Hot Bottom Burning in Red Giants

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Abstract. We present results of hot-bottom burning calculations for a Population II $5M_\odot$ star using OPAL opacities, and a post-processing code to compute detailed nucleosynthesis with time-dependent convective mixing. In particular we look at the abundances of Li, Al and CNO isotopes.

INTRODUCTION

Over the past few years, evidence has been accumulating for hot-bottom burning (HBB) in red-giants. A number of AGB stars have been identified in the LMC and SMC (1,2) which are enhanced in both lithium and s-process elements, the latter indicating third dredge-up. None were carbon stars. Further observations of four Li-rich SMC stars (3) have shown that these have a low (C^{12}/C^{13}) ratio of about 7±3. It has been suggested that the low ratio is due to C^{12} depletion as a result of HBB, and the high Li abundance ($\log\epsilon(Li^7)\sim 3$ for the SMC), to the beryllium-transport mechanism proposed by Cameron and Fowler (4). This requires temperatures in excess of 50×10^6K.

Other clues to nuclear processes in AGB stars come from isotopic abundances in meteorites. Zinner et. al. (5) found (Al^{26}/Al^{27}) ratios of up to 0·06 in graphite and 0·2 in SiC grains, and Amari et. al. (6) found that SiC grains with lower (C^{12}/C^{13}) ratios $(3<(C^{12}/C^{13})<20)$ tend to have higher (Al^{26}/Al^{27}) ratios. As AGB stars are considered to be a possible source of graphite and SiC grains, these ratios may be an important guide to the production of Al^{26} and the Mg-Al cycle in these stars. Again, these processes require high temperatures.

To investigate the synthesis of these elements, we intend to evolve a series of models with a range of masses and compositions from the pre-Main Sequence through to the TP-AGB. We have begun with a $5M_\odot$ star with initial Z=0·003 and Y=0·25, and followed its evolution through 20 thermal pulses.

COMPUTATIONAL METHODS

The Mount Stromlo Stellar Structure Code was used to evolve the star from pre-Main Sequence through to the TP-AGB. OPAL opacities (7), including tables enhanced in C and O (8), were used. Nuclear reaction rates were taken from CF88 (9), and mass loss was not included. A value of 1·71 was assigned to the mixing-length parameter α after using this to construct a standard solar model.

A post-processing code used the structure obtained from the evolution code to calculate detailed nucleosynthesis with time-dependent convective mixing (10). A network of 39 nuclear species ranging from H^1 to Si^{30} was included, with reaction rates taken from Thielemann et. al. (11). Reactions involving neutrons were not included.

RESULTS

CNO Ratios

The changes of the surface (C^{12}/O^{16}) and (C^{12}/C^{13}) ratios with time are shown in Figure 1. The (C^{12}/O^{16}) ratio begins to increase with the sixth pulse (for which the dredge-up parameter, λ, is about 0·7), reaching a peak of $\sim$0·36 after the eighth pulse. During each subsequent interpulse phase, $T_{bce} \geq 72 \times 10^6$K, and CN cycling destroys the C^{12}, thus decreasing the (C^{12}/O^{16}) ratio until the dredge-up associated with the next pulse. A minimum of $\sim$0·098 is reached just prior to the thirteenth pulse, after which (C^{12}/O^{16}) increases again. This is because the amount of carbon destroyed by HBB is slightly smaller than the amount dredged-up in the previous pulse. Carbon is also being replenished by CNO-cycling, which gradually destroys O^{16}. The total result is an increase in the (C^{12}/O^{16}) ratio.

On the other hand, the (C^{12}/C^{13}) ratio decreases during the interpulse phase until the tenth pulse, after which the interpulse value becomes nearly constant at $\sim$3·2, indicating CN equilibrium and agreeing with the minimum

FIGURE 1. Plot of the surface abundance ratios $(Y(C^{12})/Y(O^{16}))$ and $\log(Y(C^{12})/Y(C^{13}))$ versus time, where Y is the number density.

of the observed values (4-10) in the SMC (1,2). The abundance of C^{13} peaks after the ninth pulse, declining afterwards as it is transformed into N^{14}. A minimum is reached prior to the thirteenth pulse, corresponding to the minimum in C^{12}, and thereafter C^{13} increases again.

Lithium

The surface abundance of Li^7 as a function of time is shown in Figure 2. The abundance increases during each interpulse period, reaching a maximum after the seventh pulse, and then decreases slowly. This behaviour was noted by Sackmann and Boothroyd (12), who ascribed it to the destruction of large amounts of Be^7 at the base of the envelope before it could be mixed to lower temperatures where it would decay to Li^7. The maximum value of $\log\epsilon(Li^7)\sim4.2$ agrees well with (12), who found $\log\epsilon(Li^7)\sim4{\cdot}5$ across a range of masses and compositions.

Aluminium

The production site of Al^{26} in AGB stars has been debated. Lattanzio (13) suggested that Al^{26} might be produced by HBB. However, Forestini et al (14) found that for a $3M_\odot$ star, Al^{26} was synthesised in the hydrogen shell during the interpulse phase and mixed to the surface during third dredge-up. Our model indicates that both processes are occurring. Figure 2 shows the surface abundance of Al^{26}. Initially the change in abundance is anti-correlated with Li^7, increasing rapidly with dredge-up and only very slowly between pulses. This is because the majority of Al^{26} is produced in the H-shell. However, the scenario changes with later pulses as Al^{26} *decreases* during dredge-up, despite having a higher abundance in the shell than in the envelope. The reason is that during the expansion following a pulse, the Al^{26} decays prior to dredge-up. When the envelope penetrates into the H-processed region, it now adds material of lower Al^{26} abundance, causing a decrease at dredge-up. However, the abundance increases overall because of HBB.

FIGURE 2. Plot of the log(Y) versus time at the surface for Li^7 and Al^{26}.

The (Al^{26}/Al^{27}) ratio approaches a constant value of $\sim$0·001. This is considerably smaller than the ratios found in meteorites (5,6). However, our results for aluminium are uncertain because in these preliminary calculations we have not treated the Al^{26} ground and meta-stable states separately. The high temperature dependance of aluminium decay will make it very sensitive to pulse-induced expansion; this is the subject of further study.

DISCUSSION

The preliminary results presented here show good agreement with observations and with the theoretical research of others. Much work will be done in expanding the study to include more nuclear species, especially neutrons to investigate the production of fluorine and s-process elements.

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REFERENCES

1. Smith, V. V., and Lambert, D. L., *Astrophys. J. Lett.***345**, L75-L78 (1989)
2. Smith, V. V., and Lambert, D. L., *Astrophys. J. Lett.* **361**, L69-L72 (1990)
3. Plez, B., Smith, V. V., and Lambert, D. L., *Astrophys. J.* **418**, 812-831 (1993)
4. Cameron, A. C., and Fowler, W. A., *Astrophys. J.* **164**, 111-114 (1971)
5. Zinner, E., Amari, S., Anders, E., and Lewis, R., *Nature.* **349**, 51-54 (1991)
6. Amari, S., Hoppe, P., Zinner, E., Lewis, R. S., *Nature.* **365**, 806-809 (1993)
7. Rogers, F. J., and Iglesias, C. A., *Astrophys. J. Suppl. Ser.* **79**, 507-568 (1992)
8. Iglesias, C. A., and Rogers, F. J., *Astrophys. J.* **412**, 752-760 (1993)
9. Caughlan, G. R., and Fowler, W. A., *Atomic Data Nucl. Data Tables* **40**, 283-334 (1988)
10. Cannon, R. C., *Mon. Not. R. Astr. Soc.* **263**, 817-838 (1993)
11. Thielemann, F.-K., Arnould M., and Truran, J. W., eds. E. Vagioni-flam et. al. in *Advances in Nuclear Astrophysics*, Editions frontiers, Gif-sur-Yvette, 1987, p525
12. Sackmann, I.-J., and Boothroyd, A. I., *Astrophys. J.* **392**, L71-L74 (1992)
13. Lattanzio, J. C., "Hot Bottom Burning in a $5M_\odot$ Star", in *Proc. Astron. Soc. Austr.*, 1992, pp.120-121
14. Forestini, M., Paulus, G., and Arnould, M., *Astron. Astrophys.* **252**, 597-604 (1991)