NUCLEOSYNTHESIS IN INTERMEDIATE MASS AGB STARS

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ABSTRACT. We present a summary of the main sites for nucleosynthesis in intermediate mass Asymptotic Giant Branch (AGB) stars. We then discuss some detailed evolutionary models and how these have been used to create a synthetic evolution code which calculates the nucleosynthesis very rapidly, enabling us to investigate changes in some uncertain parameters in AGB evolution, such as mass-loss and dredge-up. We then present results for C, C/O, Mg and Al. We also discuss the changes due to the recent NACRE compilation of reaction rates.

1. Introduction

Asymptotic Giant Branch (AGB) stars show a rich variety of nucleosynthesis processes. There are two primary sites for these processes: the helium burning shell and the hydrogen burning shell. The reason that these are of more interest in an AGB star is that the helium shell shows periodic thermal excursions, and the hydrogen shell overlaps the bottom of the convective envelope (in some cases), producing what is called "hot bottom burning" (HBB).

1.1. The Helium Shell

The main nucleosynthesis occurring in the helium shell is the production of alpha elements (via helium burning) as well as neutron capture reactions. The details of these processes depend primarily on the mass of the hydrogen exhausted core, hereafter M_H, and the so-called C^{13}-pocket which is believed to form as a result of partial mixing of the convective envelope with carbon-enriched matter, during the dredge-up phase (Iben & Renzini 1982a,b; Herwig 1999). As many of the star's characteristics are determined primarily by M_H it is possible to parametrise the detailed models in terms of M_H (and other variables) and then run "synthetic" evolutionary models. This allows us to explore the domains of uncertainties of the input physics of the models. Indeed, detailed models are extremely time consuming, and to the extent that these parametrisations represent the main features of the evolution, they are very useful in determining the behaviour of populations of AGB stars, which would not be possible if we were forced to use only full evolutionary and nucleosynthesis calculations.

1.2. The Hydrogen Shell: Hot Bottom Burning

In stars more massive than about $5M_\odot$ the bottom of the convective envelope dips into the top of the hydrogen burning shell. This then brings a fresh supply of nuclides into the burning region, and mixes the products of these reactions to the surface. The temperature at the bottom of the envelope reaches as high as 100 million degrees, and hence not only the CNO cycles but also the Ne-Na and Mg-Al chains/cycles are substantially active. These produce changes in the photospheric composition which are visible via spectroscopy. Unfortunately, the temperature at the base of the convective envelope T_{bce} is dependent not only on the core mass M_H but also on the envelope mass M_{env} as well as the stellar composition. Such stars are not as easily modeled by synthetic calculations.

2. Detailed Models

Recently Frost (1997) has calculated the detailed evolution of nine cases, for masses of 4, 5 and $6M_\odot$ each with heavy metal content $Z = 0.02$, 0.008 and 0.004, appropriate to the solar neighbourhood, and the Large and Small Magellanic Clouds, respectively. These evolutionary calculations began before the main sequence and went through to the end of the AGB, as was determined by a failure of the evolution code to converge on further models. This appears to be due to the reduction of gas pressure (and concomitant super-Eddington luminosity) as previously found by Faulkner & Wood (1985) and Sweigart (1998). Typically there was about $1M_\odot$ of envelope still remaining at this stage, which would presumably be ejected as a planetary nebula.

Each of these cases has been the subject of a detailed nucleosynthesis study using a heavily modified post-processing code (Cannon 1993) which include 74 species and over 500 reactions. Some results from these models have been published (eg Frost et al 1998, Lattanzio & Forestini 1998) but this paper presents the first of a series examining the detailed results.

3. Synthetic Models

Our present approach is to use the detailed stellar models of Frost (1997) as the basis of synthetic models, using the code of Forestini & Charbonnel (1997). In this way we force the synthetic models to follow the results of the detailed models (accuracy is within 10%) yet we are then free to vary those parameters which will not have substantial feedback on the evolution, and determine (rapidly) the effect of such changes. For example, changes in nuclear reaction rates are not expected to have any effect on the evolution (unless they are for the major energy producing reactions, such as the pp or CNO cycles) but they can produce substantial changes in the predicted envelope composition. These can be checked very easily with the synthetic code. Likewise, changes in the mass loss rates and the dredge-up law, if not too substantial, will have a minimal effect on the evolution.

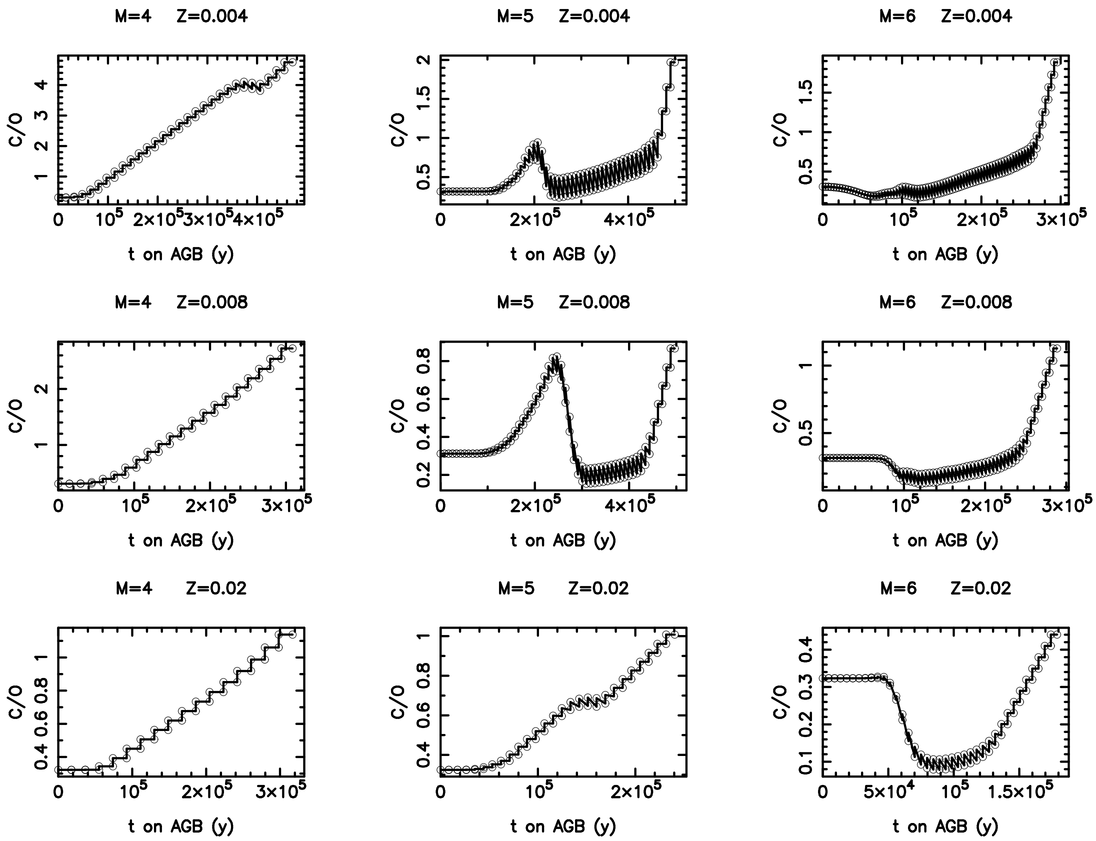

Fig. 1. Surface C/O ratios for the nine cases described in the text.

The models presented here are the standard case, as considered by Frost (1997), but we also investigate the effect of the new NACRE compilation of reaction rates (reference).

4. Standard Case

We will present the results in the form of surface abundances, or isotopic ratios, during the AGB lifetime of the nine cases discussed above. Each figure shows nine cases, on a 3×3 grid with mass varying along the x-axis and Z decreasing along the Y-axis: in this way we expect HBB to increase for increasing x (mass) or increasing y (decreasing Z). The most extreme HBB is for the top right hand graph, the $M = 6, Z = 0.004$ case.

4.1. Li

We do not show here the results for Li^7, but note that they agree qualitatively and quantitatively with those of Sackmann & Boothroyd (1992). We also note that the

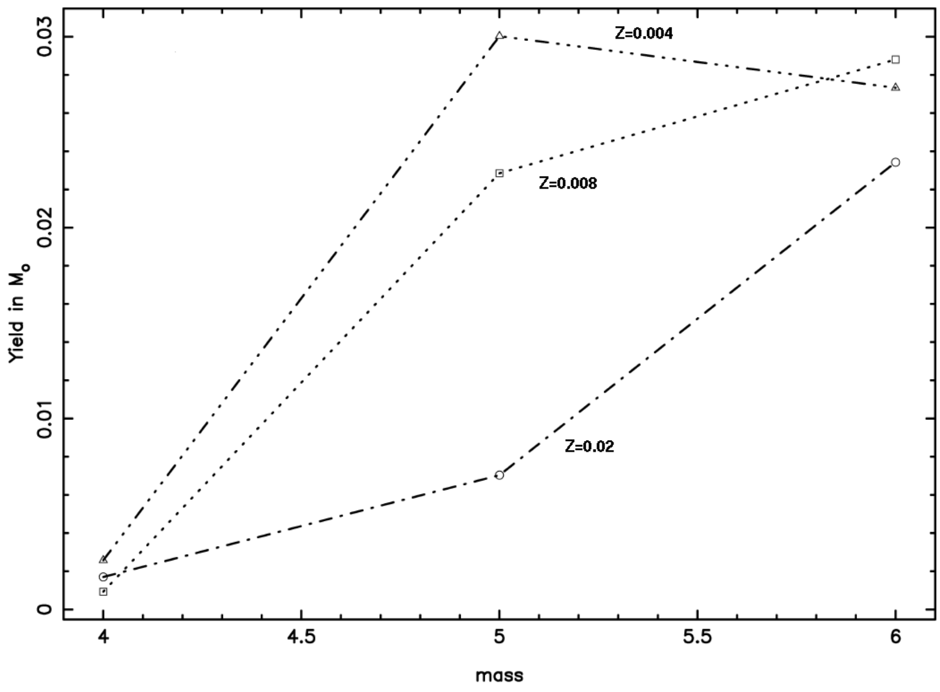

Fig. 2. Yields of ^{14}N, in solar masses, for each case considered.

$M = 4, Z = 0.004$ case is both a Li-rich star (with $\epsilon(\mathrm{Li}^7) \simeq 4$) and a Carbon star, for about 10^5 years: for just under half of this period (about $40,000$ years) it shows $\mathrm{C}^{12}/\mathrm{C}^{13} < 10$ and would be classed as a J star, but earlier in the evolution this isotopic ratio was as high as 100.

4.2. C/O

Figure 1 shows the C/O ratio for the nine cases under consideration. Note that dredge-up increases this ratio (by adding carbon to the stellar envelope) and then HBB, where it exists, decreases it again as it transforms C into N. We also see in this figure that HBB can prevent the formation of C stars, in some cases, and in others it merely delays their formation to a time when the HBB has stopped and the dredge-up continues (see Frost et al 1998 for details).

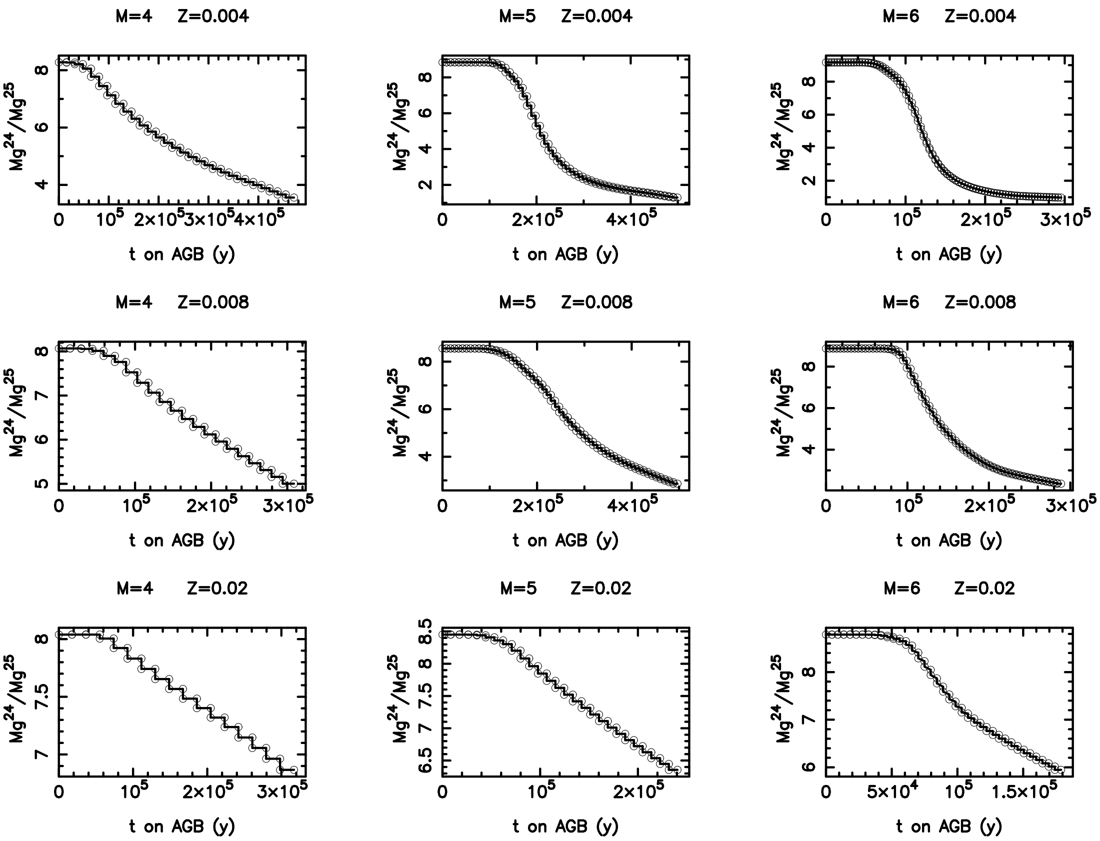

Fig. 3. Surface ^{24}Mg/^{25}Mg ratios for the nine cases described in the text.

4.3. ^{12}C/^{13}C and ^{14}N

A useful indicator of HBB is the ratio of ^{12}C/^{13}C, which increases due to dredge-up but then decreases once HBB begins processing the envelope via the CN cycle. So much material is cycled through the (thin) burning region that this carbon isotopic ratio reaches its equilibrium value of about 3.5. A consequence of this significant CNO cycling is that there is a substantial amount of ^{14}N produced, as shown in Figure 2, which plots the yield of ^{14}N for each of the nine cases. Note that up to $0.03M_\odot$ of ^{14}N is returned *per star* in extreme cases.

4.4. Mg isotopes

Of particular interest to us here is the production of ^{25}Mg and ^{26}Mg. In the intermediate mass stars considered in this work, the main neutron source in the helium shell is ^{22}Ne(α,n)^{25}Mg where the ^{22}Ne is made from successive alpha captures on ^{14}N. Hence the ^{22}Ne is primary, as in the resulting ^{25}Mg. Further, substantial ^{26}Mg is also produced

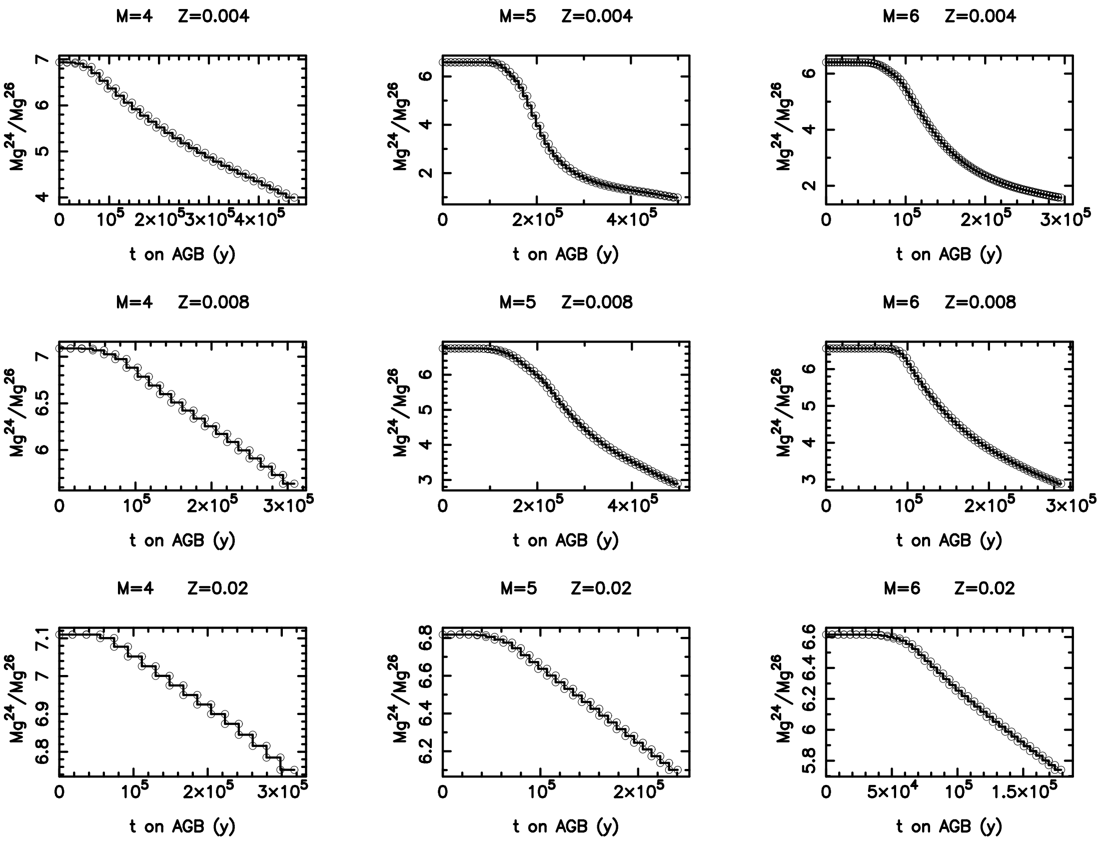

Fig. 4. Surface ^{24}Mg/^{26}Mg ratios for the nine cases described in the text.

by the Mg-Al cycle. Throughout, there is a negligible change in the ^{24}Mg abundance of the stars, so that overall the ratios of ^{24}Mg/^{25}Mg and ^{24}Mg/^{26}Mg decrease from solar values of about 8 to about 1 or 2, as shown in Figures 3 and 4. Note that this is primary ^{25}Mg and ^{26}Mg which is produced.

This is important for explaining the observed Al enhancements seen in giants in globular clusters: to obtain the Al abundances as observed it appears that substantial enhancements of ^{25}Mg and ^{26}Mg are required (Denissenkov et al. 1998) and the models presented here indicate that intermediate mass AGB stars of low metallicity may produce such abundances. This will be the subject of further work.

4.5. ^{26}Al/^{27}Al

We show in Figure 5 the isotopic ratios of ^{26}Al/^{27}Al in our stellar models. The substantial HBB is responsible for producing a large amount of ^{26}Al and ratios of ^{26}Al/^{27}Al as high as 0.15 are obtained. This is in quantitative agreement with the most extreme

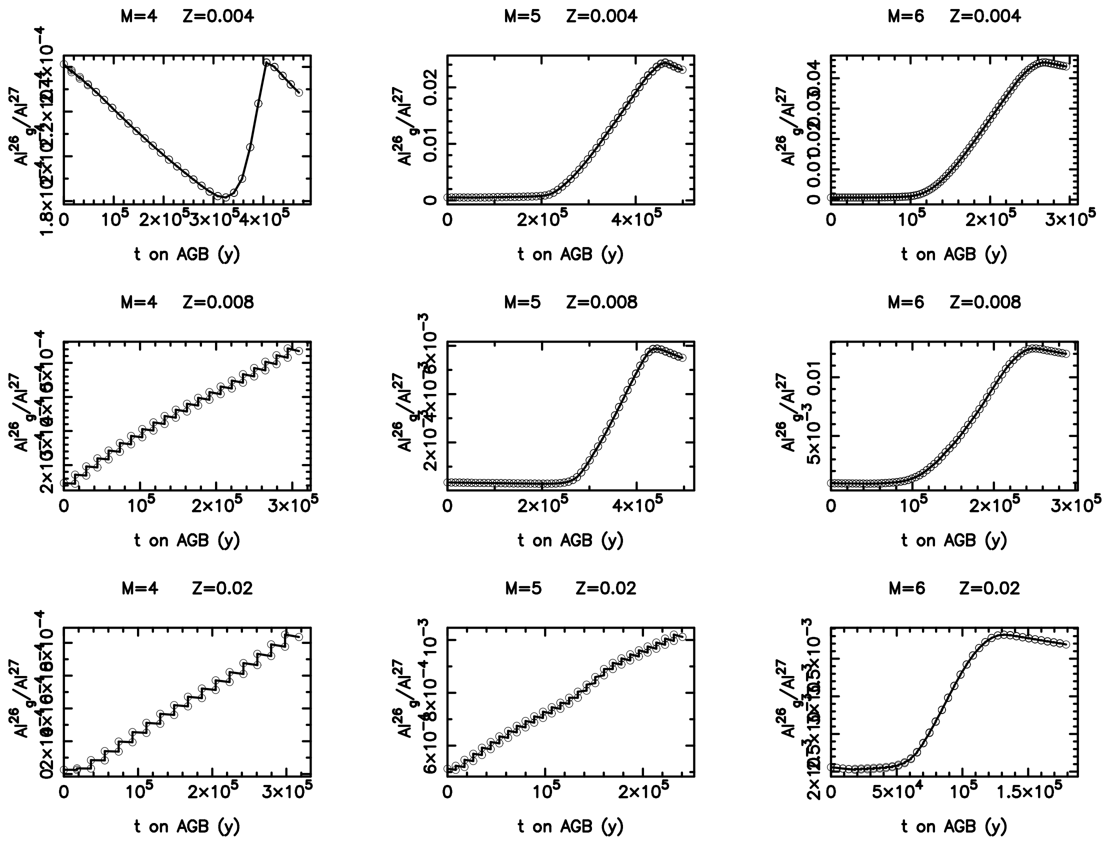

Fig. 5. Surface ^{26}Al/^{27}Al ratios for the nine cases described in the text.

meteoritic grains which show ratios as high as 0.10.

5. NACRE rates

The calculations presented so far use the same rates given in Forestini & Charbonnel (1997). We have repeated these calculations with the new nuclear reaction rates published by the NACRE consortium. The only substantial change is a reduction in the amount of ^{26}Al production, with a subsequent reduction on the ^{26}Al/^{27}Al ratios of a factor of 2 to 4. If this rate is correct then AGB stars are unlikely to be the source of the most extreme ^{26}Al/^{27}Al ratios seen in meteoritic grains. Such grains may then be produced in WR stars. The rate needs further checking, of course.

6. Conclusions

Intermediate mass AGB stars are important sources of primary ^{14}N, and produce Mg isotopic ratios that are far from solar. This could be important for Al production in globular cluster red giants.

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