Super-AGB stars

bridging the divide between low-mass and high-mass stars

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Abstract & Introduction

Super asymptotic giant branch (super-AGB) stars are in the mass range ~ 6.5-10 Mo and are characterised by off-centre carbon ignition prior to a thermally pulsing AGB phase which can consist from 10s to even 1000s of thermal pulses (TPs).
Their fates are quite uncertain and depend primarily on the competition between the core growth and mass-loss rates.
If the stellar envelope is removed prior to the core reaching the mass for electron captures in the core ~1.375 Mo (Nomoto 1984), an ONe white dwarf will remain, otherwise the star will undergo an electron-capture supernova leaving behind a neutron star.
We briefly describe the factors which influence these different fates, determine their relative fractions and provide mass boundaries.

Method / Model Descriptions

The evolution of massive AGB and super-AGB stars was calculated using the Monash stellar evolution program (MONSTAR).
This program is a 1D hydrostatic evolution program which includes 7 main species; H, ^{3}He,^{4}He,^{12}C, ^{14}N, ^{16}O and Z.
For a current review of MONSTAR see Campbell and Lattanzio (2008) & Doherty et al 2010 & 2015.
A large grid of models were computed with initial masses ~5-10 $M_{\odot}$ over 5 metallicities in the range Z=0.02-0.0001.
Our models were run from the zero age main sequence to near the end of the TP-AGB phase.
We examine the important boundaries such as M_{up} (the minimum mass for carbon ignition), M_{mass} (lower limit for massive star) and M_n (the lower limit for neutron star formation).

Pre/Post second dredge-up core mass

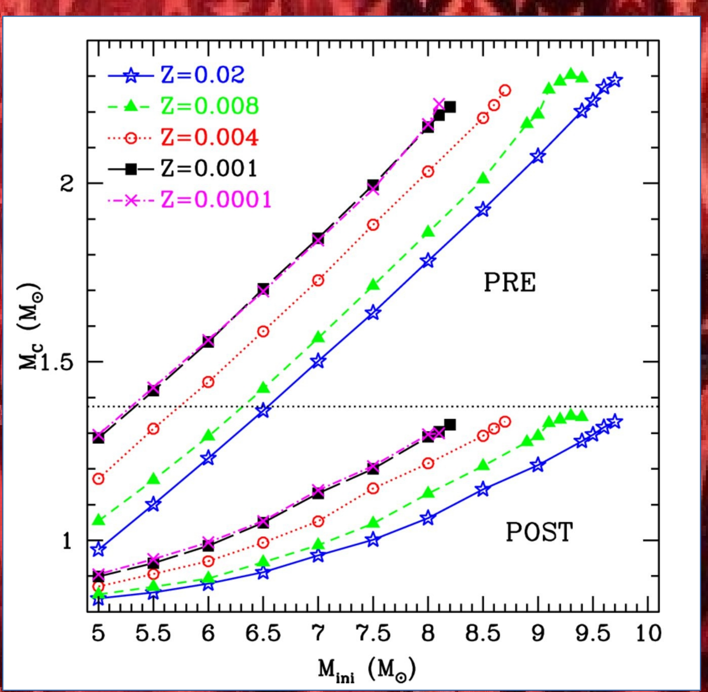

Figure 1: Pre and post 2DU core masses. The dotted black horizontal line represents the M_{ec} (mass limit for electron captures in the core ~1.375Mo).

After core H, He and C burning, the core mass of the star is reduced due to second dredge-up (2DU) – see Fig 1.
This post 2DU core mass is the core mass at the start of the AGB phase, with the final fate of the star determined by the subsequent competition between the core and mass loss from the stellar envelope.

Mass-loss rates

The mass-loss rate for super- & massive AGB stars is very uncertain, e.g in Fig.2 we see large variation using different commonly used mass loss prescriptions.
The uncertainty in mass-loss rate increases at lower metallicity!
For our calculations we use the (relatively rapid mass-loss rate) from Vassiliadis & Wood (1993) & do not apply an explicit metallicity scaling.

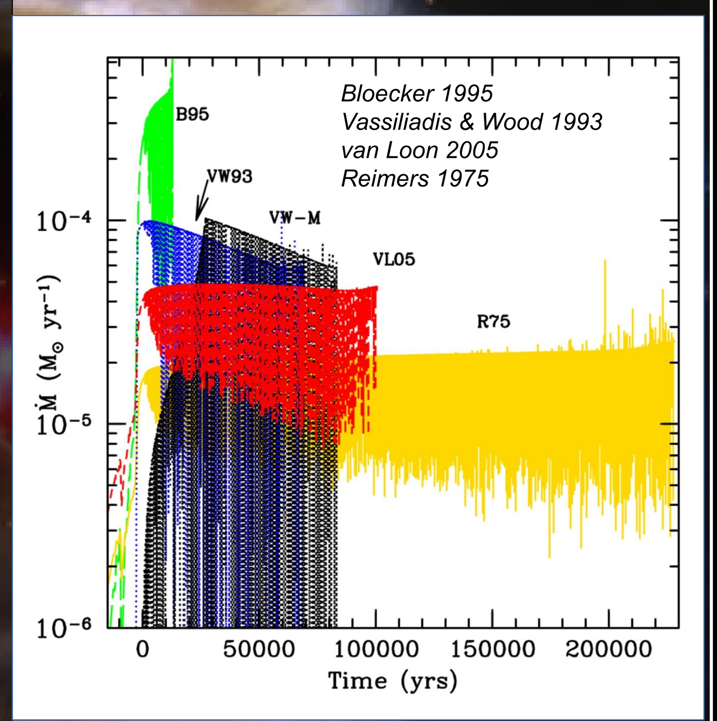

Figure 2: Mass loss rates for commonly used prescriptions during the super-AGB phase for a 8.5 Mo Z=0.02 model. Time axis offset with t=0 corresponding to the 1st TP.

Core growth - Third Dredge-up?

Rubidium observations in luminous O-rich AGB stars (e.g. Garcia-Hernandez et al. 2006) are strong evidence for the occurrence of third dredge up (3DU) in the massive AGB and super-AGB stars.
In Fig 3. we show the 3DU efficiency λ* as a function of core mass from our calculations. Two main points of interest are; the clear lack of a metallicity dependence (at large core masses) and a decrease of λ with increasing core mass. This efficient 3DU reduces the likelihood that super-AGB stars grow enough to explode as EC-SN.

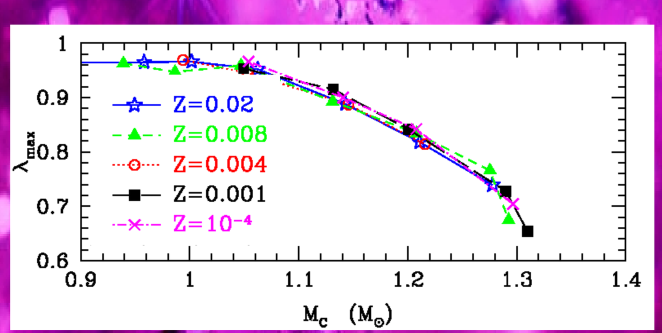

*Figure 3: Maximum λ as a function of core mass. * Where λ is the ratio of mass dredged up by the envelope compare to the mass growth of the core. A λ value of one equates to no core growth.*

Convergence Issues Fe-Peak Instability

All computations of super-/massive AGB stars cease converging prior to the removal of the entire envelope!
In some cases > 2 $M_{\odot}$ of envelope remains.
The cause of this "instability" is due to Fe-peak bump in the opacity that causes the local luminosity at the base of the envelope to exceeds the Eddington luminosity.
The star is therefore no longer in hydrostatic equilibrium and the code crashes (e.g. Lau et. al. 2012).
What would happen in a real star? most likely:
i) total expulsion of the remaining envelope, or
ii) envelope expansion with an enhanced mass-loss rate
This instability is an interesting problem which should be explored with hydrodynamic simulations.

Initial to final mass relation (IFMR)

In Fig. 4 we show our calculated IFMRs, which includes 3 types of white dwarfs (WDs): ONe,CO(Ne)*&CO WDs

Lower metallicity models (stars) leave more massive WDs for the same initial masses.

Due to the fast mass-loss and slow core growth rates our models grew by at most 0.03 Mo during the entire (S)AGB phase.

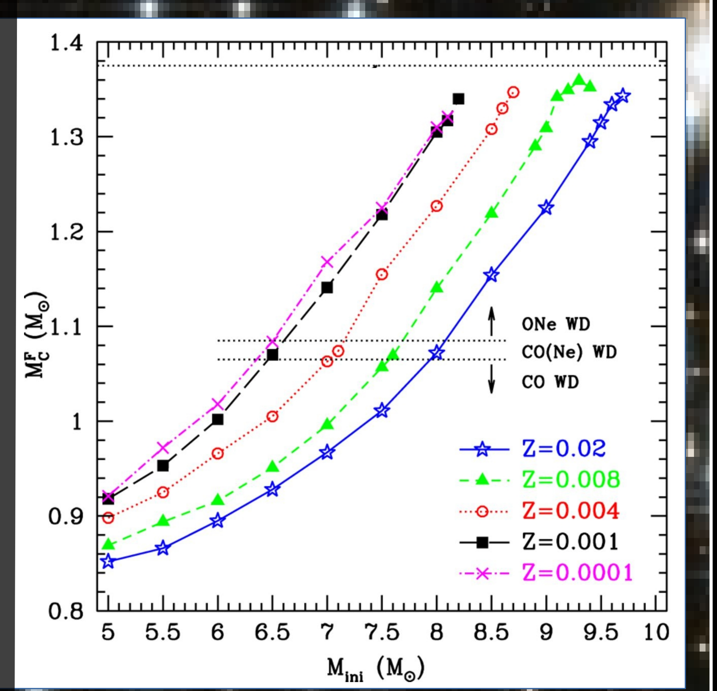

Figure 4: Initial final mass relation for the range of metallicities Z=0.02-0.0001.

*Note: CO(Ne) white dwarfs are those that have undergone off-centre carbon ignition but the flame did not reach the centre (e.g. Doherty et al. 2010)

Supernovae from Super-AGB stars?

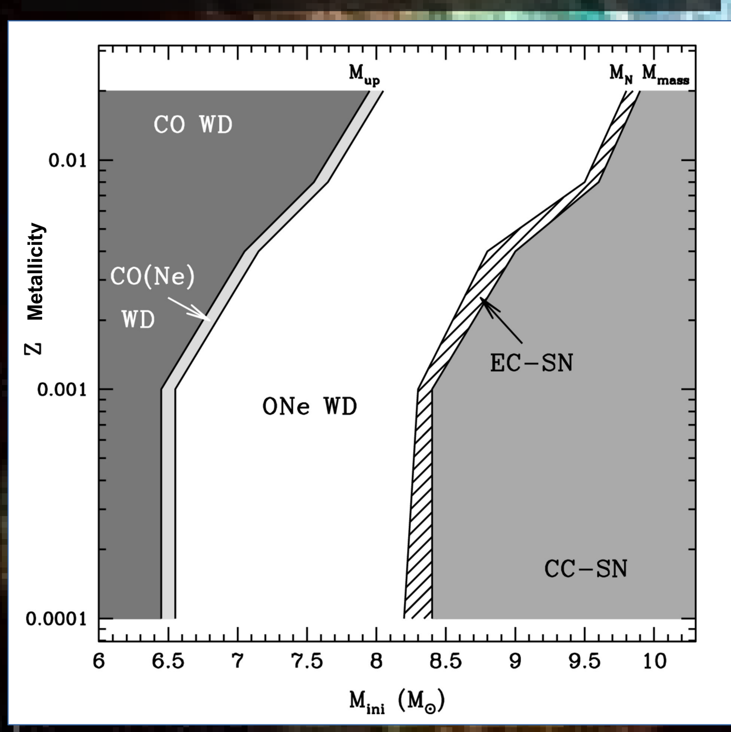

Figure 5: Final Fates Diagrams, M_{up} ,M_n and M_{mass}. CC=Core Collapse, EC=Electron capture

We find the mass range for EC-SN is very fine (see Fig 5) ~ 0.1- 0.2 Mo.
Using a Kroupa initial mass function (IMF) we find ≈ 2-5 % of all CC-SN will be EC-SN.

At high Z our models compare favorably with parametric studies by Poelarends et.al 2008 & Siess 2007, but at lower Z, because we do not apply at Z mass loss scaling, we find far fewer EC-SN.

Comparisons

Observations and other model results

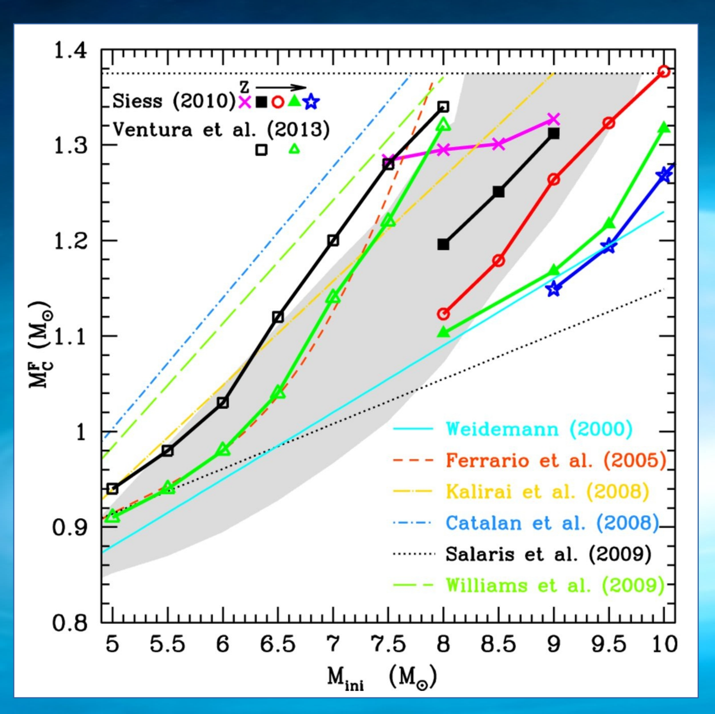

Figure 6: Initial to final mass relation. Grey shading represents the range of our model results from Fig. 4 (see Doherty et al. 2015)

We compare our predictions to observationally derived IFMRs.
Large spread in results with maximum WD mass ~7.6 - 10+ Mo

Large variation in model predictions cf. Siess 2010 & Ventura et al. 2013. This is primarily due to differences in treatment of convective boundaries during core He burning.

Conclusion

We have computed the full thermally pulsing evolution of a large grid of massive AGB and super-AGB stars over a range of metallicities Z=0.02-0.0001.
Our models with moderate mass loss and efficient 3DU increase their core mass by only ≈ 0.01–0.03 Mo during the TP- (S)AGB phase.
Due to this, the majority of our super-AGB star models end their lives as ONe white dwarfs.
We also note a fine ~0.1 Mo region for production of hybrid CO(Ne) white dwarfs.
We predict (for single stars and assuming a Kroupa IMF), that at maximum. between 2 to 5 % of all supernova will be electron capture supernova.

References

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