Hot Bottom Burning in Asymptotic Giant Branch Stars

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We review the current state of knowledge about the phenomenon of Hot Bottom Burning as seen in Asymptotic Giant Branch stars. This is illustrated with some results from new $6M_{\odot}$ stellar models.

1. Introduction and Motivation

Hot Bottom Burning (hereafter "HBB") is the colourful name given to the circumstance where the temperature at the bottom of a star's convective envelope is sufficiently high for non-negligible nucleosynthesis to take place. It is perhaps better to think of this as the bottom of the convective envelope penetrating into the top of the hydrogen-burning shell, although these definitions are, of course, equivalent (due to the monotonicity of the temperature profile). It is also sometimes known as "convective envelope burning" or simply "envelope burning".

The first calculations of HBB were performed by Scalo, Despain & Ulrich (1975), inspired by the existence of Li-rich stars in the Galaxy. These calculations extended calculations of Sackmann, Smith & Despain (1974) who also used a diffusion equation for the mixing, but had assumed that during the thermal pulse the intershell convective zone actually joined the convective envelope, producing one large convective zone, extending from the surface into the helium shell. Such was, in fact, the result of one evolutionary calculation, by Schwarzschild & Härm (1967), but this was later shown to be due to the neglect of radiation pressure. No subsequent calculation has ever shown contact between these two convective zones (although this does not rule out such an event in real stars, of course!)

Strong observational impetus for the study of HBB was given by Wood, Bessell & Fox (1983). They investigated the brightest red-giants in the Magellanic Clouds. These were known to have $n(\mathrm{C})/n(\mathrm{O}) < 1$ and hence were not Carbon stars (N-type). Instead it was thought that they may be core helium-burning super-giants. Wood *et al.* showed that these stars contained enhanced absorption bands of ZrO. Zr is an s-process element which is produced in thermal pulses on the AGB (*e.g.* Lattanzio *et al.* 1996). Hence these stars were identified as AGB stars which had suffered repeated third dredge-up events without becoming Carbon stars. Because dredge-up of carbon always accompanies the dredge-up of s-process elements the explanation proposed by Wood *et al.* was that HBB had burned the carbon into nitrogen via CN cycling.

These same stars were also investigated by Smith & Lambert (1989; see also Smith & Lambert 1990 and Smith *et al.* 1995) who discovered that they were super-rich in ^{7}Li. This was interpreted by these authors as further evidence for HBB, because it is believed that ^{7}Li can be produced by the Cameron-Fowler Beryllium Transport mechanism, to be discussed below. Soon after, theorists independently discovered that the more massive of the intermediate-mass AGB stars developed thin, but hot, zones at the bottom of their convective envelopes (Blöcker & Schönberner 1991, Lattanzio 1992). Typically, the temperatures at the bottom of the convective envelope reached $T_{bce} \simeq 80 \times 10^6$K but only in a region of thickness $\simeq 10^{-4} M_\odot$.

2. The Core-Mass *vs.* Luminosity Relation

Early in the study of AGB stars it was discovered by Paczyński (1970) that there was a linear relationship between the surface luminosity of a star (just prior to the thermal pulse) and the mass of the hydrogen-exhausted core at the same stage. Since then many authors (*e.g.* Wood & Zarro, 1981; Lattanzio, 1986; Boothroyd & Sackmann, 1988) have improved this relation to allow for more recent input physics, as well as the variation due to chemical composition. Havazelet & Barkat (1979) emphasised the importance of radiation pressure (and its variation with core-mass) to the core-mass *vs.* luminosity relation, and Kippenhahn (1981) reconciled apparently different relations by taking this into account. A linear relation is found when there is non-negligible radiation pressure, which means core-masses exceeding about $0.5 M_\odot$. Tuchman, Glasner & Barkat (1983) found that a necessary condition for the luminosity to depend solely on the core-mass was the existence of a thin (in mass) "transition zone"where the thermodynamic variables changed very quickly. They noted that in the case of HBB a core-mass *vs.* luminosity relation may not hold. Scalo *et al.* (1975) seemed also to be aware of this complication. Indeed, Blöcker & Schönberner (1991) found a $7 M_\odot$model where HBB existed and where the luminosity variation was some ten times steeper than the Paczyński (1970) relation. This was soon confirmed by Lattanzio (1992) for a $5 M_\odot$model. Indeed, HBB had been found by Iben (1975) in a $7 M_\odot$model, and this was presumably the reason for a weak mass-dependence in his core-mass *vs.* luminosity relation quoted in Iben (1977). These developments soon led to a systematic study of where HBB could be expected.

3. Nucleosynthesis of ^{7}Li

A method for the production of ^{7}Li was outlined by Cameron (1955) and Cameron & Fowler (1971) and is known as the "Beryllium Transport Mechanism". The idea here is to combine mixing with the usual pp-chain reactions. We begin with some ^{3}He left over from the early main sequence evolution of the star. When the bottom of the convective envelope reaches into the hydrogen shell, the high temperatures found there are able to produce ^{7}Be by ^{3}He$(\alpha,\gamma)^7$Be. Now, if the ^{7}Be is left *in situ*, then it burns by proton capture into ^{8}B which decays into two ^{4}He nuclei, completing the ppIII chain. If, however, convection can mix the ^{7}Be away from the hot region, then electron capture can occur, to produce ^{7}Li. This is the basic idea of the Cameron and Fowler mechanism. Note that it simply involves normal hydrogen burning reactions, but relies on convection to transport the ^{7}Be to cooler regions, thereby enabling the production of ^{7}Li. Of course, on subsequent passes through the bottom of the envelope there is some destruction of the ^{7}Li by ^{7}Li$(p,\alpha)^4$He which completes the ppII chain. So there is always a competition between the production of ^{7}Li (from the seed ^{3}He, until it is all used up) and the destruction of ^{7}Li from proton capture. Initially, production wins, but once the ^{3}He abundance decreases sufficiently then the proton captures dominate and the ^{7}Li content begins to decrease again. Hence the Li-rich phase is only temporary.

The first systematic calculations of ^{7}Li-production by HBB were carried out by Sackmann & Boothroyd (1992). The key ingredient is an algorithm for time-dependent mixing because it is essential that the timescale for mixing be much shorter than the electron capture lifetime for ^{7}Be. This is indeed true for AGB stars in the mass range ~ 4–$7M_\odot$, depending on the composition (primarily the metallicity). The abundance of ^{7}Li very quickly (within about six pulses) grows to $\epsilon(^7\mathrm{Li}) \simeq 4$ from a typical red-giant envelope value of $\simeq -1$ to 1 (recall that $\epsilon(\mathrm{X}) \equiv \log_{10}[n(\mathrm{X})/n(\mathrm{H})] + 12$). Conversely, if the usual assumption of complete instantaneous mixing is made, then the ^{7}Li abundance decreases to values more like $\epsilon(^7\mathrm{Li}) \simeq -5$. This is the ingredient lacking in the attempt by Iben (1973) to produce Li-rich giants. Sackmann & Boothroyd (1992) used a diffusion formulation to model the time-dependence of mixing, and this appears to work well. An alternative has been used by Lattanzio *et al.* (1996, 1997), based on the Thorne-Żytkow calculations of Cannon (1993), which allowed for upward and downward moving streams with some horizontal diffusion between the streams. This also gives results very similar to those obtained by Sackmann & Boothroyd (1992).

Sackmann & Boothroyd (1992) showed that ^{7}Li was produced as soon as T_{bce} exceeded 50×10^6K, and produced abundances in the range $\epsilon(^7\mathrm{Li}) \simeq 4.5$ in stars with $M_{bol} \simeq -6$ to -7. This is in excellent agreement with the observations of Smith & Lambert (1989, 1990) as well as Smith *et al.* (1995), which found Magellanic Cloud AGB stars of M_{bol} between -6 and -7 to have $\epsilon(^7\mathrm{Li})$ in the range 2.2 to 3.8. Note that there are also galactic giants with even higher lithium values, such as WX Cyg with $\epsilon(^7\mathrm{Li}) = 4.7 \pm 0.5$ (Abia *et al.*, 1991).

4. Nucleosynthesis of CNO Elements

One of the main effects of HBB is to take the ^{12}C which is dredged to the surface and process it into ^{14}N via the CN cycle. This will necessarily involve the production of ^{13}C also, and the ^{12}C destruction prevents the star from becoming a Carbon star.

Boothroyd, Sackmann & Ahern (1993) have made extensive calculations of the effects of HBB on the carbon isotopes. Significant destruction of ^{12}C together with production of ^{13}C and ^{14}N required temperatures of at least 80×10^6K. This was found for masses greater than about 4 or $5M_\odot$, depending on the metallicity (decreasing as Z increased). From their model results, these authors expect a maximum luminosity of $M_{bol} = -6.4$ for Carbon stars, as higher luminosities will result in HBB processing the ^{12}C into ^{13}C and ^{14}N. Indeed, despite the shallowness of the burning layer, the mixing timescale is such that the entire envelope is processed through the burning region many times during the interpulse phase and ^{12}C comes into equilibrium with ^{13}C, reaching $^{12}\mathrm{C}/^{13}\mathrm{C} \simeq 3$ (by number) for stars with $M_{bol} \gtrsim -6.3$. Thus there is a narrow region (in luminosity) where the stars may be rich in ^{13}C prior to further processing of ^{12}C (and ^{13}C) into ^{14}N.

This is shown in Figure 1, which shows the surface abundances of ^{12}C, ^{13}C and ^{14}N in a $6M_\odot$model with $Z = 0.02$, taken from Lattanzio *et al.* (1997). One can clearly see the increase in ^{13}C as HBB begins. Soon after, ^{12}C and ^{13}C come into equilibrium. Following this one can clearly see a continued rise in ^{14}N content. Figure 2 shows the ratio of $^{12}\mathrm{C}/^{13}\mathrm{C}$ and $^{12}\mathrm{C}/^{16}\mathrm{O}$ during this phase. Note that the star shows a decrease in the C/O ratio due to the destruction of the ^{12}C which is periodically added via dredge-up.

As pointed out by Boothroyd *et al.* (1993), higher temperatures are required for CN cycling than for the production of ^{7}Li. Hence this would appear to explain the existence of some Carbon stars with high $\epsilon(^7\mathrm{Li})$; these stars have begun HBB at temperatures in excess of 50×10^6K, which produces ^{7}Li, but have not (yet) reached the more extreme values ($\sim 80 \times 10^6$K) required for carbon destruction. However, this picture may be complicated by ^{19}F (see below).

The situation with oxygen isotopes is a little more complicated. The Third dredge-up

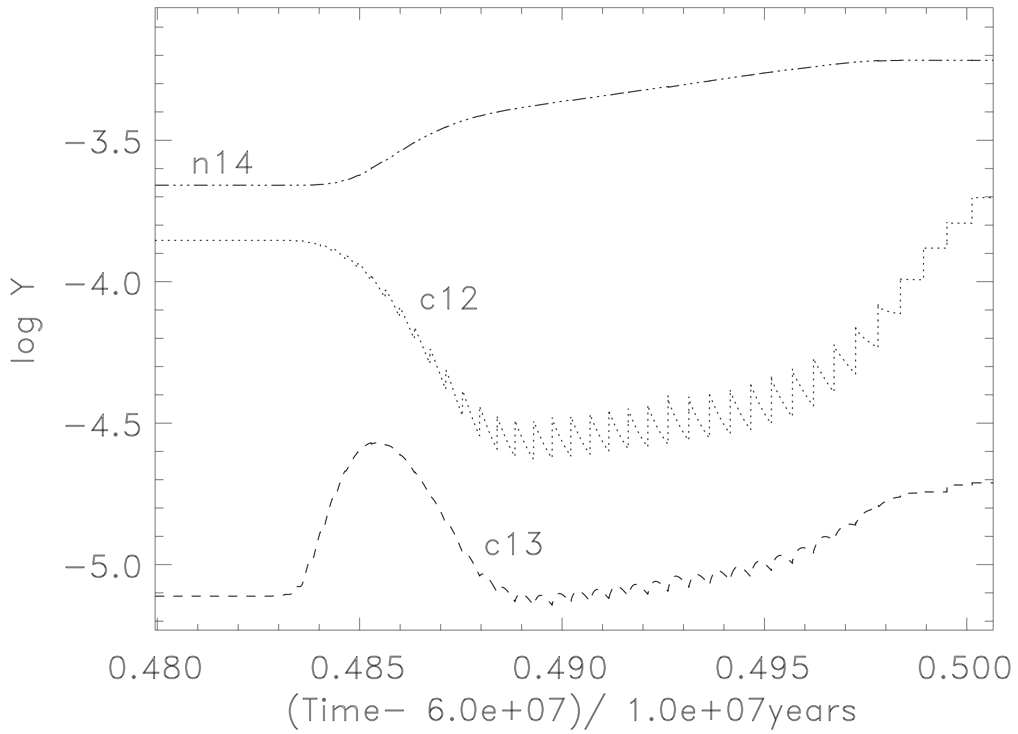

FIGURE 1. Surface abundances during the AGB evolution for a $6M_{\odot}$model with $Z = 0.02$. Note that increased mass loss, near the end of the evolution, turns off HBB and hence the CN cycling stops during the last few pulses.

appears to have a negligible effect on the oxygen isotopes. HBB initially destroys any ^{18}O which is present, and then follows this by producing some ^{17}O, as shown by Boothroyd, Sackmann & Wasserburg (1995). The complication comes from the fact that many AGB stars do not seem to fit this pattern. This is despite the fact that extremely accurate meteoritic grain analysis (*e.g.* Nittler *et al.* 1994) reveals isotopic ratios which do fit the results of standard first and second dredge-up models quite well (see Boothroyd, Sackmann & Wasserburg, 1994). It now appears that to match the observations of S and C stars we must invoke some form of "deep-mixing" during the AGB evolution (possibly in addition to the first ascent of the giant branch). We cannot discuss this fascinating topic here, but refer the interested reader to Wasserburg, Boothroyd & Sackmann (1995), Charbonnel (1995), Sackmann & Boothroyd (1997) and Boothroyd & Sackmann (1997).

5. Nucleosynthesis of ^{19}F

It was shown by Jorrisen, Smith & Lambert (1992) that there was a correlation between the C/O ratio and the [^{19}F/^{16}O] value in galactic red-giants of various spectral types. Since the C/O ratio is a direct result of dredge-up (at least for masses where HBB is not initiated) this implies that shell-flashes are also a source of ^{19}F enhancement. Some of these enhancements are quite large, reaching values of [^{19}F/^{16}O] as high as 1.5. In an accompanying paper, Forestini *et al.* (1992) outlined possible production mechanisms for this ^{19}F. These ideas were further refined by Mowlavi, Jorissen & Arnould (1996).

Before describing the suspected mechanism, it is necessary to review (briefly) the role played by ^{13}C. This isotope is produced (albeit in small quantities) by CNO cycling, and is believed to be the neutron source acting in most AGB stars via the $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ reaction. It appears, however, that the small amount of ^{13}C produced by hydrogen

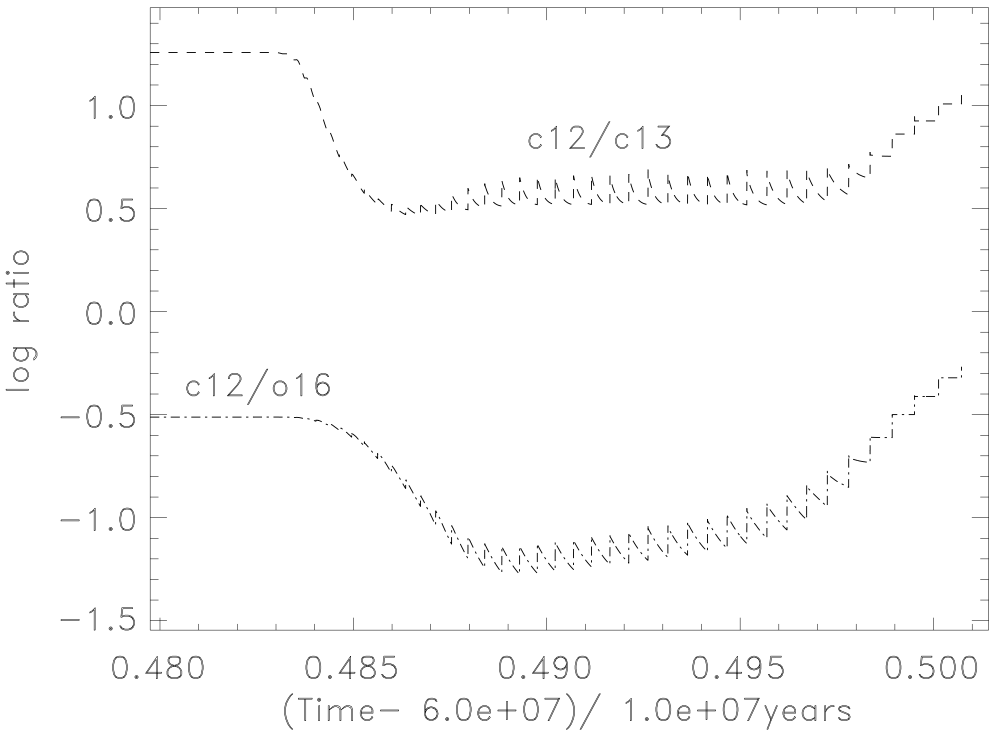

FIGURE 2. Surface abundance ratios during the AGB evolution for a $6M_\odot Z = 0.02$ model.

burning is insufficient to produce the large enhancements of s-process elements seen in many AGB stars. Hence some extra ^{13}C seems to be required. Iben & Renzini (1982a,b) suggested that this was due to some semiconvection at the bottom of the convective envelope during the dredge-up phase. For further details see Frost & Lattanzio (1995). In this scenario some hydrogen is mixed into the intershell zone, where ^{12}C burns into ^{13}C during the interpulse phase. When this ^{13}C pocket is engulfed by the convective shell at the next pulse, the ^{13}C suffers alpha captures to produce neutrons, as outlined above. But recently Straniero *et al.* (1995a,b) have shown that the ^{13}C burns *between* pulses, during the interpulse phase. Hence the neutrons are released, and the s-processing occurs, *in situ* in radiative zones. This has been verified by other authors also, such as Lattanzio *et al.* (1996, 1997) and Mowlavi, Jorissen & Arnould (1996).

The idea behind the production of ^{19}F, is shown in Figure 3. We begin interior to the hydrogen shell, in the region consisting mostly of ^{4}He and the ^{14}N ashes from CNO cycling. ^{14}N captures an alpha particle to produce ^{18}F which then beta decays to ^{18}O. Assuming a source of protons (see below!) ^{18}O then produces ^{15}N via $^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}$. This ^{15}N can then capture another ^{4}He nucleus to produce ^{19}F. But we need a proton source for this chain of reactions to take place. There are two likely sources of protons. ^{13}C left over from CNO cycling suffers (α, n) reactions to produce ^{16}O and neutrons. These neutrons are used to produce the enhancements in s-process elements seen in these stars, but they are also available for ^{14}N and ^{26}Al to capture. Each undergoes (n, p) reactions and hence produces protons (together with ^{14}C and ^{26}Mg, respectively). The details of this process depend primarily on the temperature of the intershell region, both during a pulse (when it is convective) and during the interpulse phase. The temperature, of course, also depends on the metallicity of the star as well as the core-mass, and details are provided in Mowlavi, Jorissen & Arnould (1996). An important point for our purposes is that once ^{19}F is dredged to the surface, it is destroyed by any HBB present via $^{19}\mathrm{F}(p,\alpha)^{16}\mathrm{O}$. Thus stars with enhanced ^{19}F are presumably those of lower masses, where HBB does not take

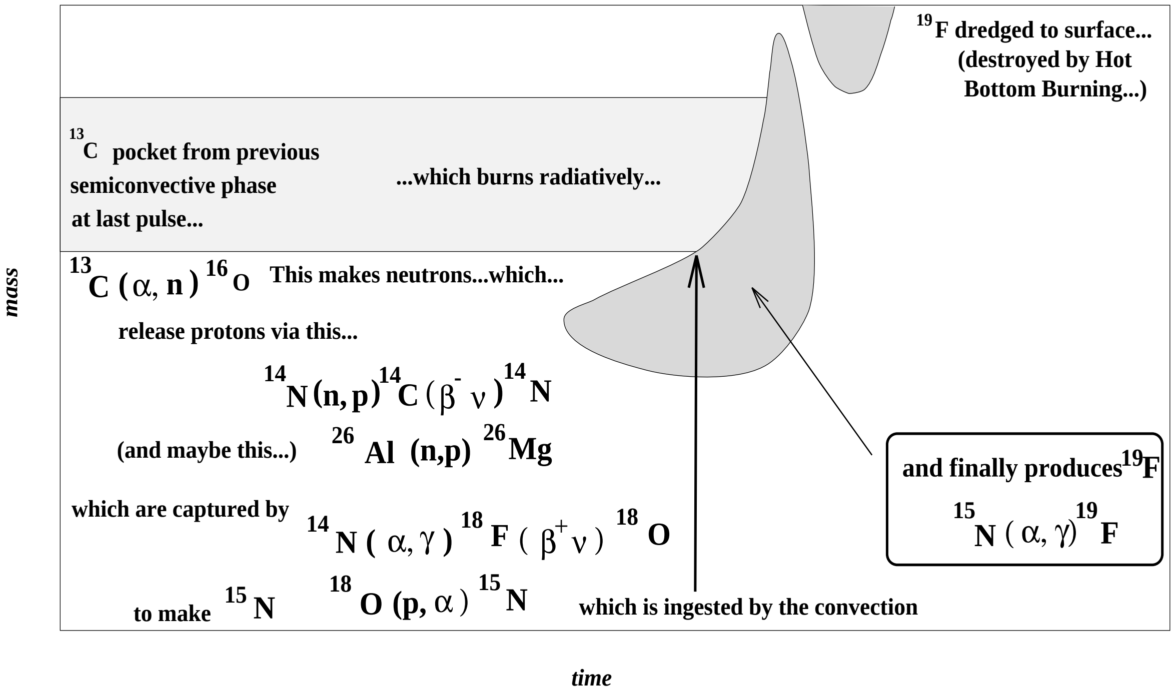

FIGURE 3. A schematic showing how ^{19}F is believed to be produced in AGB star interiors.

place. This is consistent with the correlation between C/O and [^{19}F/^{16}O] and means that we should not find stars with both enhanced ^{7}Li (indicating the presence of HBB) and enhanced ^{19}F, which is destroyed by HBB. In this context the Carbon star WZ Cas may represent a problem, as emphasised by Mowlavi, Jorissen & Arnould (1996).

Finally, we note that to produce the largest observed enhancements of ^{19}F seems to require a substantial source of ^{13}C, just as is needed for the *s*-process abundances. The exact mechanism responsible for producing this ^{13}C remains unknown.

6. Nucleosynthesis of ^{26}Al

The last decade has seen the development of a new technique for the determination of stellar abundances. Meteorities have long been identified as a source of information on the chemical composition of the early solar-system. The development of refined isolation techniques and the use of the ion-microprobe, has enabled the determination of isotope ratios for *individual grains* from *individual stars*. Reviews of this field can be found in Anders & Zinner (1993), Ott (1993), and the many references therein. Further, these isotopic ratios are determined with an accuracy previously never even dreamed of in stellar spectroscopy. Of course, the disadvantage is that we do not know *a priori* which stars produced these grains.

This exciting field has generated many challenges and problems, and a few successes, for stellar models. Primarily, it has led to a new generation of quantitative predictions from stellar models, with much larger nuclear reaction networks than are required purely for evolutionary calculations. In this paper, we want to discuss only the situation with Al. This is found in many grains, such as SiC (believed to form in the carbon-rich atmospheres of Carbon stars), graphite (a very complex and heterogeneous sample of grains) and corundum (Al_2O_3, from both first giant-branch stars and AGB stars). Often we see enhancements of ^{26}Mg, which are taken as evidence for the *in situ* decay of ^{26}Al (lifetime of 720,000y). From this we infer ratios of ^{26}Al/^{27}Al of up to 10^{-2} for corundum grains, and up to 0.1 for the graphite grains. (There are even some SiC grains with ratios heading toward unity! See Zinner (1995) for details.) How can we explain these ratios?

Forestini *et al.* (1992) investigated the production of ^{26}Al in a $3M_{\odot}$stellar model. Although ^{26}Al was indeed produced by proton captures within the hydrogen shell, the maximum abundances reached by this method was relatively low, being $\sim 1.5 \times 10^{-3}$. Of course, with a smaller envelope mass the dilution which occurs with the third dredge-up would be less, and higher concentrations may occur. But it appears that the more natural place to look for higher isotopic ratios (at least within AGB stars) is HBB.

Observations of IRC+10216 by Guélin *et al.* (1995) inferred a value of $^{26}\mathrm{Al}/^{27}\mathrm{Al} = 0.04$. These authors also calculated HBB models for solar compositions of various masses, and obtained $^{26}\mathrm{Al}/^{27}\mathrm{Al}$ values between 0.01 and 0.08, in excellent agreement with the data. In $6M_{\odot}$models calculated by the authors we have obtained ratios up to 0.6 for metallicity $Z = 0.004$, 0.25 for $Z = 0.008$ and 0.03 for solar composition. Of course, there are many uncertainties in these numbers, not least of which is the effect of dredge-up (Frost & Lattanzio, 1996) and mass-loss (which finally terminates both HBB and dredge-up), together with some quite large uncertainties in the reaction rates, as discussed by Arnould & Mowlavi (1995). Nevertheless, it appears that these models can explain the observed isotopic ratios, at least qualitatively, and we have reason for optimism that a quantitative understanding will soon be reached.

7. Conclusions

There has been an exciting growth in quantitative nucleosynthesis calculations in recent years, inspired by new data (such as pre-solar grain analysis) as well as theoretical devlopments like HBB. At the moment, we appear to have a reasonably good qualitative understanding of the majority of stars, but problems appear when quantitative predictions are tried. The main problem seems to be in determining the edges of convective boundaries, as outlined by Frost & Lattanzio (1996). Other sources of mixing, such as shear instabilities in rotating stars, are also likely to complicate the picture, but may provide a mechanism for understanding the richness and variety of the compositions seen in the photospheres of AGB stars.

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