M_e}{M_\odot} - 0.48 \right)} \right) \]

if the core mass at the first thermal pulse, \( M_{e,1TP} \), is \( \geq 0.58 M_\odot \). \( L_{\text{env}} \) is the contribution due to hot bottom burning (e.g., I04: 32),

\[ L_{\text{env}} = 1.50 \times 10^4 \left( \frac{M_{\text{env}}}{M_\odot} \right)^{1.3} \left[ 1 + 0.75 \left( 1 - \frac{Z}{0.02} \right) \right] \times \max \left( \frac{M_e}{M_\odot} + \frac{1}{2} \frac{\Delta M_{e,\text{nodup}}}{M_\odot} - 0.75, 0 \right) \].

Here \( M_e \) is the core mass, and \( M_{\text{env}} \) is the envelope mass. The quantity \( \Delta M_{e,\text{nodup}} \) is the change in core mass without third dredge-up and is defined by \( \Delta M_{e,\text{nodup}} = M_{e,\text{nodup}} - M_{e,1TP} \), with \( M_{e,\text{nodup}} \) the core mass as if there was no third dredge-up and \( M_{e,1TP} \) the core mass at the first thermal pulse. \( Z \) is the metallicity. Note that we use a lower exponent than I04 in the contribution of the envelope mass, i.e., 1.3 instead of 2, which resulted in good fits for models between 7 and 11.5 \( M_\odot \).

The function

\[ f_t = \min \left( \left( \frac{\Delta M_{e,\text{nodup}}/M_\odot}{0.04} \right)^{0.2}, 1.0 \right) \]

accounts for the steep rise in luminosity at the beginning of the TP-AGB. The function

\[ f_t = 1 - 0.2180 \exp[-11.613(M_e/M_\odot - 0.56189)] \]

corrects for the short-timescale dips in the luminosity during the thermal pulse cycle.

For the fit to the radius we use an expression of the same form as given by I04, but with coefficients adjusted to the STERN models:

\[ \log(f_r R) = -0.26 + 0.75 \log(L/L_\odot) - 0.41 \log(M_{\text{env}}/M_\odot), \]

with

\[ f_r = 0.09 \log\left( M_{\text{env}}/M_{\text{env},0} \right) \]

a factor that accounts for the removal of the envelope, where \( M_{\text{env},0} \) is the mass of the envelope at the first thermal pulse. This correction factor is determined by a fit to a 9 \( M_\odot \) model to which an extreme mass-loss rate of \( 10^{-3} M_\odot \) yr\(^{-1} \) was applied. For envelope masses below \( M_{\text{env}} = 2 M_\odot \), the fit predicts too large radii and is not valid for temperatures below 2500 K as calculated from \( R \) and \( L \).

5.2.2. Third Dredge-up

For the dependence of the third dredge-up on the initial mass we use the data from Karakas et al. (2002). Our own EVOL SAGB models, however, show smaller dredge-up (\( \lambda = 0.5 \) for \( M_{\text{ini}} = 9 M_\odot \)) than the extrapolation of the Karakas et al. (2002) data (Fig. 7). We therefore extend the fit to higher masses with a relation that reflects our own data at \( M_{\text{ini}} = 9 M_\odot \). To simulate a situation with no dredge-up, we also include in our synthetic code an option to set \( \lambda = 0 \).

5.2.3. Core Growth and Hot Bottom Burning

The growth rate of the He core in the interpulse phase is given by

\[ \frac{dM_e}{dt} = Q L, \]

where \( L \) is the total luminosity of the star and \( Q \) gives the mass of nuclear ashes accreted onto the core per energy released by the star. \( Q \) depends on several model properties, especially on the hot bottom burning efficiency, and less on the chemical composition of the envelope. For massive AGB and SAGB stars its strength depends on the envelope mass. If the hot bottom burning is efficient, \( Q \) can be small (see discussion in § 4.1), and the core may not significantly grow at all. Figure 8 shows the decrease of \( Q \) with increasing envelope mass. We parameterize \( Q \) as

\[ Q = \min \left( 1.43 \times 10^{-11}, 1.40 \times 10^{-11} + \frac{4.166 \times 10^{-12}}{X_H} - 1.5 \times 10^{-12} \frac{M_{\text{env}}}{M_\odot} \right). \]

This parameterization is in reasonable agreement with I04, who set \( Q \) to \( 1.585 \times 10^{-11} M_\odot L_\odot^{-1} \text{yr}^{-1} \), Hurley et al. (2000), who found \( 1.27 \times 10^{-11} M_\odot L_\odot^{-1} \text{yr}^{-1} \), and \( 1.02 \times 10^{-11} M_\odot L_\odot^{-1} \text{yr}^{-1} \) in Wagenhuber & Groenewegen (1998).

5.2.4. Mass Loss

As discussed in § 5.1, the mass loss of SAGB stars is the other important factor to determine the initial mass range of ECSNe.
SAGB stars are O-rich (because of hot bottom burning) and have stellar parameters around $\log T_{\text{eff}} = 3.5$ and $\log (L/L_\odot) = 5$ at solar metallicity. It is not clear what the dominant mass-loss mechanism for these stars is. Are they cool enough to develop dust-driven winds, or is mass loss simply driven by radiation pressure?

Table 2 shows a compilation of observational and theoretical mass-loss rates, for a combination of typical SAGB parameters. Note, however, that these rates are not constant over time and that the variation itself during the AGB phase is important for the final outcome. We preferentially use the observed mass-loss rates for massive AGB stars and red supergiants by vL05. If dust formation does not play an important role, then the Reimers mass-loss rate (Reimers 1975) may be applicable. It is derived from observations of RGB stars with a small range in temperatures and radii; however, Schröder & Cuntz (2005) have revised the Reimers rate. For the more massive RSG stars their new approach, which also includes surface gravity, gives about 3 times larger mass loss than the Reimers formula. This places it, for given temperature and luminosity (see Table 2), within a factor of 2 of the observational mass-loss determination by vL05. The mass-loss formula by Vassiliadis & Wood (1993, hereafter VW93), which is often used for AGB star evolution calculations, is also close to the observational value. The AGB mass loss formulated by Blöcker (1995) and based on the hydrodynamic wind models by Bowen (1988) has a higher luminosity exponent and gives very high mass-loss rates for SAGB stars. From our first estimate in § 5.1 it is clear that with the Blöcker mass loss SAGB stars would never explode as ECSNe.

6. RESULTS

We perform a series of synthetic calculations, with two assumptions on third dredge-up and three assumptions on mass loss. For dredge-up we assume either the parameterization of § 5.2.2 or $\lambda = 0$. For mass loss, we consider the cases Reimers, vL05, and VW93 (§ 5.2.4).

6.1. Initial Mass Range for ECSNe

The resulting initial mass ranges for ECSNe are illustrated in Figure 9 for the case with parameterized $\lambda$ and in Figure 10 for $\lambda = 0$. Stars that end their evolution as white dwarf, i.e., below the Chandrasekhar mass, do not explode as ECSNe. With the parameterized prescription for the third dredge-up, the width of the initial mass window for which ECSNe occur is between 0.25 and 0.65 $M_\odot$, depending on the assumed mass-loss rate. The mass-loss prescriptions of vL05 and VW93 give an initial mass window of 0.20–0.25 $M_\odot$. With zero dredge-up, the core grows at the maximum possible rate. The width of the initial mass window for ECSNe is between 1.4 $M_\odot$ for the Reimers mass-loss rate and 0.45–0.5 $M_\odot$ for the VW93 and vL05 mass-loss rates.

6.2. ECSN Fraction

Based on the inferred mass ranges from the synthetic model, we determine the ratio of the number of ECSNe to the total number of SNe. Table 3 gives an overview of the results for the cases of parameterized dredge-up and without dredge-up ($\lambda = 0$), assuming the Salpeter initial mass function. The value of $\lambda$ has a strong influence on the predicted fractions. With the parameterized dredge-up and the VW93 or vL05 mass-loss rates the ECSN fraction of all supernovae is about 3.5%. With the Reimers mass-loss rate 8% of all supernovae are ECSNe. The largest ECSN
fraction of 20% is obtained without dredge-up and using the Reimers mass-loss rate.

6.3. Final Mass and SN Properties

Figure 11 shows the initial-final mass relation for the mass range from 1.0 to 14 $M_\odot$ using the parameterized dredge-up prescription and the vL05 mass-loss rate. For ECSNe, we find a large spread in progenitor and envelope masses (Table 4). The least massive SAGB SN progenitors lose almost their entire envelope, growing the core just barely enough to still make an ECSN before the envelope is lost. The most massive SAGB SN progenitors, on the other hand, undergo very little TP-AGB mass loss before they explode and contain a massive hydrogen-rich envelope at that time.

This diversity is a natural consequence of the competition between core growth and mass loss during the SAGB stage, and thus independent of the choice of mass-loss rate and dredge-up parameterization. The expected envelope mass range, from almost zero to about 8 $M_\odot$ (Fig. 12), implies a diversity of supernova light curves of ECSNe, which may range from light curves of so-called Type IIIb and Type IIL supernovae to those of typical Type IIP supernovae (Falk & Arnett 1977; Young 2004).

However, ECSNe may show three properties that might allow us to distinguish them from ordinary Type II supernovae. First, they might produce low-energy explosions (Kitaura et al. 2006) and possibly low neutron star kicks (Podsiadlowski et al. 2004). A consequence of the low explosion energy may be a small nickel mass produced by the explosion, and thus a low luminosity of the tail of the light curve that is produced by the decay of $^{56}$Ni and $^{58}$Co (Kitaura et al. 2006). The Type IIP SN 1997D may provide an example (Chugai & Utrobin 2000). Second, however, the enormous mass-loss rate of the supernova progenitor (Fig. 13) may produce clear signatures of a supernova–circumstellar medium interaction in the supernova light. Such signatures are in particular an exceptionally bright and long-lasting light curve (Sollerman et al. 2001) and narrow hydrogen emission lines superimposed to a typical SN II spectrum (Pastorello et al. 2002). Third, ECSN progenitors are extremely bright, with luminosities of the order of $10^5 L_\odot$ (Fig. 14). Thus, progenitor identifications on pre-explosion images (Maund & Smartt 2005; Hendry et al. 2006) may be able to identify ECSNe. They may be distinguished from very massive (>20 $M_\odot$) progenitors of similar luminosity by their much cooler effective temperatures (<3000 K for ECSN progenitors vs. ~3400 K for CCSN progenitors).

6.4. The Reference Model, Examples

As shown above, the results of our synthetic SAGB calculations employing the VW93 and the vL05 mass-loss prescriptions are rather similar. Since it is unclear whether the Reimers mass-loss rate is really applicable, and as the vL05 mass-loss rate relies on very recent observations, we adopt the latter as the fiducial mass-loss prescription for our synthetic SAGB modeling. Concerning the third dredge-up efficiency, we adopt the mass-dependent formulation shown in Figure 7 as our reference efficiency. These assumptions define our reference model for the synthetic SAGB evolution.

In the following, we discuss some explicit examples to illustrate the TP-SAGB evolution and to further motivate the choice of our reference model and analyze its uncertainty. The first example is a star with an initial mass of 9.1 $M_\odot$, with an He core mass at the end of the second dredge-up of 1.348 $M_\odot$.

During the evolution on the TP-SAGB, the luminosity first increases from log ($L/L_\odot$) = 4.9 to 5.02 and then drops slightly due to decreasing envelope mass, which decreases the efficiency of hot bottom burning. As a result, the interpulse core growth rate increases from $3 \times 10^{-7}$ to $1.5 \times 10^{-6} M_\odot$ yr$^{-1}$, but the effective core growth is significantly lower (by about a factor of 0.5) due to the effect of dredge-up. The mass-loss rate increases from $3 \times 10^{-5}$ to $1 \times 10^{-4} M_\odot$ yr$^{-1}$ (Fig. 15). In this model the SAGB ends after ~4.4 $\times 10^4$ yr when the core reaches its Chandrasekhar mass. The remaining envelope has a mass of 4.27 $M_\odot$.

For a 10% larger dredge-up efficiency the TP-SAGB time increases to ~4.8 $\times 10^4$ yr, and the remaining envelope decreases to 3.82 $M_\odot$. For a 10% smaller dredge-up efficiency the SAGB decreases to ~4.0 $\times 10^4$ yr, and the final envelope mass increases to 4.61 $M_\odot$. For the case of no dredge-up the SAGB time is ~2.4 $\times 10^4$ yr and the final envelope mass is 6.1 $M_\odot$.

Using the mass-loss prescription of VW93 and the parameterized dredge-up, the result is only different in the mass-loss history, resulting in a smaller final mass. The main reason is that this mass-loss prescription accounts for the superwind phase for TP-AGB stars, which gives a significantly different evolution of the envelope. The TP-AGB phase starts with low mass loss but makes a transition to the superwind phase after 1000 yr with mass-loss rates around $1 \times 10^{-6} M_\odot$ yr$^{-1}$, decreasing slowly due to the waning luminosity (Fig. 15, top panel). After 4.7 $\times 10^4$ yr, the core reaches its Chandrasekhar mass with a final envelope mass of 2.43 $M_\odot$.

An initially 8.8 $M_\odot$ star with the same mass loss and dredge-up (Fig. 16) becomes an ONe WD. The He core mass at the beginning of the SAGB is 1.296 $M_\odot$. During the SAGB evolution the
luminosity increases to $\log \left( \frac{L}{L_\odot} \right) = 4.95$, then decreases due to mass loss. Assuming the vL05 mass-loss rate, the envelope is lost after $\frac{1}{C_{24}} \times \frac{1}{C_{12}} \times 10^5$ yr. The mass-loss rate increases steadily during the TP-AGB phase, but as the star reaches a surface temperature of 2500 K ($\frac{1}{C_{5.2}}$), we assume a constant mass-loss rate of $\dot{M} = \frac{1}{C_{12}} \times 10^{-4} \frac{M_\odot}{C_0} \text{yr}^{-1}$ during the last phase of the evolution. This is consistent with the observations of vL05, who find only one star with a higher mass-loss rate. The remaining ONe core has a mass of $1.338 \frac{M_\odot}{C_{12}}$. Repeating this calculation with the mass-loss rate of VW93 does not show large differences (Fig. 16).

### 7. CONCLUDING REMARKS

We show that both the lower initial mass for SAGB stars and the maximum initial mass for ECSNe sensitively depend on the assumptions for mixing during core H and He burning. EVOL models that include core overshooting and are consistent with the observed width of the main sequence predict a smaller maximum initial mass for SAGB stars. Rotation would act similar to overshooting during the core-burning phases. The STERN models include neither rotation nor overshooting, and the maximum initial mass for SAGB stars and ECSNe is larger by up to $2.5 \frac{M_\odot}{C_{12}}$. Equally important is the treatment of semiconvection during He burning.

On the other hand, the lower initial mass limit for ECSNe is determined by the stellar properties on the SAGB. Most important are the third dredge-up efficiency, the mass-loss rate, and the hot bottom burning efficiency and its dependence on the adopted convection theory for the envelope. In general, larger mass loss, larger dredge-up efficiency, and large hot bottom efficiency all decrease the initial mass range for ECSNe, or even suppress the ECSN channel. In order to increase the accuracy of the transition initial mass between ECSNe and CCSNe and of the lower mass limit for ECSNe, these classical issues of stellar evolution need to be improved specifically for the initial mass range of $6-12 \frac{M_\odot}{C_{12}}$.

We have discussed here the SAGB stars with C ignition and formation of ONe cores as the most likely progenitors of an ECSN class of supernovae. It is in principle possible that initially less massive stars that develop CO cores could increase their core size on the TP-AGB up to the Chandrasekhar mass, resulting in a supernova explosion. Despite the uncertainties still involved, we...
can rule out this possibility for solar metallicity. There are two main reasons that prevent these Type 1.5a supernovae from occurring: First, the mass loss would have to be much lower than observed. Second, models predict that the third dredge-up is larger for massive AGB stars with initial mass between 4 and 7 $M_\odot$ than for SAGB stars (Fig. 7; Karakas et al. 2002). This makes it even more unlikely for massive AGB stars to significantly grow their cores.

We did not take into account mass loss until the beginning of the thermally pulsing phase. If mass loss were applied during the main sequence and up to the TP-AGB, less than half a solar mass would have been lost (Siess 2006, their Table 5). This may shift the quoted initial masses to a slightly higher value.

We note that there is large disagreement between the different studies on the dredge-up efficiency in SAGB stars (Ritossa et al. 1996; Doherty & Lattanzio 2006; Siess & Pumo 2006). Whereas Ritossa et al. (1996) and Siess & Pumo (2006) find negligible amounts of dredge-up, Doherty & Lattanzio (2006) find very efficient dredge-up with $\lambda \sim 0.7$. This situation is similar to the divergent modeling results obtained in the past on the third dredge-up in low-mass AGB stars. For the low-mass regime there is now some consensus that most of the differences were related to different physical and numerical treatments of the convective boundaries. Possibly the same applies to the divergent results for SAGB stars. In our synthetic model we adopted a parameterized prescription (Fig. 7) that is based on state-of-the-art full stellar evolution calculations. To test the effect of dredge-up, we also considered a case with no dredge-up. Clearly, the third dredge-up in SAGB stars needs to be studied in more detail. It is closely related to the mixing conditions at the bottom of the convective boundary. This is a hydrodynamic situation that requires multidimensional simulation, which is complicated by the fact that for these extremely massive cores the dredge-up seems to be hot (Herwig 2004a), i.e., any small amount of H that could be mixed across the convective boundary will instantly burn violently with all the associated feedback on the evolution of the convective instability in that region. On the other hand, the amount of material that is dredged up from the He intershell will be very small, even with large values of $\lambda$, due to the thin intershell, and will therefore easily dilute in the envelope.

It is presently not known whether ECSNe from SAGB stars contribute to the $r$-process pattern in the universe. Explosions from stars in this mass range have been investigated as a promising site for the astrophysical $r$-process (Wheeler et al. 1998; Sumiyoshi et al. 2001; Wanajo et al. 2003), based on the work of Hillebrandt et al. (1984), who exploded an ONe core model from Nomoto (1984, 1987). Other groups were not able to confirm the $r$-process contribution due to the low entropy (e.g., Burrows & Lattimer 1985; Baron et al. 1987; Mayle & Wilson 1988; Bethe & Wilson 1985). Kitaura et al. (2006) ruled out this possibility based on updated physics and two different nuclear equations of state.

In any case, our study outlines that ECSNe from SAGB stars are likely to occur, if only at a level of a few percent of the Type II supernova rate in the local universe. However, at low metallicity, the key physical ingredients to the evolution of thermally pulsing SAGB stars may change. In particular, the stellar wind mass-loss rate may be lower, which might open the ECSN channel appreciably and may even allow Type 1.5 supernovae. This issue will be discussed in a forthcoming paper.

Fig. 14.—Maximum luminosity as a function of the initial mass at the end of the evolution. Progenitors of CO white dwarfs reach luminosities up to $\log (L/L_\odot) \sim 4.6$, while progenitors of ONe white dwarfs reach luminosities up to $\log (L/L_\odot) \sim 5$. Progenitors of ECSNe are the most luminous, with $\log (L/L_\odot) \geq 5$, while progenitors of the least massive CCSNe have preexplosion luminosities of $\log (L/L_\odot) \sim 4.6$.

Fig. 15.—Synthetic AGB mass evolution for an initial mass of 9.1 $M_\odot$. Top: Mass-loss rate for two cases (vL05 and VW93; § 5.2.4); the superwind regime in the VW93 mass-loss prescription sets in at 1000 yr right at the beginning of the AGB phase. Bottom: Evolution of the core and the total stellar mass.

Fig. 16.—Similar to Fig. 15, but for an 8.8 $M_\odot$ star. The core does not reach the Chandrasekhar mass but loses its envelope and becomes a massive ONe white dwarf.
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