Mem. S.A.It. Vol. 77, 840

Memorie della

Synthetic super–AGB stars

Robert G. Izzard[1,2] and Arend Jan T. Poelarends[1]

1. Sterrenkundig Instituut, Universiteit Utrecht, P.O. Box 80000, 3508 TA Utrecht, The Netherlands.
2. The Carolune Institute for Quality Astronomy, www.ciqua.org

Abstract. We describe our first attempt at modelling nucleosynthesis in massive AGB stars which have undergone core carbon burning, the super-AGB stars. We fit a synthetic model to detailed stellar evolution models in the mass range $9 \leq M/\mathrm{M}_{\odot} \leq 11.5$ ($Z = 0.02$), and extrapolate these fits to the end of the AGB. We determine the number of thermal pulses and AGB lifetime as a function of mass and mass-loss prescription. Our preliminary nucleosynthesis calculations show that, for a reasonable mass-loss rate, the effect of hot-bottom burning in super-AGB stars on the integrated yield of a stellar population is not large. There are many uncertainties, such as mass-loss and convective overshooting, which prevent accurate yield calculations. However, as potential progenitors of electron-capture supernovae, these stars may contribute 7% of non-type-Ia supernovae.

Key words. stars: abundances – stars: AGB – nucleosynthesis

Introduction

Stars are traditionally divided into those which explode and those which do not. Stars which explode as supernovae by a core-collapse mechanism are the massive stars, while their lower-mass cousins enter a thermally pulsing asymptotic giant branch (TPAGB) phase where rapid mass-loss ends their evolution. It is difficult to specify the exact mass boundary between these populations, with estimates ranging from $7\,\mathrm{M}_{\odot}$ (Girardi et al. 2000) up to more than $11\,\mathrm{M}_{\odot}$ (Ritossa et al. 1999), depending on metallicity and convective overshooting.

The problem relates to the fate of the star after carbon ignition, which depends on the degeneracy of the core. In high-mass stars the non-degenerate core burns carbon, then neon, oxygen and silicon. A core-collapse supernova soon follows, leaving a neutron star or black hole. A lower-mass, but massive enough to ignite carbon, (partially) degenerate core burns carbon in a series of flashes (e.g. Siess 2006) and then moves to a *super* thermally pulsing AGB (SAGB) stage, with double-shell burning above a degenerate oxygen-neon core, where mass-loss terminates the evolution, leaving a white dwarf (Siess, this volume). In a small number of stars the oxygen-neon core may grow beyond $1.368\,\mathrm{M}_{\odot}$ during the pulsing phase, which leads to a collapse of the core due to electron capture on ^{24}Mg (Poelarends, this volume). Detailed models of these stars have been constructed by Garcia-Berro & Iben (1994); Ritossa et al. (1996); Garcia-Berro et al. (1997); Iben et al. (1997) and more recently by Eldridge & Tout (2004) who consider

Send offprint requests to: R.G.Izzard@phys.uu.nl

SAGB stars as observable supernova progenitors (see also Poelarends, this volume).

Once carbon ignition and second dredge-up have finished, SAGB stars pulse in much the same way as normal TP-AGB stars, albeit with a shorter interpulse period. By virtue of their high mass, one expects high temperatures at the base of the convective envelope and associated hot-bottom burning (HBB; e.g. Boothroyd et al. 1995). Their envelopes should be processed by the hydrogen-burning CNO, NeNa and MgAl cycles. For studies of Galactic chemical evolution, these stars may be an important source of nitrogen, sodium and aluminium and they may play a part in the globular cluster Na – O anticorrelation mystery (D'Antona, this volume; Ventura & D'Antona 2005). It is unclear whether third dredge-up occurs in SAGB stars – current models suggest either it does (Doherty, this volume), does not (our models and Siess, this volume), or is inefficient (Ritossa et al. 1996). There are no detailed studies of chemical yields from SAGB stars, probably because detailed stellar models take a long time and are difficult to construct, and suffer from the usual uncertainty due to mass-loss and convective overshooting. A synthetic modelling technique speeds up modelling and enables us to explore the uncertain parameter space.

In this paper we calculate the chemical yields of SAGB stars using a synthetic model based on the AGB model of Izzard et al. (2004,I04). We approximate stellar structural variables with formulae and interpolation tables, and use a simple model for HBB to follow the CNO, NeNa and MgAl cycles and surface abundances of C, N, O, Ne, Na, Mg, Al and Si. The synthetic model is then used to extrapolate evolution beyond the detailed models to the end of the SAGB phase. This is possible because the structure of AGB stars is such that after a number of pulses, the evolution reaches a limit cycle (Ritossa et al. 1996). We calculate supernova rates and chemical yields, and also change the input physics (especially the mass-loss rate) to determine the effect of uncertainties. Such a parameter space exploration is currently impossible with a normal stellar evolution code, because the CPU time required is simply too large.

Models, full and synthetic

Our full evolution models were constructed with the STERN code (Heger, Langer, & Woosley 2000). We constructed models of mass 8.5, 9.0, 10.0 and 11.5 $M_{\odot}$ which undergo 12, 26, 10, 16 pulses respectively, with metallicity $Z = 0.02$, no convective overshooting, no mass loss and no rotation. Further description of these models can be found in Poelarends et al. (this volume).

Our synthetic models are based on those of I04 with some updates and changes for the SAGB phase (a detailed description will be found in a later paper; Izzard and Poelarends, in preparation). The luminosity formula was altered to fit our detailed models, and the radius follows from $\log R \sim \log L$. The initial and post-second-dredge-up abundances, core mass at the end of core helium burning and core mass at the first thermal pulse, are interpolated from tables based on the detailed models. Stars with a helium core mass above $1.6\,M_{\odot}$ during the early AGB ignite carbon, while stars with a degenerate oxygen-neon core with mass greater than $1.38\,M_{\odot}$ collapse to neutron stars. We assume there is no third dredge up.

The synthetic HBB model was described in I04 but we use the latest version which includes the NeNa and MgAl cycles as well as CNO. It approximates the burn-mix-burn-mix… cycle in a real convective envelope (which has a thin HBB shell at the base) as a single burn-mix event during each interpulse period, with a large fraction of the envelope burned for a given time. The temperature and density at the base of the envelope are fitted to simple formulae of the form $1 - \exp(-N_{\mathrm{TP}})$ which approaches a constant as N_{TP}, the number of thermal pulses, increases. The fraction and the burn time are calibrated as a function of stellar mass, as in I04.

We apply one of the following mass-loss prescriptions during the SAGB phase: none, original Vassiliadis & Wood (1993,VW93), VW93 but Karakas et al. (2002,K02) variant, Reimers with $\eta = 1$ or $\eta = 5$ (Reimers 1975)

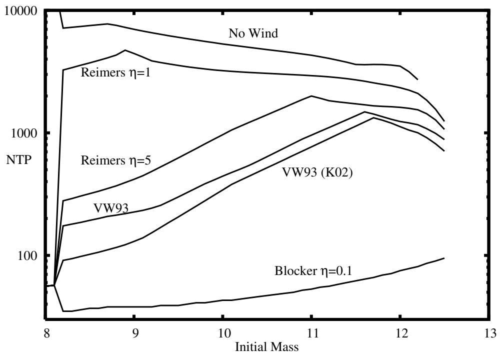

Fig. 1. Number of thermal pulses as a function of initial stellar mass for different mass-loss prescriptions: no wind at all or pre-SAGB wind of Hurley et al. (2002) with Reimers ($\eta = 1$ or 5), VW93 or Blöcker mass-loss during the SAGB.

or Blöcker & Schönberner (1991) with $\eta = 0.1$. Prior to the SAGB, we either apply no mass loss, or the compilation of Hurley, Tout, & Pols (2002,H02). In the cases where mass loss does not expose the core before it grows to $1.368\,M_\odot$, the core is quietly converted into a neutron star while the envelope is ejected to space (this is the subject of some debate e.g. Nomoto 1987, Gutiérrez, Canal, & García-Berro 2005).

Results

We are confident that our extrapolation of the stellar structure (luminosity, radius, mass and core mass evolution) is reasonable, within the uncertainty that is mass loss, because a very similar model works well for lower-mass AGB stars (I04). The mass-loss rate for SAGB stars is unknown, so we consider all the possibilities. Figure 1 shows the number of thermal pulses during the SAGB phase which ranges from 30 (Blöcker, with SAGB lifetimes of $4,000$ to 5×10^4 years) to $4,000$ (Reimers $\eta = 1$, with lifetimes of 10^5 to 10^6 years), or $8,000$ with no mass loss. Mass loss during core helium burning, prior to the SAGB, is included in the H02 prescription and is not negligible for stars above $8\,M_\odot$ – they lose around $0.5\,M_\odot$ during this phase, which affects the subsequent evolution and HBB.

One way of constraining the value of mass-loss rate is through supernova counts. If there is little mass loss during the SAGB, many stars' cores should reach the electron capture limit of $1.368\,M_\odot$ before their envelope is lost. In the limit of no mass loss during the SAGB, we find the ratio of the electron-capture to type-II supernova rates is about one[1]. With the VW93 (K02 variant) mass-loss the ratio drops to 7%. If electron capture supernovae are distinguishable from normal core-collapse types (and accretion induced collapses in binaries; Podsiadlowski et al. 2004) then we can constrain the mass-loss rate[2].

In figure 2 we show the results of our HBB calibration and extrapolation for a $10\,M_\odot$ star. The detailed models truncate their abundance output to the nearest 10^{-3} in the log, which causes the stepping behaviour, while the stepping in the synthetic model is because HBB is done at the end of each pulse. Ten pulses is just enough to calibrate the isotopes which change rapidly, ^{13}C, ^{17}O and ^{21}Ne are also useful in this regard, while other isotopes such as ^{16}O are not. We have to assume the other species ($^{20,22}Ne$, ^{23}Na, Mg and Al) follow from this calibration. The situation is little better in the $9\,M_\odot$ star: it has 26 pulses, but its lower temperature slows the burning.

Finally, we consider the magnesium isotopes. Figure 3 shows the surface abundance of ^{24}Mg and ^{25}Mg as a function of time for $9 \leq M/M_\odot \leq 12$ with H02 mass loss prior to the SAGB, and VW93 (K02 variant) mass loss during the SAGB. Only the 11 and $12\,M_\odot$ models show significant burning of ^{24}Mg to ^{25}Mg, with up to a factor of two increase. For $M \leq 10\,M_\odot$ the HBB is simply not hot enough to enable the MgAl cycle. At all masses, rapid

[1] We do not include an upper mass limit for SNe, so ratios quoted are lower limits.

[2] We only model single stars here, binary interactions will alter the result.

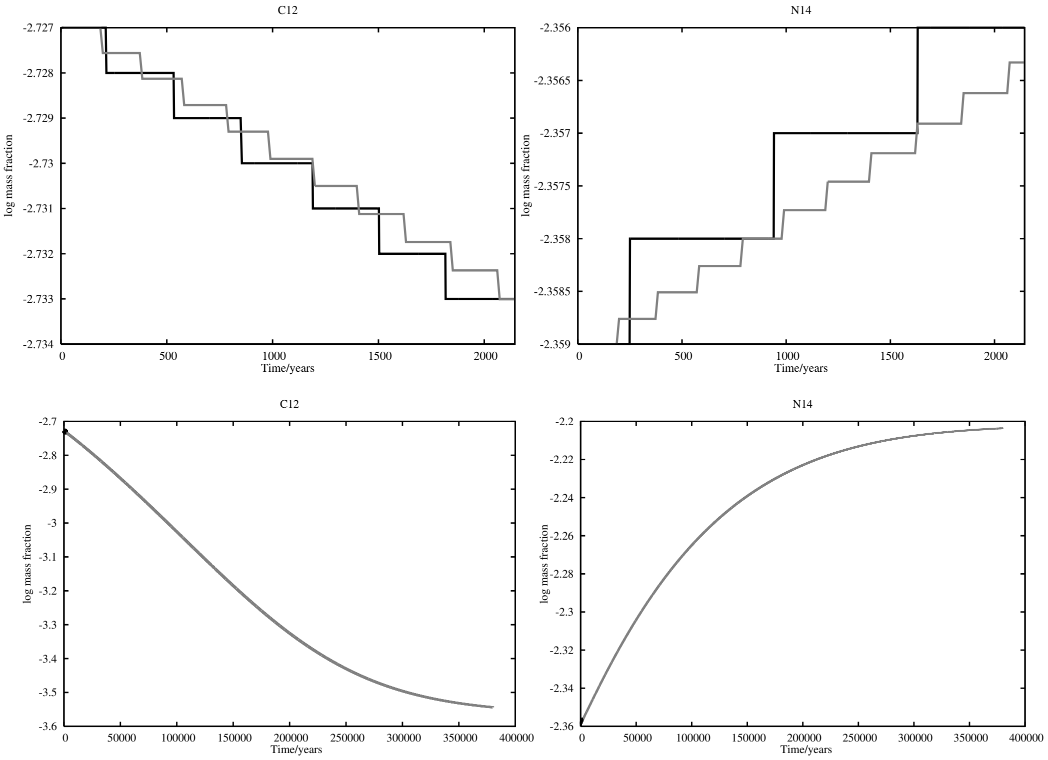

Fig. 2. Log surface abundance by mass fraction vs time for ^{12}C and ^{14}N for our $10\,M_{\odot}$ detailed (black lines) and synthetic (grey lines) models, both with no mass loss. The top panels show the result of our HBB calibration, the bottom panels the same models extrapolated to the end of the SAGB.

mass loss turns off the MgAl cycle after about 2×10^4 years[3].

Discussion

This was our first attempt to model these stars synthetically and, at least for the structure variables such as luminosity, radius, core mass (and growth), we have confidence in our model. However our HBB model is not as solid, given that we have extrapolated forward by a factor of ten or more in time compared to our detailed models. It is clear that we must extend our detailed models to at least cover, say, half the evolution (which may still be many thousand pulses), and see if the synthetic model predictions match the detailed model[4].

Even when we have extended the detailed models, we will still suffer from the mass-loss uncertainty. It seems, from figure 1, we can get as many pulses as we like. New observations are providing insight into the mass-loss rates in oxygen-rich AGB stars and we integrate these new rates into our next calculations (van Loon et al. 2005). We have also neglected the problem of convective overshooting, which reduces the mass for formation of SAGB stars

[3] As in I04 we modulate the temperature with a factor $(M_{\rm env}/M_{\rm env,1TP})^{0.02}$ to turn off HBB as mass is lost.

[4] The numerical problems seen in figure 2 will become irrelevant in that case.

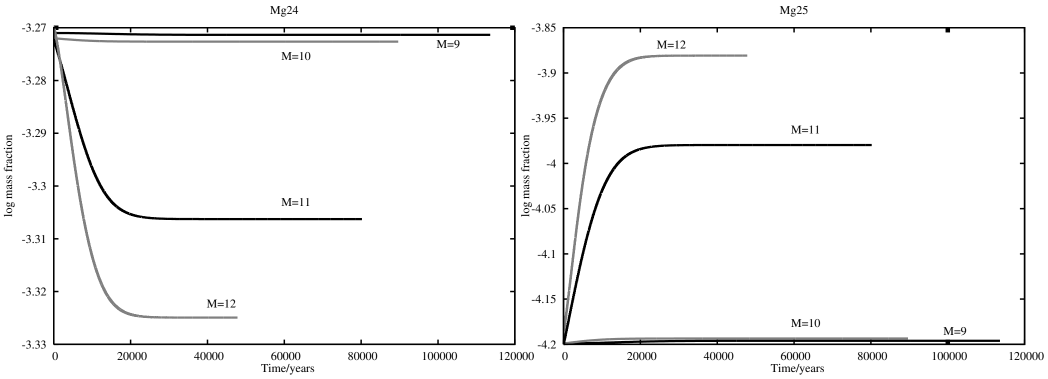

Fig. 3. The surface abundance of ^{24}Mg and ^{25}Mg during the super-AGB phase for the initial mass range $9 \leq M/\mathrm{M}_{\odot} \leq 12$. Hot-bottom burning converts ^{24}Mg into ^{25}Mg, while mass-loss stops the burning and terminates the evolution.

by about 2 $\mathrm{M}_{\odot}$ (Siess, this volume). The initial mass function is a steep power law in mass, so a lower mass limit means more SAGB stars, and their lifetimes will be longer (lower mass means smaller luminosity, radius and $\dot{M}$).

Our preliminary results suggest that SAGB stars are not very important either for Galactic or globular cluster chemical evolution. The bulk of element production comes from either lower-mass AGB stars or higher-mass stars and type II supernovae. This conclusion may change if SAGB stars suffer either third dredge-up, or dredge-out, a phenomenon where the carbon flash causes helium-burned material to be mixed to the surface (Ritossa et al. 1999; Siess 2006). Also, we only consider envelope ejection for a collapsing oxygen-neon core. In reality, some of the core may be ejected too, particularly if some carbon remains after the core flashes (Gutiérrez, Canal, & García-Berro 2005).

Conclusions

In the context of galactic chemical evolution, chemical yields from hot-bottom burning SAGB stars are not important, at least for most isotopes. If mass-loss rates are much lower than those expected from extrapolation of normal AGB rates, if there is dredge-up or dredge-out, or if our simple extrapolations fail, this conclusion may be premature. We are working to extend our detailed model set to remove the extrapolation problem.

The ratio of electron-capture to type-II supernovae in single stars is about 7% if we assume a Vassiliadis & Wood (1993) wind for the SAGB phase – this should be detectable, if it is possible to distinguish electron-capture from core collapse supernovae.

Acknowledgements. RGI and AJP are supported by the NWO.

References

Blöcker, T. & Schönberner, D. 1991, A&A, 244, L43

Boothroyd, A. I., Sackmann, I.-J., & Wasserburg, G. J. 1995, ApJ, 442, L21

Eldridge, J. J. & Tout, C. A. 2004, Memorie della Società Astronomica Italiana, 75, 694

Garcia-Berro, E. & Iben, I. 1994, ApJ, 434, 306

Garcia-Berro, E., Ritossa, C., & Iben, I. J. 1997, ApJ, 485, 765

Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371

Gutiérrez, J., Canal, R., & García-Berro, E. 2005, A&A, 435, 231

Heger, A., Langer, N., & Woosley, S. E. 2000, ApJ, 528, 368

Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, MNRAS, 329, 897

Iben, I. J., Ritossa, C., & Garcia-Berro, E. 1997, ApJ, 489, 772
Izzard, R. G., Tout, C. A., Karakas, A. I., & Pols, O. R. 2004, MNRAS, 350, 407
Karakas, A. I., Lattanzio, J. C., & Pols, O. R. 2002, PASA, 19, 515
Nomoto, K. 1987, ApJ, 322, 206
Podsiadlowski, P., Langer, N., Poelarends, A. J. T., et al. 2004, ApJ, 612, 1044
Reimers, D. 1975, Circumstellar envelopes and mass loss of red giant stars (Problems in stellar atmospheres and envelopes. (A75-42151 21-90) New York, Springer-Verlag New York, Inc., 1975, p. 229-256.), 229–256
Ritossa, C., Garcia-Berro, E., & Iben, I. J. 1996, ApJ, 460, 489
Ritossa, C., García-Berro, E., & Iben, I. J. 1999, ApJ, 515, 381
Siess, L. 2006, A&A, 448, 717
van Loon, J. T., Cioni, M.-R. L., Zijlstra, A. A., & Loup, C. 2005, A&A, 438, 273
Vassiliadis, E. & Wood, P. R. 1993, ApJ, 413, 641
Ventura, P. & D'Antona, F. 2005, ApJ, 635, L149