NUCLEOSYNTHESIS IN INTERMEDIATE MASS STARS

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Abstract. We discuss nucleosynthesis within $6\,M_\odot$ models with $Z = 0.02$, 0.008 and 0.004. The emphasis is on the AGB phase of evolution, with particular reference to thermal pulses and Hot Bottom Burning. We find strong CN cycling, with substantial Al production, especially at low metallicities.

1. Introduction and Method

Our knowledge of AGB stars has increased dramatically recently, driven primarily by observational studies, with theory lagging somewhat behind. Studies are desperately needed of the nucleosynthesis which occurs during thermally pulsing evolution and particularly "Hot Bottom Burning" (hereafter HBB), where the bottom of the convective envelope of a star reaches temperatures sufficiently high for significant nucleosynthesis to take place. Thus there is a thin layer at high temperatures, and envelope material is mixed through this region and then into the outer envelope. For nuclear reactions with time-scales no longer than the mixing time-scale, we cannot make the usual assumption of instantaneous mixing, and an average burning rate. The historical motivation for realising the importance of HBB has been briefly summarised in Lattanzio et al (1996), and is not repeated here. We emphasise the importance of recent ion-probe studies of meteorites which reveal unusual isotopic compositions in some grains (such as SiC) which were almost certainly formed in the envelopes of AGB stars.

Our study requires both detailed nucleosynthesis and evolution models, with a time-dependent mixing algorithm. We have chosen to do this with two separate calculations. Firstly, we perform the evolutionary calculations with the Mt Stromlo evolution code, modified to include the OPAL opacities (Rogers and Iglesias 1992). Following this, a nucleosynthesis code is used to calculate the detailed nuclear burning of 74 species with the stellar structure as previously calculated by the evolution code. Time-dependent mixing is included at this stage, in the way described by Cannon (1993). Nuclear reaction rates are primarily taken from the data base of Thielemann et al (1987). There are some notable exceptions, such as the recent alpha-particle capture rate for ^{18}O (Käppeler et al 1994). Further details of both the code and the nuclear reaction rates may be found in Cannon et al (1996).

2. Pre-AGB Evolution

The evolution of our models is qualitatively well understood, so we concentrate on composition changes. We will discuss the $M = 6\ \mathrm{M}_{\odot}$, $Z = 0.02$ case (hereafter referred to as M6Z02) and then draw comparisons with other Z. (All masses given are in units of $\mathrm{M}_{\odot}$.)

2.1. CORE HYDROGEN BURNING AND FIRST DREDGE-UP

Following core hydrogen exhaustion, all models show similar composition profiles to the M6Z02 case seen in Figure 1. As we move inward from the surface, the increasing temperature starts the CN cycle, so we see an increase in ^{13}C at the cost of ^{12}C. The same region shows a decrease in the ^{15}N due to ^{15}N(p,α)^{12}C, and then a slight increase due to ^{18}O(p,α)^{15}N. Just slightly interior to $M = 3$ the ^{13}C is itself destroyed in the production of ^{14}N, which now starts to rise. From here inwards the carbon isotopes are in equilibrium. Interior to $M \simeq 2.5$ we see substantial destruction of ^{18}O from the proton captures described above. At $M \simeq 1.8$ we see the production of ^{17}O from proton captures on ^{16}O, as the ON cycle starts to function more strongly. As the star ascends the first giant branch the convective envelope reaches down to $M = 1.256$ with consequent mixing from this point outward. This is known as the First Dredge-Up, and the key abundance changes are listed in Table 1.

2.2. CORE HELIUM BURNING AND SECOND DREDGE-UP

Within the helium core the star produces ^{12}C and ^{16}O. The abundant ^{14}N left over from CNO cycling means that ^{14}N$(\alpha,\gamma)^{18}$F$(\beta^{+}\nu)^{18}$O produces ^{18}O and then ^{18}O$(\alpha,\gamma)^{22}$Ne which produces some neutrons via ^{22}Ne(α,n)^{25}Mg. The hydrogen shell burning shows the usual signature of the CNO cycles, much as seen in Figure 1. The nucleosynthesis between the hydrogen "exhausted" region and the edge of the convective helium core mimics that

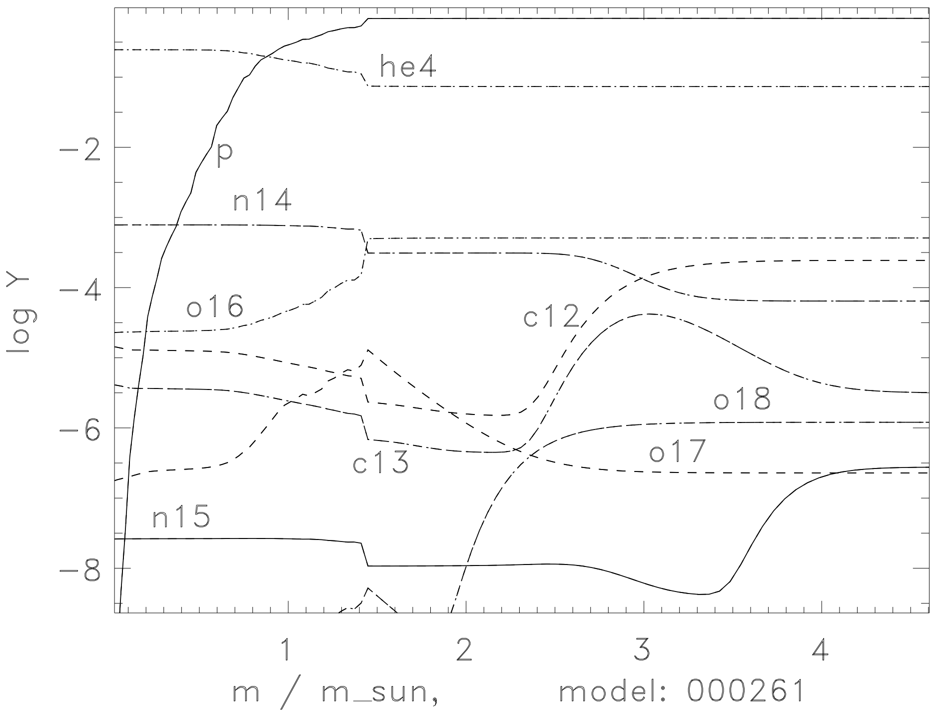

Figure 1. Composition profiles at the time of core hydrogen exhaustion for the M6Z02 model. Note that during first dredge-up the convective envelope will reach down to $M/\mathrm{M}_{\odot} = 1.256$, thus homogenising the material from that point to the surface.

TABLE 1. Selected isotopic ratios after the first (FDU) and second (SDU) dredge-up events.

Ratio	Initial	$Z = 0.02$ FDU,SDU	$Z = 0.008$ FDU,SDU	$Z = 0.004$ FDU,SDU
$^{12}C/^{13}C$	90	19.2, 18.0	18.8, 18.1	18.8, 17.8
$^{14}N/^{15}N$	273	1297, 1931	1122, 2009	881, 2327
$^{16}O/^{17}O$	2632	453, 408	708, 340	1746, 327
$^{16}O/^{18}O$	500	562, 572	562, 590	501, 597

which we will later see in the intershell region on the AGB. Outside the convective core the ^{13}C is destroyed by (α,n) and produces neutrons, which feed (n,p) reactions on ^{14}N to produce ^{14}C. Thus we see an increase in ^{14}C and in the protons. Further inward the ^{14}C has decayed into ^{14}N.

3. Early AGB Evolution

The second dredge-up phase occurs early on the AGB. Table 1 gives some abundance ratios, but note that for $6\,M_\odot$ there is the complication that HBB begins during second dredge-up. After second dredge-up the star begins pulsing, which drives convection from the helium shell almost to the hydrogen shell (for details see Frost and Lattanzio 1996b). Later, envelope convection extends inwards, and penetrates the carbon-rich region after the 7^{th} pulse for M6Z02, the 6^{th} pulse for M6Z008 and the 5^{th} pulse for M6Z004. This periodic third dredge-up becomes very deep, and we soon find the dredge-up parameter $\lambda \simeq 0.9$ (see also Vassiliadis and Wood 1993). This is discussed further in Frost and Lattanzio (1996a).

With the onset of HBB the Cameron-Fowler Beryllium transport mechanism produces large amounts of ^{7}Li (see Boothroyd and Sackmann 1992). Our results are in agreement with these authors, to whom we defer for details.

The carbon-rich convective pocket mixes the products of helium burning throughout the intershell region, and at the next dredge-up, the products of this nucleosynthesis are mixed to the surface. This pocket contains a relatively large amount of ^{22}Ne at the cost of ^{14}N and ^{18}O. Also produced in the intershell zone is ^{19}F from alpha captures on ^{15}N, which is also dredged to the surface following each thermal pulse.

4. Advanced AGB Evolution

As the star ascends the AGB the temperature at the base of the convective envelope increases dramatically, reaching values of up to 80 or 90 million K. This causes CNO cycling as well as processing by the Ne-Na and Mg-Al cycles. Selected isotopic ratios are shown in Figure 2 for the thermally pulsing phase of the M6Z02 model. Mass loss (included here from Vassilliadis and Wood 1993) decreases the mass of the envelope, and eventually this shuts off the HBB. For M6Z02 this happens long before the third dredge-up ends (calculations for other models have not proceeded this far, yet) when the envelope mass is about $2.4\,M_\odot$. The details of the surface composition at this stage depend critically on the competition between these effects (e.g. Groenewegen and deJong 1993). Thus, for most of its lifetime on the AGB, HBB prevents the M6Z02 model from becoming a carbon star. But when HBB ends, the third dredge-up may yet produce a carbon star (we will address this in a later paper). We now look in more detail at the nucleosynthesis which occurs between the 30^{th} and 31^{st} pulses of M6Z02, being a typical interpulse phase showing HBB.

In the deepest layer of the convective envelope the temperatures are about 82 million K, and there is hydrogen burning via the CNO cycle.

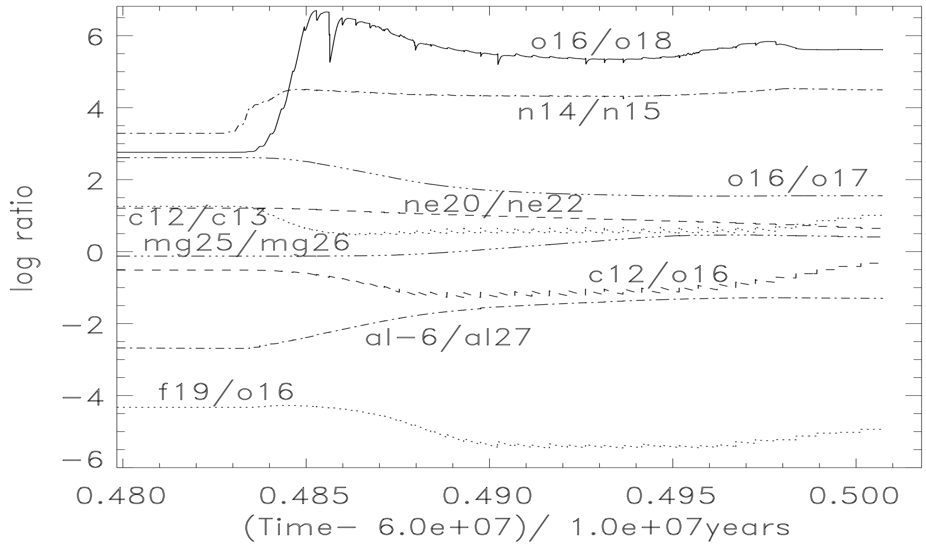

Figure 2. Selected isotopic ratios seen at the surface of the M6Z02 model during its thermally pulsing AGB evolution.

Initially the ^{12}C/^{13}C ratio is out of equilibrium because of the ^{12}C added to the envelope by the previous dredge-up episode. Thus the ^{13}C rises and ^{12}C falls as these come into equilibrium. The convective turnover timescale is such that the entire envelope passes through the hot bottom many times during the interpulse phase, producing the equilibrium abundances of ^{12}C and ^{13}C. Then both C isotopes fall as they are processed into ^{14}N. Further, at these high temperatures ^{26}Mg suffers substantial proton captures and produces ^{27}Al. Also, the envelope ^{19}F is destroyed by (p,α) reactions. Thus it would appear that stars experiencing HBB should not show increases of both ^{19}F and ^{7}Li simultaneously. This point has recently been made by Mowlavi et al (1996), to whom we defer for details.

Figure 3 shows the region just below the convective envelope near the end of the interpulse phase; a region which has been processed by the hydrogen shell during the interpulse. Firstly look at the ^{13}C profile. It leaves the hydrogen shell with $\log Y_{13} \simeq -4.9$, yet during the interpulse phase this burns totally via alpha captures, with a resulting increase in ^{16}O. This was seen first in low mass stars by Straniero et al (1995) and later verified in more massive stars by Mowlavi et al (1996). Some of the neutrons so released are absorbed by the abundant ^{14}N (not shown) to produce ^{14}C via (n,p) reactions, as discussed above. This ^{14}C also captures an alpha particle to produce the ^{18}O rise seen in Figure 3. This will be absorbed by the next thermal pulse, to produce ^{22}Ne and hence neutrons

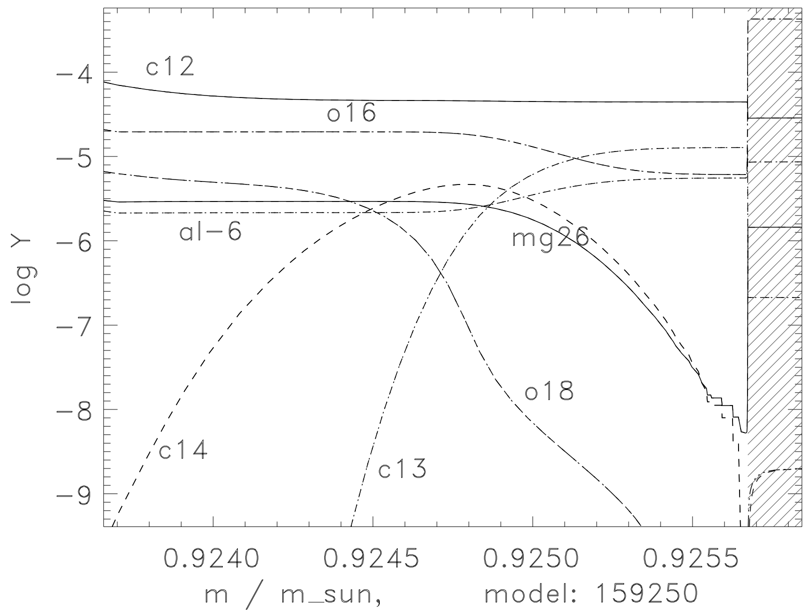

Figure 3. Compositions in a model near the end of the interpulse phase. The hatched region represents convection. "al-6" refers to the ground state of ^{26}Al.

(the subject of a subsequent paper). The hydrogen shell also produces ^{27}Al at the level $\log Y_{27} \simeq -5.3$ in the envelope, but it rises to -4.7 interior to the hydrogen shell, due to the proton captures on ^{26}Mg which occur there. When this material is added to the envelope after the next dredge-up phase it will enhance the surface composition of ^{27}Al.

We have seen the surface composition changes for the first 43 pulses of the M6Z02 model. The same calculation is shown in Figures 4 and 5 for $Z = 0.008$ and 0.004 respectively. In each case the increase in ^{14}N from CN cycling by HBB is quite apparent. As we have seen earlier, the ^{18}O is almost completely destroyed within the envelope as soon as HBB begins. Likewise, ^{15}N is seen in equilibrium with ^{14}N for most of the evolution. We also see in the figures the production of ^{25}Mg, ^{26}Al and ^{27}Al, all due to the operation of the Mg-Al cycle both in the hot-bottomed envelope as well as in the hydrogen shell, with subsequent dredge-up.

Having discussed the M6Z02 case we can see the contrasts with the lower metallicity cases. Decreasing Z causes higher temperatures for HBB. This is seen in the higher ratio of ^{26}Al/^{27}Al as Z decreases. Note that with the most ^{26}Al-rich meteorite grains (which reach values of ^{26}Al/^{27}Al up to 0.1; Zinner 1995), the current models are easily able to explain this mea-

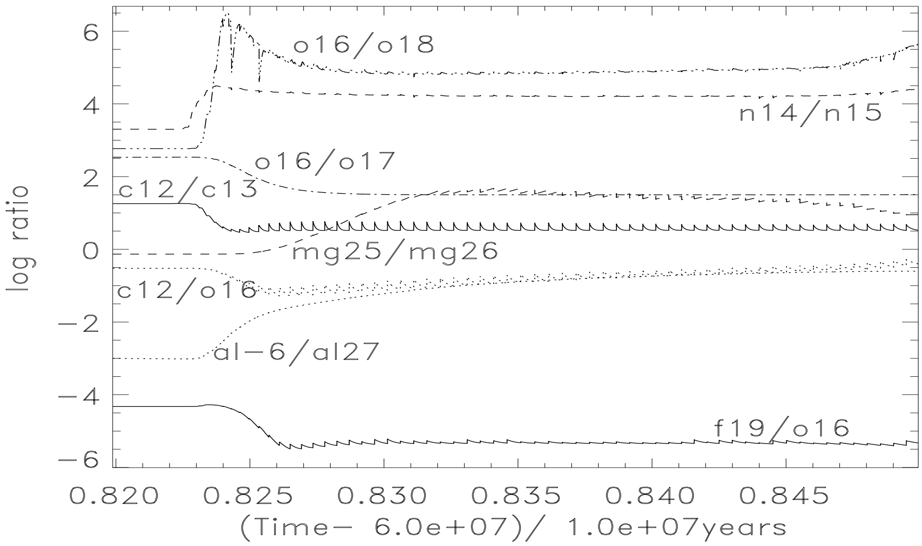

Figure 4. Surface composition for the M6Z008 model.

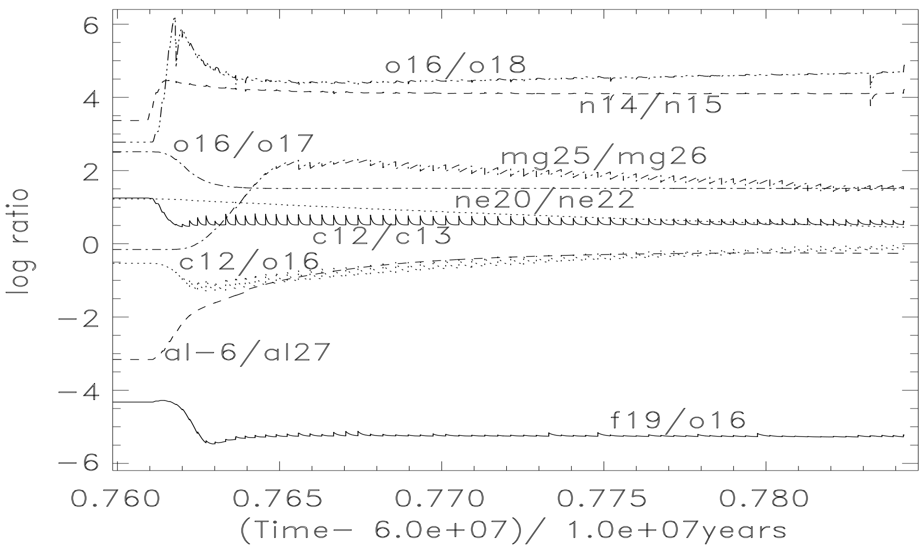

Figure 5. Surface composition for the M6Z004 model.

surement. A somewhat surprising result is the continued growth of $^{12}C/^{16}O$ during the HBB phase for the lower metallicity models. The dredge-up is so efficient at adding carbon to the envelope that despite the CN cycling, there is a continual increase in the $^{12}C/^{16}O$ ratio. The figures show that the $^{12}C/^{16}O$ ratios are close to unity (and the total C/O will be higher because of the ^{13}C present). This raises the possibility of a population of very high luminosity carbon stars. At the end of the calculations shown the M6Z008 case has $M_{bol} = -6.6$ and for M6Z004 we have $M_{bol} = -7.2$. These stars may not be visible, however, because of the high mass-loss rates seen as they near the end of their lifetimes. Nevertheless, we note the identification of high luminosity, high mass-losing carbon stars by Van Loon et al (1996) at this meeting.

5. Conclusions

We have presented a brief summary of the nucleosynthesis in three model stars of $6\,M_\odot$ with $Z = 0.02$, 0.008 and 0.004. We find very deep dredge-up occurs with the dredge-up parameter λ approaching unity. We have calculated the detailed processing during 43 ($Z = 0.02$) to 66 ($Z = 0.004$) pulses, and found that the models match quite well many known constraints (e.g. first and second dredge-up isotopic ratios). Further, during the AGB evolution a combination of dredge-up and HBB leads to many surface composition changes. A full analysis of these models, as well as six others of differing mass, will form the subject of later papers.

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