Nucleosynthesis in AGB Stars

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Abstract. We give a qualitative review of the nucleosynthesis occurring in AGB stars. We the summarise some new calculations of intermediate mass stars which include all thermal pulses until the star is about to leave the AGB, as well as a detailed nucleosynthesis network. We will show that hot bottom burning delays, rather than prevents, the formation of carbon stars; those that form are not optically visible.

1. Introduction

Although only a brief phase compared to the overall stellar lifetime, the Asymptotic Giant Branch is crucial because it is here that stars experience substantial nucleosynthesis, which is the topic of this review.

The AGB phase is the last phase of evolution for low and intermediate mass stars (about 1–8$M_\odot$). The evolution leading up to this phase has been discussed in detail in Lattanzio & Boothroyd (1997) and Lattanzio (1998). Briefly, stars begin by burning hydrogen in their cores. Following the exhaustion of their central hydrogen supply, they become red-giants. During this phase the stars develop a deep convective envelope which extends inwards and can reach into regions where partial hydrogen burning has taken place. This is called the "first dredge-up" event, and it results in polluting the stellar surface with the products of hydrogen burning.

The ascent of the giant branch is terminated by ignition of the central helium supply, either degenerately in a core flash (in the case of low mass stars, below about 2.5$M_\odot$) or non-degenerately (for higher masses). The subsequent evolution is characterized by helium burning in a convective core and a steadily advancing hydrogen burning shell. For low mass stars the evolution is complicated by semi-convection, but this a detail we do not need for our present purposes. The fusion of helium produces ^{12}C, and this carbon is in turn subject to alpha capture to form ^{16}O. Eventually the helium supply is totally consumed, leaving a core of carbon and oxygen (the exact proportions of which depend on the infamously uncertain rate for the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction. In any event, following the exhaustion of central helium the star begins to ascend the giant branch again. It is now called the "second" or "asymptotic" giant branch.

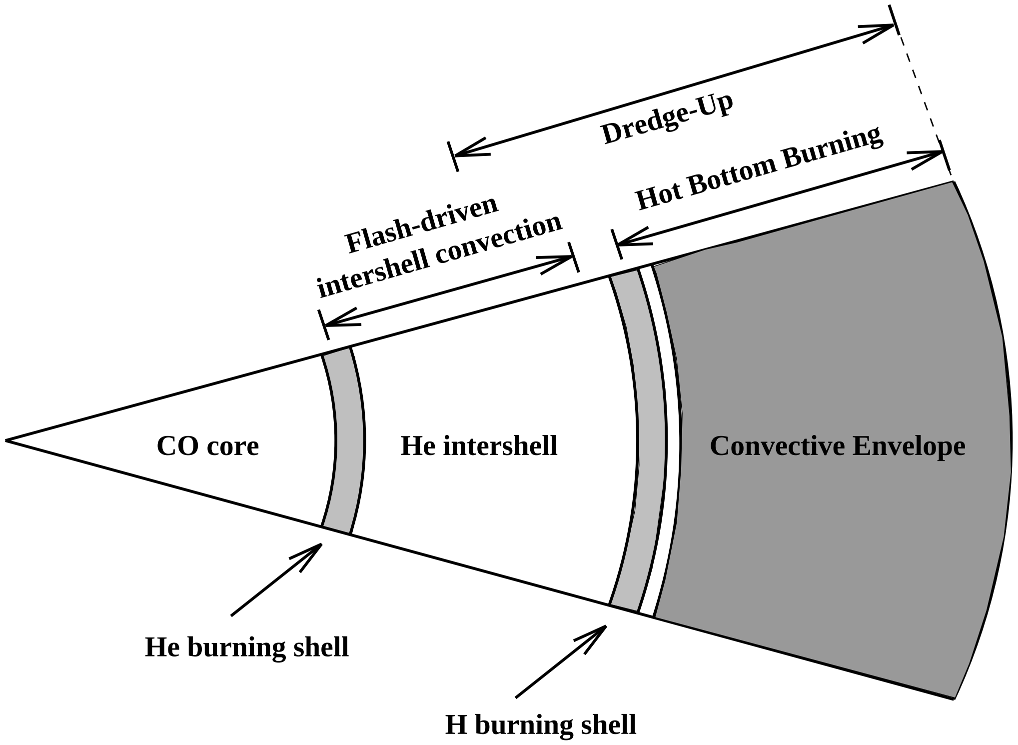

Figure 1. Schematic of the interior of an AGB star.

So when a star reaches the AGB it has the structure shown in Figure 1. If its mass is above about $4M_\odot$ the shifting of helium burning from the core to a shell causes the extinguishing of the hydrogen shell. In lower mass stars this nuclear burning stops the inward advance of the convective envelope, but in more massive stars the envelope penetrates the erstwhile hydrogen shell, and the products of hydrogen burning are again mixed to the stellar surface, in what is known as the "second dredge-up" episode. Note that low mass stars do not experience the second dredge-up.

Perhaps the most important aspect of AGB stars lies in the nucleosynthesis which occurs during their evolution. During this phase they show an electron degenerate carbon-oxygen core, and two nuclear shells: one burning helium and one burning hydrogen. The subsequent nucleosynthesis comes from two sources: the thermal instability of the helium shell (known as "thermal pulses" or "shell flashes") and, for masses above about $5M_\odot$, nuclear burning at the bottom of the convective envelope (known as "hot bottom burning", hereafter HBB).

2. Thermally Pulsing AGB Evolution

For most of the evolution on the AGB, the helium shell is largely inactive. But periodically the shell suffers a thermal runaway and generates enormous quantities of energy, at rates up to $10^8 L_\odot$ or so, for short periods of time (of order a year). This energy release results in a "flash-driven convection zone" which extends from the helium shell almost to the hydrogen shell, as shown in Figure 1. This mixes the ^{12}C produced by the helium shell throughout this convective region. As the helium flash dies down, the energy deposited in the star causes a substantial expansion and cooling. The hydrogen shell is extinguished and the convective envelope reaches in beyond its old location, and (for later pulses) into the carbon-rich region left behind by the flash convection. This mixes carbon to the surface of the star, and is known as the "third dredge-up". It is responsible for the production of N-type carbon stars. As the star now contracts again, the hydrogen shell is re-ignited and the star begins an extended "interpulse" phase of order 10^4 years (but depending primarily on the mass of the hydrogen exhausted core, hereafter called the core-mass). During this period the hydrogen shell provides essentially all of the star's luminosity. Eventually there is another flash, and the cycle repeats.

Another important consequence of thermal pulses is the production of elements beyond iron, produced by slow neutron capture, and known as s-process elements. For a detailed review see Gallino, Busso & Lugaro (1997). For our purposes here, we simply note that some partial mixing of hydrogen from the envelope into the carbon-rich intershell region is required. These protons are captured by ^{12}C to produce ^{13}C which later releases neutrons via the ^{13}C(α,n)^{16}O reaction. Early calculations by Iben & Renzini (1982a,b) found that a small semiconvective zone formed at the bottom of the convective envelope, during the dredge-up phase. But other calculations have failed to reproduce the process. (Normal, complete mixing will not suffice, incidentally, because the number of protons must be small, or else the CN cycle will go to completion and produce ^{14}N rather than ^{13}C.) Nevertheless it, or something very much like it, almost certainly occurs. Observations of these stars clearly show the s-process enhancements that these ideas would predict. Quantitative calculations are performed by Gallino and co-workers (e.g. see Gallino, Busso & Lugaro 1997) and are very successful, although the amount of ^{13}C present is a parameter which must be specified in advance. Other possible mixing mechanisms are overshoot, and partial mixing (see Herwig *et al* 1997), or possibly something like shear mixing.

A related issue is the production of ^{19}F within these stars. Jorissen, Smith & Lambert (1992) discovered that the ^{19}F/^{16}O ratio in AGB stars increases with the ^{12}C/^{16}O ratio, which implicates thermal pulses in the origin of this ^{19}F. They investigated many possible scenarios, and this was followed by Forestini *et al* (1992) who investigated the most promising scenario in more detail, and to whom we defer for details (see also Mowlavi, Jorissen & Arnould 1996). The mechanism is shown in Figure 2. Here, some ^{13}C produces neutrons via the ^{13}C(α,n)^{16}O reaction, and some of these neutrons are captured by ^{14}N to produce ^{14}C and protons. These protons, plus possibly some from ^{26}Al(n,p)^{26}Mg, are then captured by ^{18}O and the sequence $^{18}\mathrm{O}(\mathrm{p},\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ produces the observed ^{19}F, which is then dredged to the surface in the usual way following the pulse. For all except those stars with the highest abundances of ^{19}F it appears that the amount of ^{13}C left from the CN cycling H-shell is sufficient. Yet for those stars showing more enhanced ^{19}F we may need to invoke some extra-mixing, just as is required for the s-process production.

For stars above about $5M_\odot$ a second important phenomenon is the occurrence of hot bottom burning. Here the convective envelope is so deep that it penetrates

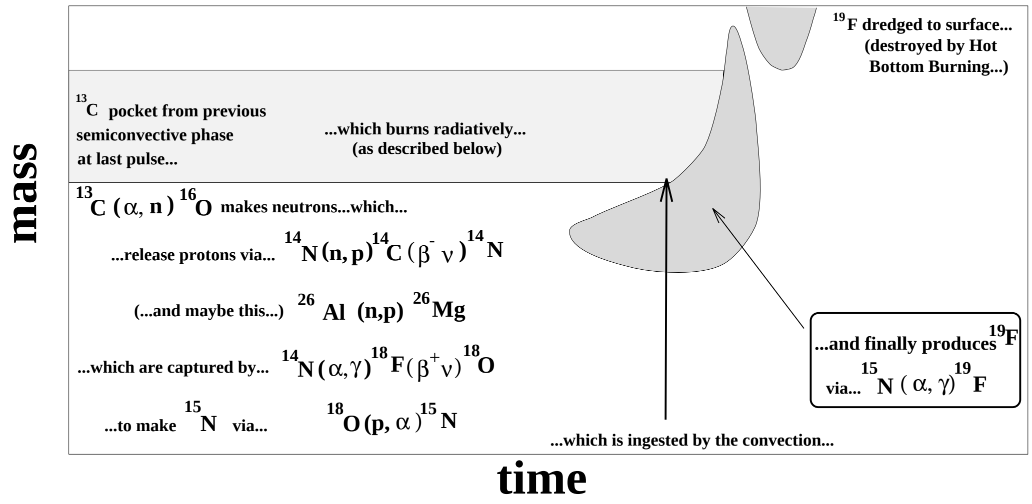

Figure 2. Production of ^{19}F in AGB stars.

into the top of the hydrogen burning shell, so that nucleosynthesis actually occurs in the envelope of the star. Temperatures can reach as high as almost 10^8K. This results in the activation of the CN cycle within the envelope, and the consequent processing of ^{12}C into ^{13}C and ^{14}N. This prevents the star from becoming a carbon star, because the primary carbon dredged to the envelope is then transmuted into nitrogen, keeping the C/O ratio less than unity (e.g. Boothroyd *et al* 1993).

Perhaps the most striking consequence of hot bottom burning is the production of ^{7}Li by the Cameron-Fowler Mechanism. Sackmann & Boothroyd(1992) showed that ^{7}Li was produced as soon as the temperature T_{bce} at the bottom of the convective envelope exceeded 50×10^6K, and produced abundances which match the Magellanic Cloud observations very nicely (see below). Another consequence of HBB is the substantial production of ^{26}Al by the Mg-Al cycle. The amount produced can be substantial, and this is implicated in explaining the ^{26}Al/^{27}Al isotopic ratios seen in meteorite grains (for a review please see Zinner 1997).

3. Complete AGB Evolution for Intermediate Mass Stars

We have recently completed detailed evolutionary calculations for stars of intermediate masses from the ZAMS through to the end of the AGB evolution (Frost 1998). These calculations covered three compositions: Z= 0.004 (corresponding to the Small Magellanic Clouds), Z= 0.008 (Large Magellanic Clouds) and Z= 0.02 (solar neighbourhood). For each composition we have considered three masses, $M/M_\odot = 4, 5$ and 6. Subsequent nucleosynthesis has been calculated using the Monash University Nucleosynthesis Code (based on that of Cannon 1993). Results from these calculations have not yet been published, with the exception of one preliminary report (Lattanzio *et al* 1996) and two short papers (Frost *et al* 1998 and Frost, Lattanzio & Wood 1998). A brief summary will be given here, and details will be published elsewhere.

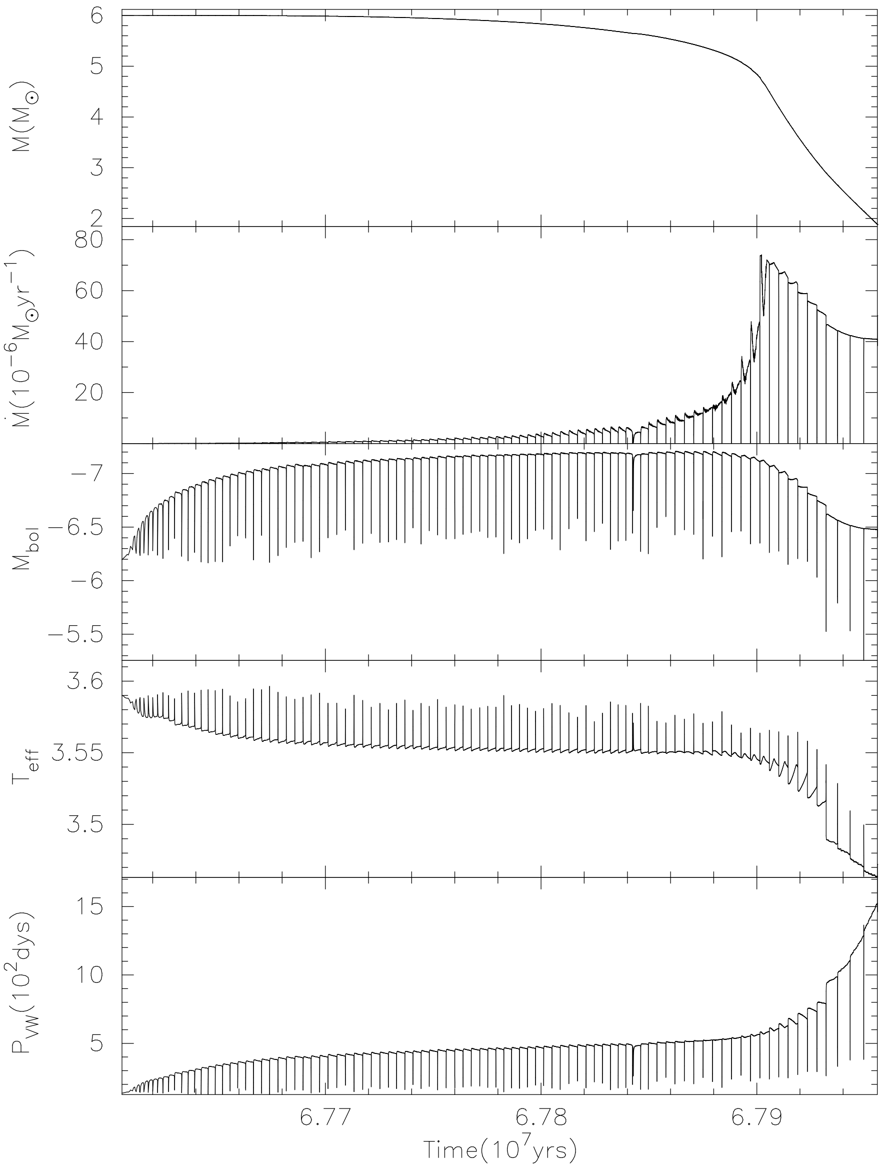

Figure 3. AGB evolution for a $6M_\odot$ model with $Z = 0.004$. The upper panel shows the variation in total mass; the second panel shows the variation in the mass-loss rate; next is the bolometric magnitude, then the effective temperature; finally we show the period as calculated by the formula of Vassiliadis & Wood (1993).

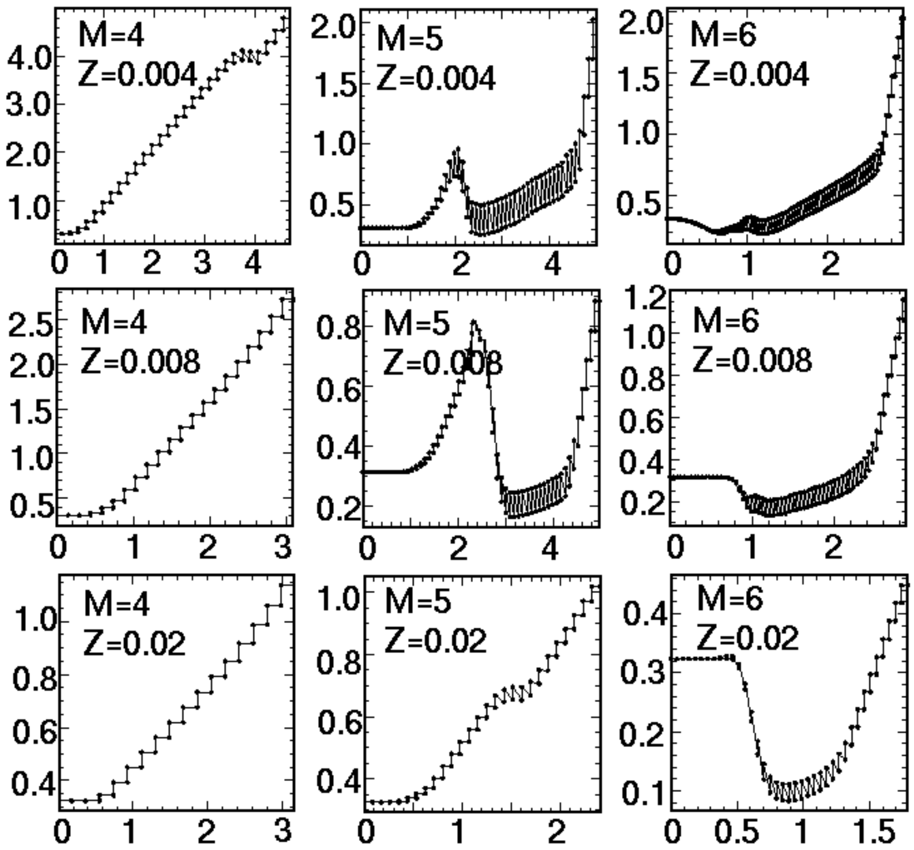

Figure 4. Surface value of C/O for the nine cases discussed in the text. The x-axis is the time elapsed (in millions of years) since the first thermal pulse.

3.1. Model Calculations

Models were calculated with the Mt Stromlo Stellar Structure Code, updated to include the OPAL opacities. Mass-loss was included using the prescription of Vassiliadis & Wood (1993), but without the modification for M above $2.5M_\odot$. As an example of the AGB evolution, Figure 3 shows a summary of the case for the $6M_\odot$ model with $Z = 0.004$. We note a crucial aspect of this evolution: mass-loss is relatively small until near the end of the evolution, when the rate becomes very high. We will see the consequences of this below.

The nucleosynthesis calculations include all elements up to sulphur and also a small s-process network based on the iron-peak. We have also developed the extrapolation code of Forestini & Charbonnel (1997) to include the results of these detailed calculations. For many variables we have found it best to interpolate within envelope mass, rather than the traditional core-mass. Some of the results presented below actually come from the synthetic code (and agree with the detailed calculations to within 10%).

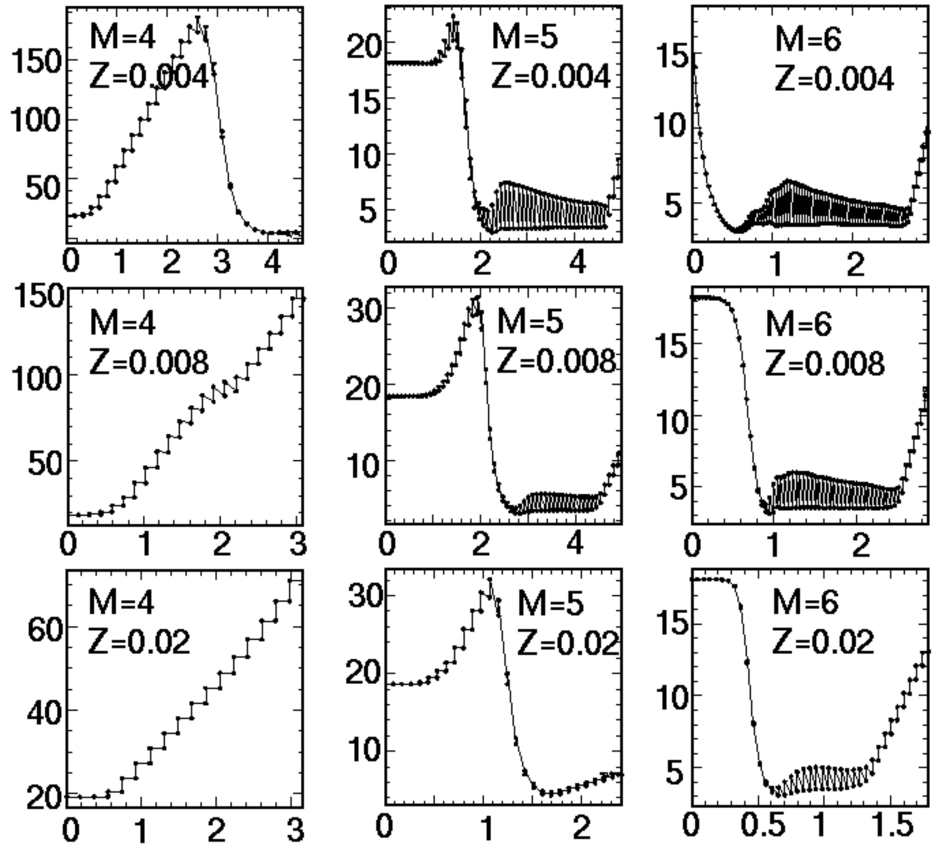

Figure 5. Same as Figure 4 but for $^{12}C/^{13}C$.

3.2. The Brightest Carbon Stars

Figure 4 shows the surface C/O ratio for the nine models considered. The repeated effects of dredge-up are clearly visible in the discontinuous changes in the ratio at each dredge-up event. The effect of HBB can also be seen as a smooth decrease in the ratio between dredge-up events. Note that there is no HBB in the three $4M_\odot$ models, and the C/O ratio increases monotonically for these cases (in fact, there is a small amount of HBB in the $Z = 0.004$ case at a time of about 4 million years).

The effects of HBB are clearly seen in the 5 and $6M_\odot$ models. Consider firstly the $5M_\odot$ cases, where the HBB is important at low metallicities (due to higher temperatures in these cases). Although dredge-up begins in the M5Z004[1] case and produces a C/O ratio almost unity, the start of HBB then reduces this value dramatically and keeps it below unity until an AGB age of about 4 million years. This is also seen in the M5Z008 case, where the C/O ratio reaches 0.8 before HBB reduces it to about 0.2. Even in the M5Z02 case we see the start of

[1]MaZb refers to the case with $M = aM_\odot$ and $Z = b$.

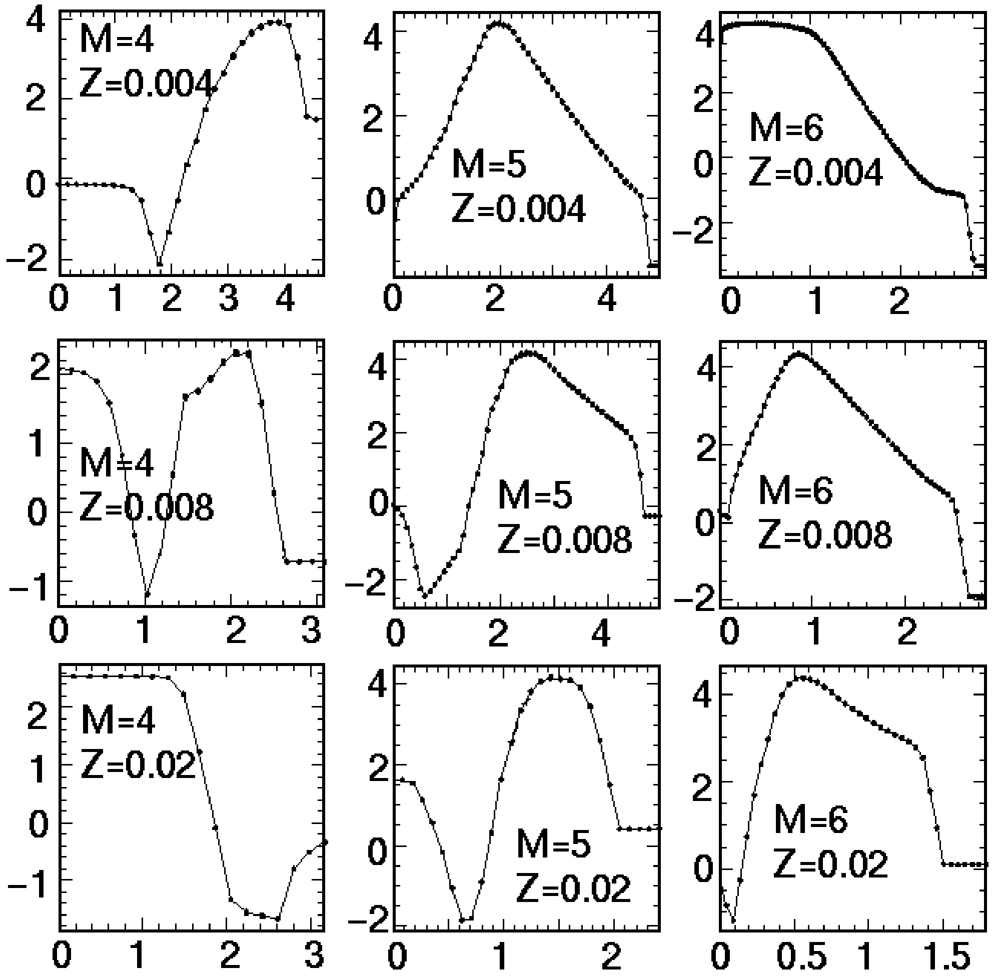

Figure 6. Same as Figure 4 but for $\varepsilon(^7\mathrm{Li})$.

HBB at an AGB age of 1.7 million years. Yet in each of these three cases the C/O ratio finally increases. This is due to mass-loss.

The continued decreasing of the envelope mass finally reduces the weight of the envelope to such an extent that HBB is terminated. Yet dredge-up continues. This is a new result from these calculations, and it is very important for understanding the final stages of AGB evolution. Hence the C/O ratio again begins to increase as ^{12}C is added to the envelope without being burned by HBB. This effect shows itself most dramatically when the mass decreases the most, which is near the end of the AGB lifetime (see Figure 3). Note that HBB is quite extreme in the $6M_\odot$ cases, where the C/O ratio is kept very small (due to HBB) until the end of the star's lifetime when it can indeed exceed unity. Thus we predict a population of bright ($M_{bol} \simeq -6.6$) carbon stars, but these would not be optically visible because of their high mass-loss. This result was reported in Frost *et* *al* (1998) and seems to explain the infra-red population of carbon stars reported by van Loon *et al* (1998) and earlier by Kastner *et al* (1993).

HBB produces ^{13}C by the CN cycling at the bottom of the envelope. This is shown in Figure 5. The timescales are such that the entire envelope is processed by HBB and this can result in the ^{12}C/^{13}C ratio reaching its equilibrium value of $3-3.5$, as is seen in many cases in Figure 5. In fact, one may use this ratio, with care, as an indicator of HBB. An observed low value is strong evidence for HBB, whereas a high value is evidence for dredge-up of ^{12}C without HBB. Intermediate values, however, are not very enlightening!

An important consequence of HBB in these stars is the production of primary ^{14}N. Substantial enhancement factors can be obtained, especially for the more massive low metallicity models. These stars are likely to be an important source of ^{14}N in the galaxy, especially at earlier times when the metal content of intermediate mass stars is low.

Finally, we show in Figure 6 the surface ^{7}Li abundance in the models. This is also a good indicator of the occurrence of HBB, although in the more massive and lower metallicity models we can find substantial Li production during the second dredge-up phase, so that models such as M6Z004 begin their thermally-pulsing AGB with high Li abundances. Note also that when the initial supply of ^{3}He is used up, there is again a decrease of the Li content. The models agree very well with the observations of Smith & Lambert (1989, 1990) and Smith *et al* (1995) which show Magellanic Cloud AGB stars of M_{bol} between -6 and -7 to have[2] $\log\varepsilon(^{7}\mathrm{Li})$ in the range 2.2 to 3.8. This was also shown (first!) by Sackmann & Boothroyd (1992).

During the evolution of the models discussed above, we found a different kind of thermal pulse would occasionally occur. This resulted from the prolonged occurrence of deep dredge-up on the AGB. This cools the intershell region and extinguishes the helium burning before the tail of the helium shell has burned fully, and results in a long tail extending deeply into the star, and experiencing partially degenerate conditions. Eventually this tail ignites in a "degenerate pulse" and produces a shell flash of unusually high temperatures, as reported in Frost, Lattanzio & Wood (1998). The nucleosynthesis occurring in these cases is currently under investigation.

4. Conclusion

We have made an extensive investigation of the evolution and nucleosynthesis of intermediate mass stars. This is not to say that there are no uncertainties: the details of how to calculate dredge-up remain a serious problem. But we have the tools for a consistent investigation of the behaviour of the stars, given this caveat. Intermediate mass stars were investigated first, but it is well known that the majority of the carbon stars and *s*-process enriched stars are of lower masses, about $1-3M_{\odot}$. These are the subject of current work.

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[2] $\log\varepsilon(^{7}\mathrm{Li}) \equiv \log\{n(^{7}\mathrm{Li})/n(\mathrm{H})\} + 12)$.

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