Hot Bottom Burning Nucleosynthesis in 6 $M_\odot$ Stellar Models

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We present a brief summary of some nucleosynthesis calculations for 6 $M_\odot$ stellar models with metallicity $Z = 0.02, 0.008$, and 0.004. The calculations include Hot Bottom Burning. Our main results are the verification of earlier calculations of a super Li-rich phase, as well as substantial production of aluminium isotopes, especially at lower metallicities.

1. Background and Motivation

Our knowledge of the AGB phase of evolution has increased dramatically over the last decade or so, driven primarily by observations. Theoretical studies are desperately needed to quantify the nucleosynthesis which occurs in intermediate mass stars during their thermally pulsing evolution. While there are many calculations of the thermal pulses there are few calculations with much nucleosynthesis, or which include the recently discovered "hot bottom burning" (hereafter HBB). This is the colourful name used when the bottom of the convective envelope reaches temperatures sufficiently high for nucleosynthesis to take place. There is a thin layer at high temperatures, and material is mixed through this region and then into the outer envelope. The motivation for studying HBB can be briefly summarised: When the brightest AGB stars in the Magellanic Clouds were observed [1] they were found not to be carbon stars. It was suggested by [1] that perhaps the ^{12}C dredged to the surface after thermal pulses had been burned by HBB into ^{13}C and ^{14}N. Further observations of these stars [2] showed that they were also super-rich in ^{7}Li. This was taken as evidence for the "Beryllium Transport mechanism" [3], which requires HBB. Quantitative theoretical studies [4] showed that models could indeed match the ^{7}Li observations. In the meantime, studies of meteorites revealed unusual isotopic ratios in some grains, including large enhancements of ^{26}Al, which was taken as further evidence for HBB. (Herein we refer only to the ground state of ^{26}Al although both it and the isomeric state were included in the calculations.) It is our aim to study the detailed nucleosynthesis occurring in these stars.

Our approach is to perform two separate calculations: evolution followed by nucleosynthesis (based on the code of Cannon [5]). Further details may be found in [6]. Here we present a summary for three 6 $M_\odot$ models with metallicity $Z = 0.02, 0.008$ and 0.004.

2. Surface Compositions During Advanced AGB Evolution

The evolution of our stellar models is qualitatively well understood, and we do not give details here (see, e.g. [7]). Rather, we concentrate on composition changes in the photosphere during the AGB phase. Dredge-up begins after a small number of pulses and soon becomes very deep [8]. As the star ascends the AGB the temperature at the base of the convective envelope increases dramatically, reaching values of up to ~ 80 million K. Calculations of ^{7}Li production by Boothroyd and Sackmann [4] fit the observations very well, and our models agree with their calculations. There is also substantial hydrogen burning via the CN cycle. The convective turnover timescale is such that the entire envelope passes through its hot bottom many times during the interpulse phase, and thus obtains equilibrium abundances of ^{12}C and ^{13}C. This can be seen in Figure 1, which shows surface abundances for the $Z = 0.02$ case. The Mg-Al cycle is producing ^{26}Al and ^{25}Mg so that the ratios ^{26}Al/^{27}Al and ^{25}Mg/^{26}Mg both increase. A comparison with stellar and meteoritic abundances will be included in a later paper, but we already see that the high ^{26}Al/^{27}Al ratio of up to 0.05 is in good agreement with the most ^{26}Al-rich meteorite grains which reach values of up to 0.1 [9]).

The ^{19}F which is produced in the convective shell during pulses, and then dredged to the surface, is destroyed by (p,α) reactions. Stars with HBB should not show increases of both ^{19}F and ^{7}Li simultaneously. A detailed analysis of the production and destruction mechanisms for ^{19}F has been given by Mowlavi et al [10], to whom we defer for details. CNO cycling results in ^{18}O being virtually completely destroyed within the envelope as soon as HBB begins. Likewise, ^{15}N soon reaches equilibrium with respect to ^{14}N, whereas we find is an order of magnitude increase ^{17}O.

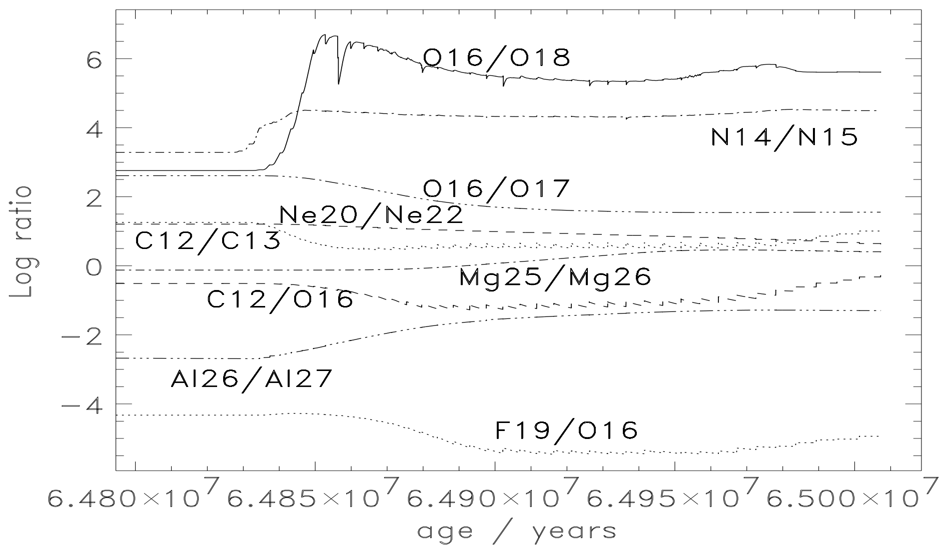

Figure 1. Surface compositions versus time for the $Z = 0.02$ model.

As the envelope mass decreases from mass loss (included via [11]) the HBB is shutdown but third dredge-up continues. The details of the surface composition in the latter stages of a star's life depend critically on the competition between these effects (e.g. [12]). We find that dredge-up is still strong at the 43rd pulse (when the mass has been reduced to $2.4\,M_\odot$) when we stopped calculations. Figure 1 shows that the C/O ratio is kept below unity (due to HBB) but begins to increase again from dredge-up of ^{12}C once the HBB ceases. Likewise, the ^{12}C/^{13}C and ^{14}N/^{15}N ratios begin to deviate from equilibrium once HBB ends. Although HBB has prevented the model from being a carbon star for most of its lifetime on the AGB, the continuing third dredge-up may yet produce a carbon star, but now rich in ^{13}C. We will address this in a later paper.

Figure 2 shows the surface compositions for the $Z = 0.008$ model. Dredge-up and HBB are still operating at the end of the calculations shown. Note that ^{26}Al/^{27}Al and ^{25}Mg/^{26}Mg are substantially higher than found for $Z = 0.02$. The ratio ^{12}C/^{13}C is still in equilibrium, although the deep dredge-up is continuing to increase the C/O ratio despite HBB. This star may also become a ^{13}C rich carbon star.

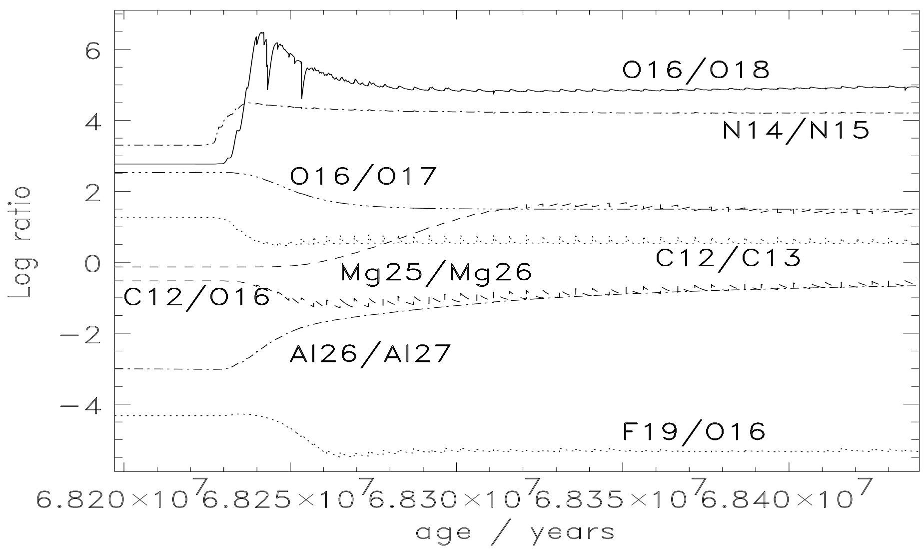

Figure 2. Surface compositions versus time for the $Z = 0.008$ model.

The surface compositions of the $Z = 0.004$ model are shown in Figure 3. The trends seen in Figure 2 continue here. The model has essentially reached C/O = 1, despite the fact that HBB is still operating, and producing a large amount of ^{13}C. Note also that we find ^{26}Al/^{27}Al $\simeq 0.6$.

3. Conclusions

We have presented a brief summary of the nucleosynthesis in model stars of $6\,M_\odot$ with various metallicities. We find substantial dredge-up occurs and becomes very deep. With a

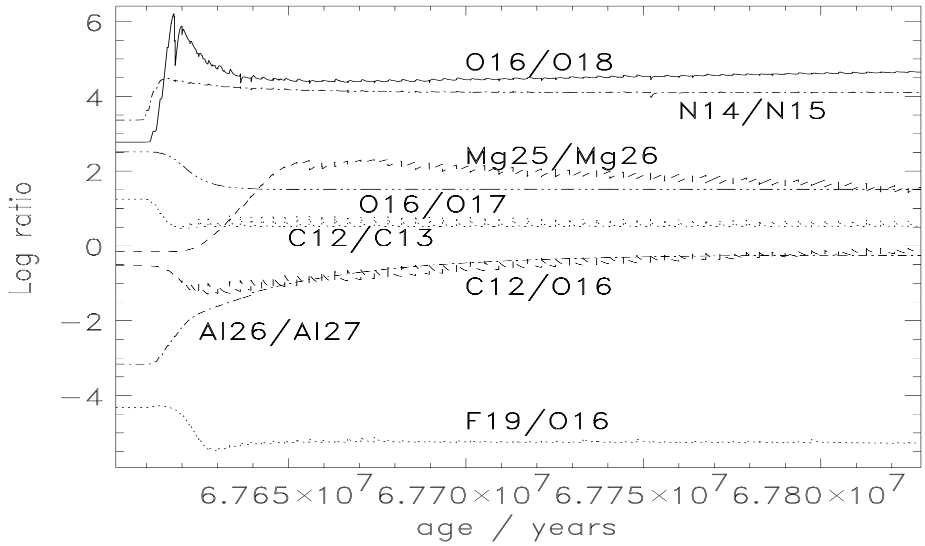

Figure 3. Surface compositions versus time for the $Z = 0.004$ model.

new nucleosynthesis code we calculated the detailed processing during the thermal pulses, and found that during the AGB evolution the combination of dredge-up and HBB leads to many surface composition changes. A full analysis of these models, and for different masses, will appear elsewhere ([6]), but we note here that we can produce for the first time ^{26}Al/^{27}Al ratios as high as those seen in the Al-rich meteorite grains.

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