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Evolution and nucleosynthesis in super-AGB stars

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Abstract.
Here we present results of an stellar evolutionary model for a 9.5 $M_{\odot}$, solar composition Super Asymptotic Giant Branch (SAGB) star onto the thermally pulsing phase. We also present preliminary nucleosynthesis results for the same star up to earlier stage of its evolution, that of carbon burning. We find stellar conditions appropriate for Hot Bottom Burning (HBB) and Third Dredge Up (TDU), and mention the effect these would have on SAGB nucleosynthesis. Comparisons with previous studies by Ritossa et. al (1996); Garcia-Berro et. al (1997) & Siess (2006) are undertaken, resulting in a major difference due to our *high* efficiency of third dredge up.

Key words. Stars: evolution - Stars: AGB - Stars: Super-AGB - Stars: nucleosynthesis

1. Introduction

Super-AGB stars (SAGBs) are a class of stars in the mass range ≈ 7-12 $M_{\odot}$ which straddle the divide between high and intermediate mass stars. What categorizes a SAGB star is the off centre carbon ignition which takes place after core hydrogen and helium burning. After carbon burning these SAGBs end their life through a thermally pulsing (TP) stage, losing mass to form a ONe white-dwarf. SAGB stars may also end life more violently, undergoing a SN explosion to become a neutron star. This occurs for a variety of reasons owing to either a slower mass loss rate, larger initial mass or lower metallicity. For further discussion on this mass cut-off between low and high mass SAGB stars see Eldridge & Tout (2004) and references therein.

As yet, only a few studies Garcia-Berro & Iben (1994); Ritossa et. al (1996); Garcia-Berro et. al (1997); Iben et. al. (1997); Ritossa et. al. (1999) and Siess (2006) have looked into these SAGB stars from a nucleosynthesis point of view. Currently no set of nucleosynthetic yield calculations to the end of the TP stage are available. These SAGB yields would have a role to play in Galactic chemical evolution models. In addition, the surface abundances could serve to find a possible observational signature leading to identification of SAGBs. Results for evolution and preliminary nucleosynthesis of a 9.5 $M_{\odot}$, solar composition SAGB star are presented. Section 2 briefly describes the codes used and input physics. The evolution and effects of carbon burning are described in Section 3. We show in Section 4, stellar conditions that are appropriate for Hot Bottom Burning (HBB) and Third Dredge Up

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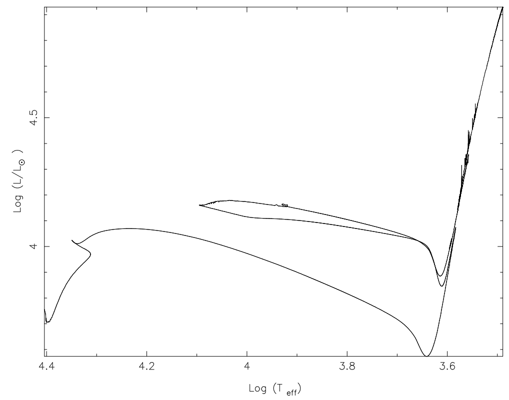

Fig. 1. HR Diagram for a 9.5 $M_\odot$ solar composition SAGB star.

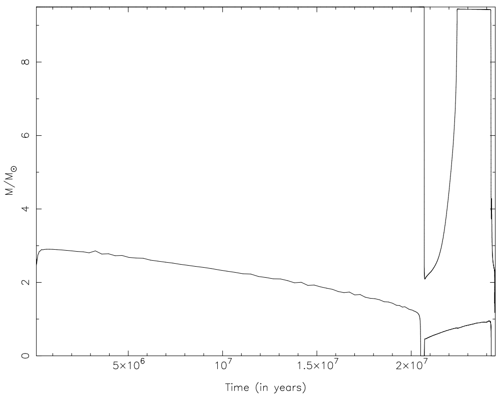

Fig. 2. Kippenhahn diagram of a 9.5 $M_\odot$ showing the convective features, core hydrogen burning, FDU, core helium burning until the onset of carbon burning.

(TDU) and mention the expected effect these would have the nucleosynthesis.

2. Summary of the Evolution and Nucleosynthesis Programs

The Monash Version of the Mount Stromlo Stellar Evolution Program (MSSSEP) was used for our stellar evolution calculation, whereas the nucleosynthesis is calculated using a separate post-processing Monash Stellar Nucleosynthesis code (MOSN). A brief summary of the major input physics for MSSSEP is as follows; neutrino losses Itoh et. al. (1996), electron screening from Graboske et. al. (1967), OPAL opacities, mass loss prescription from Vassiliadis & Wood. (1993). The treatment of convective boundaries in the study of AGB stars is always a contentious subject and for SAGBs there is no difference. The MSSSEP code uses a neutral boundary condition see Frost & Lattanzio (1996), which may lead to significant differences between code results in latter stages of evolution. As we have two separate codes for evolution and nucleosynthesis the evolution code needs only to include the most energetic and structurally important nuclear burning reactions reducing the computational time. In MSSSEP carbon burning is approximated by the overall reaction $^{12}C + {}^{12}C + {}^{16}O = 2{}^{20}Ne$ which take into account the two major carbon burning channels $^{12}C(^{12}C, p)^{23}Na$ and $^{12}C(^{12}C, \alpha)^{20}Ne$ and the absorption of the α by the ^{16}O and the p by ^{23}Na. The MOSN code performs time dependent mixing in convective regions, and currently uses a network of 74 species (Hydrogen to Sulphur and including iron peak elements) and 506 nuclear reactions.

3. Results and Discussion

3.1. Evolution Prior to Carbon Burning

The evolution of SAGBs prior to carbon burning (see Fig. 2) is very similar to that of lower mass AGB stars.

One small difference, due to the larger temperatures involved in the hydrogen burning core in SAGBs, leads to a greater production of the NaNe chain products. During the FDU (First Dredge Up) the surface is enriched in these species. These enhancements would make SAGBs - due to higher dilution in their massive envelope, very hard to distinguish from their lower mass counterparts. After FDU, SAGB stars undergo core helium burning, and later shell helium burning which continues past the onset of carbon burning.

We have run a 9.5 $M_\odot$ solar composition model using the method outlined in Section 2 until the onset of carbon burning. When compared with results by Siess (2006) Table 1 we find strong similarities for these, the long lived stages of the stellar evolution. Both studies have very similar input physics, such as mass loss rate and neutrino losses. When comparisons are made to Garcia-Berro et. al (1997) for a 9 $M_\odot$ star similar trends are found. Why the stellar results between differing programs then start to diverge is still of major interest and is under further investigation.

3.2. Carbon Burning

Carbon burning begins off centre when temperature in CO core exceeds ~ 600 MK. As seen in Fig.3 the journey of the carbon burning region towards the core is a intricate one. For our 9.5 $M_\odot$ star the carbon burning proceeds via an initial carbon shell flash and then a secondary flash, dubbed a “flame” as it propagates inwards reaching the core. These flashes input energy into the region, creating convective pockets exterior to the carbon burning.

In lower mass SAGB stars there can be a series of these initial carbon flashes before a flame front develops. Conversely for more massive SAGB stars only one flash (flame) occurs which burns all the way to the core.

When the carbon burning flame reaches the core the degeneracy is lifted, letting the carbon burn in the core quiescently for a small period until carbon exhaustion. After complete core burning, contraction ensues and the core temperature increases leading to a series of flashes which burn outwards and remove the carbon rich regions left in the middle and outer regions of the previous CO core.

Timmes & Woosley (1992) devised a theoretical model which determines the speed of a flame front propagating inwards into a degenerate CO core. By assuming a “balanced power condition” in which the energy produced in carbon burning flame convective regions equals that of the neutrino losses, Timmes & Woosley (1992) then calculate the flame speed based only on local thermodynamical properties (excluding gravity). As with studies by Garcia-Berro et. al (1997) and Siess (2006) we find close agreement to within a factor of two between our model and the analytic approximation.

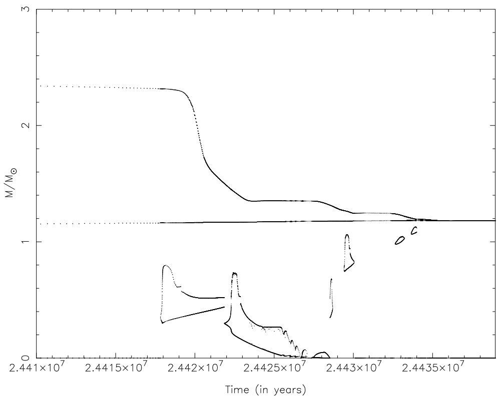

Fig. 3. Kippenhahn diagram during the carbon burning phase, showing multiple convective carbon burning regions, as well as the helium burning shell and the base of the convective envelope.

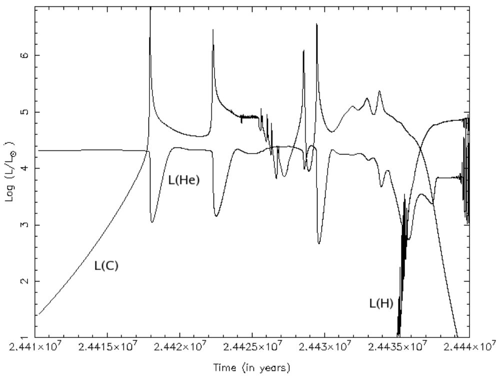

Fig. 4. Luminosities for H, He and C burning.

Fig.4 shows the luminosity behavior at the onset of carbon burning. When the carbon flashes occur the large amount of energy injected causes a decrease in the helium luminosity. At the completion of carbon burning the hydrogen luminosity increases very quickly corresponding to the re-ignition of the hydrogen burning shell.

The core composition after the completion of carbon burning comprises primarily of oxygen (50%), neon (34%), sodium (3%), carbon (3%) (note the relative large carbon abundance) as well as aluminium, magnesium, other trace elements.

Table 1. Comparison of evolution prior to the onset of carbon burning with Siess (2006). M_{HB} is the maximum extent of convection during core H burning, M_{HeB} maximum mass of convective core during helium burning, M_{FDU} maximum inward penetration of convective envelope, M_{COi} is the core mass at the start of C burning, and the X[C], X[O] are the mass fraction of carbon and oxygen respectively at the completion of core He burning

	M_{HB}	M_{HeB}	M_{FDU}	M_{COi}	$X[^{12}C]$	$X[^{16}O]$
MSSSEP	2.902	0.947	2.091	1.150	0.623	0.350
Siess	2.906	0.850	2.018	1.095	0.630	0.344

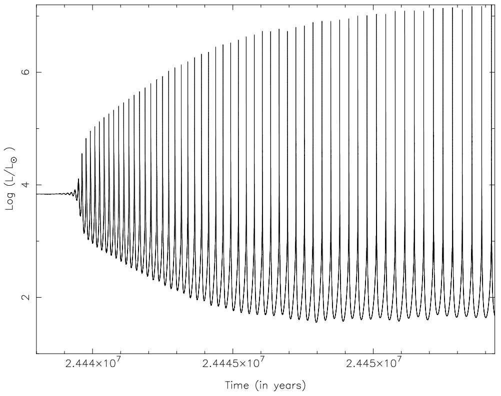

Fig. 5. Helium burning luminosities from onset of the thermally pulsing SAGB phase.

3.2.1. Second Dredge Up (SDU)

In intermediate mass AGB stars above ~ 4 $M_\odot$, SDU occurs following completion of core helium burning. For lower mass SAGB stars (~ 8-9 $M_\odot$) this is also the case. In more massive stars however, the ignition of carbon burning stalls the progress of the SDU so that it occurs *during* the carbon burning phase, or in more massive stars still, after completion of carbon burning.

3.3. Thermally Pulsing SAGB Phase

During the thermally pulsing stage of evolution there are multiple sites for nucleosynthesis. Here however we limit our investigation to the base of the convective envelope (HBB), leaving at this time, discussion of possible s-process nucleosynthesis. In Fig.5 we see the evolution of TPs highlighted by the pulsed helium luminosity. As these SAGB stars are quite massive their envelopes are significant therefore even with very efficient mass loss their journey over to the white dwarf cooling track will involve many TPs. For our 9.5 $M_\odot$ model we expect in excess of 500 thermal pulses. As the mass loss rate dictates the number of TPs, this choice of mass loss rate greatly effects the composition obtained from both HBB and TDU.

As the interpulse period is inversely related to the mass of the hydrogen exhausted core, SAGB models have substantially lower interpulse periods, smaller convective pockets and shorter convective pocket lifetime than AGB stars. Our results for our 9.5 $M_\odot$ model find an average interpulse period of ~ 350 years, convective pockets size of ~ 10^{-4} $M_\odot$ and convective pocket lifetimes (~ 5 years).

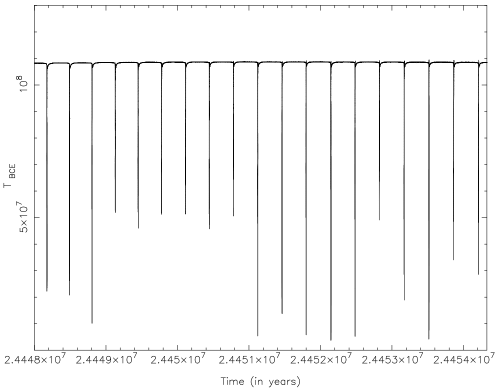

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Fig. 6. Temperatures at the base of the convective envelope during the thermally pulsing SAGB phase.

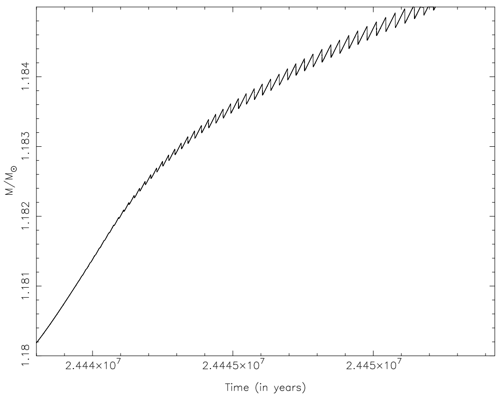

Fig. 7. Mass of the hydrogen exhausted core, from onset of thermally pulsing phase (same timescale as Fig 5) highlighting the dredge up efficiency as well as the lapse between the start of TPs and commencement of efficient TDU.

3.3.1. Hot Bottom Burning

During the thermally pulsing phase in SAGB stars the bottom of the convective envelope reaches into the hydrogen burning shell. If the temperature at the base of this convective envelope is large enough, nuclear burning begins, so this temperature is vital in determining the extent and end products of this nucleosynthesis. As the temperature involved in this region of the star peaks at over 100 MK (see Fig.6) we expect that both the NaNe and MgAl cycles as well as the CNO cycle will be very efficient.

3.3.2. Third Dredge Up (TDU)

During TPs the peak helium luminosity reaches over 10^7 L$_\odot$ resulting in a decrease in the hydrogen luminosity due to the "extinguishing" of the hydrogen burning shell. This allows the convective envelope to penetrate into the regions that have undergone partial helium burning. This TDU is found with a dredge up efficiency λ value of 0.7[1]

This is most interesting when compared with results from published studies from Garcia-Berro & Iben (1994) which find about $\lambda \approx 0.07$ (for a 10 M$_\odot$ star) and Siess (2006) finds no TDU. However, Poelarends et al.; as presented at this workshop, also finds an efficient TDU. Why the efficiency (or lack) of dredge up varies between different authors and models is currently under investigation.

For this 9.5 M$_\odot$ model the onset of TDU starts at about the 10th pulse and increases with subsequent pulses until maximum efficiency at $\sim$ 18 pulse. The effect this TDU has on altering the surface composition and yield calculation can currently be only speculated upon.

4. Conclusions

We find strong agreement between our current SAGB model and work by others for bulk characteristics in the earlier stages of evolution. Why in the later stages of evolution the differing stellar models diverge is now a subject of investigation. Many complexities remain, such as the choice of mass loss and the very important treatment of the convective boundaries. Results which will show the effects of HBB and TDU on the nucleosynthesis yields in these SAGB are greatly anticipated. Models are currently underway to compute a complete set of yield calculations for a range of masses and metallicities using the MSSSEP and MOSN code (Doherty 2006).

[1] Where $\lambda = \Delta M_{\mathrm{dredge}}/\Delta M_{\mathrm{H}}$.

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References

Doherty, C.L. In preparation. 2006.
Eldridge, J.J. & Tout, C.A. 2004, MmSAI ,75, 694
Frost, C.A. & Lattanzio, J.C. 1996, ApJ, 473, 383
Garcia-Berro, E. & Iben, Jr I. 1994, ApJ, 434,306
Garcia-Berro, E., Ritossa, C., Iben, Jr I. 1997, ApJ, 485, 765
Graboske, H.C., DeWitt, H.E., Grossman, A.S., Cooper, M.S. 1967, ApJ, 181, 457
Iben, Jr I., Ritossa, C., Garcia-Berro, E. 1997, ApJ, 489, 772
Itoh, N., Hayashi, H., Nishikawa, A., Kohyama, Y. 1996, ApJ SS, 102, 411

Ritossa, C., Garcia-Berro, E., Iben, Jr I. 1996, ApJ, 460, 489
Ritossa, C., Garcia-Berro, E., Iben, Jr I. 1999, ApJ, 515, 381
Siess, L . 2006, A&A, 448, 717
Timmes, F.X. & Woosley, S.E. 1992, ApJ, 396, 649
Vassiliadis, E. & Wood, P.R. 1993, ApJ, 413, 641