AGB Stars: What Should Be Done ?

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Abstract: We provide an overview of the current theoretical picture of AGB stars, with particular emphasis on the nucleosynthesis occurring in these stars, both in their deep interiors, associated with thermal pulses or flashes, and also during the phase of "hot bottom burning". These processes are illustrated with some new results from hot bottom burning calculations. Finally, we conclude with recommendations about "what should be done".

1 Introduction

In the last twenty years much research has been dedicated to the understanding of Asymptotic Giant Branch (AGB) stars. For particularly noteworthy reviews see Iben and Renzini (1983), Lattanzio (1989), Sackmann and Boothroyd (1991) and Iben (1991). Recent evidence for extensive nucleosynthesis at the bottom of their deep convective envelopes (known as "Hot Bottom Burning", HBB) together with extensive data from isotopic analysis of grains in meteorites is leading to a revolution in the quantitative demands being placed on the models. Further, the discovery that the ^{13}C pocket is burned under radiative conditions rather than in the intershell convective zone (see below for details) demands that we re-examine the models and their nucleosynthesis.

We begin by giving a qualitative analysis of the evolution of stars of masses $\simeq 1M_{\odot}$ and $\simeq 5M_{\odot}$ in Section 2. This illustrates the cases where we do, and do not, find the "second dredge-up", and introduces the basic principles of the evolution of all stars which spend some time on the AGB. These vary from a minimum mass (probably a little under $1M_{\odot}$) to a maximum mass of M_{up}, which just avoids core carbon ignition, and is about $9M_{\odot}$ (depending on composition).

Section 3 will outline the basic evolution during a thermal pulse, but quite briefly because this is well understood (or, rather, as well understood as it is likely to be for the present!). As an illustration of the nucleosynthesis which can occur during this stage, we will explicitly discuss the dredge-up of ^{12}C and the formation of Carbon stars. Section 4 will discuss the *s*-process, why we believe that ^{13}C is the neutron source, and how we believe the ^{13}C is produced. Here we will also discuss the problem of ^{19}F production. In Section 5 we will explain the observational motivation for considering HBB, and its consequences for the composition of the star. Particular emphasis will be placed on ^{7}Li production and how HBB can prevent the formation of Carbon stars. Section 6 will introduce meteorite grains as an important source of abundance information, which is driving models to a higher level of precision. Finally, in Section 7, we will discuss the immediate future: "what should be done?".

2 Basic Stellar Evolution

We now give a qualitative overview of the evolution of stars of masses $1M_\odot$ and $5M_\odot$, with emphasis on the mechanisms and phenomenology of the structural and evolutionary changes. In this section we consider only the evolution up to the beginning of thermal pulses on the AGB (the "TP-AGB").

2.1 Basic Evolution at $1M_\odot$

We make the usual assumption that a star reaches the zero-age main sequence with a homogeneous chemical composition (for an alternative evolutionary scenario see Lattanzio 1984). Figure 1 shows a schematic HR diagram for this star. Core H-burning occurs radiatively, and the central temperature and density grow in response to the increasing molecular weight (points 1–3). At central H exhaustion (point 4) the H profile is as shown in inset (a) in Figure 1. The star now leaves the main sequence and crosses the Hertzsprung Gap (points 5–7), while the central ^{4}He core becomes electron degenerate and the nuclear burning is established in a shell surrounding this core. Inset (b) shows the advance of the H-shell during this evolution. Simultaneously, the star is expanding and the outer layers become convective. As the star reaches the Hayashi limit ($\sim$ point 7), convection extends quite deeply inward (in mass) from the surface, and the star ascends the (first) giant branch. The convective envelope penetrates into the region where partial H-burning has occurred earlier in the evolution, as shown in inset (c) of Figure 1. This material is still mostly H, but with added ^{4}He together with the products of CN cycling, primarily ^{14}N and ^{13}C. These are now mixed to the surface (point 8) and this phase is known as the "first dredge-up". The most important surface abundance changes are an increase in the ^{4}He mass fraction by about 0.03 (for masses less than about $4M_\odot$), while ^{14}N increases at the expense of ^{12}C by around 30%, and the number ratio ^{12}C/^{13}C drops from its initial value of $\sim$ 90 to lie between 18 and 26 (Charbonnel 1994).

As the star ascends the giant branch the ^{4}He-core continues to contract and heat. Neutrino energy losses from the centre cause the temperature maximum to move outward, as shown in inset (d) of Figure 1. Eventually triple alpha reactions are ignited at this point of maximum temperature, but with a degenerate equation of state. The temperature and density are decoupled: the resulting ignition is violent, and is referred to as the "core helium flash" (point 9: see for example Deupree 1984). Following this the star quickly moves to the Horizontal Branch where it burns ^{4}He gently in a convective core, and H in a shell (which provides most of the luminosity). This corresponds to points 10–13 in Figure 1. Helium burning increases the mass fraction of ^{12}C and ^{16}O (the latter through $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$) and the outer regions of the convective core become stable to the Schwarzschild convection criterion but unstable to that of Ledoux: a situation referred to as "semiconvection" (space prohibits a discussion of this phenomenon, but an excellent physical description is contained in Castellani *et al.* 1971a,b). The semiconvection causes the composition profile to adjust itself to produce convective neutrality, with the resulting profiles as shown in inset (e) of Figure 1.

Following ^{4}He exhaustion (point 14) the star ascends the giant branch for the second time, and this is known as the Asymptotic Giant Branch, or AGB, phase. The final proportions of ^{12}C and ^{16}O in the ^{4}He-exhausted core depend on the uncertain rate for the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction (see Arnould 1995). The core now becomes electron degenerate, and the star's energy output is provided by the ^{4}He-burning shell (which lies immediately above the C-O core) and the H-burning shell. Above both is the deep convective envelope. This structure is shown in inset (f) in Figure 1. We will later see that the ^{4}He-shell is thermally unstable, as witnessed by the recurring "thermal pulses". Thus the AGB is divided into two regions: the early-AGB, prior to (and at lower luminosities than) the first thermal pulse, and the thermally-pulsing AGB (TP-AGB) beyond this. We will return to this in section 3.

2.2 Basic Evolution at $5M_\odot$

A more massive star, say of $\sim 5M_\odot$, begins its life very similarly to the lower mass star discussed above. The main initial difference is that the higher temperature in the core causes CNO cycling to

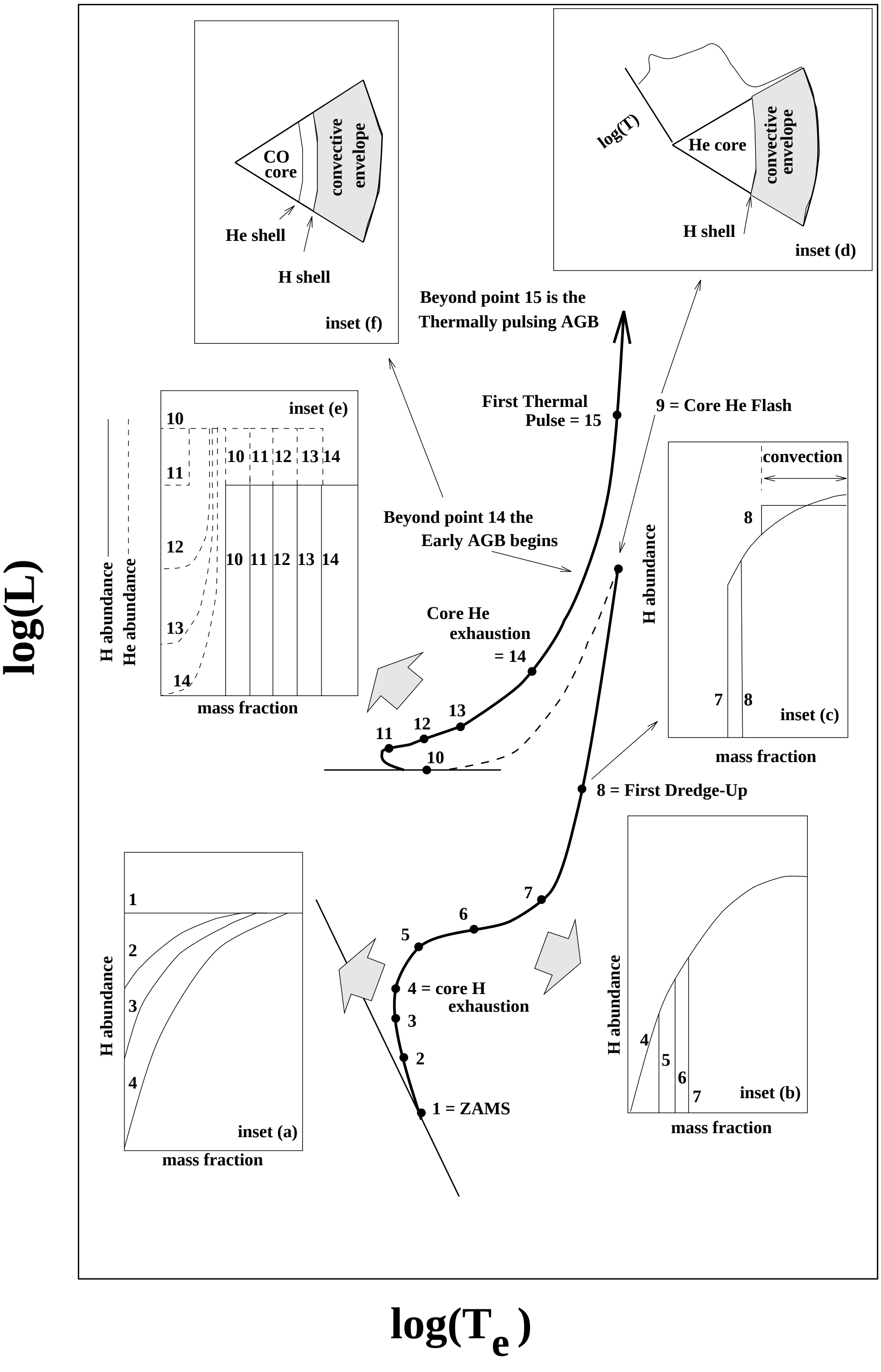

Figure 1: Schematic of evolution at $\sim 1M_{\odot}$.

be the main source of H-burning, and the high temperature dependence of these reactions causes a convective core to develop. As H is burned into ^{4}He the opacity (due mainly to electron scattering, and hence proportional to the H content) decreases and the extent of the convective core decreases with time. This corresponds to points 1–4 in Figure 2. Following core H exhaustion there is a phase of shell burning as the star crosses the Hertzsprung Gap (points 5–7 and inset (b)), and then ascends the (first) giant branch. Again the inward penetration of the convective envelope (point 8) reaches regions where there has been partial H-burning earlier in the evolution, and thus these products (primarily ^{13}C and ^{14}N, produced at the cost of ^{12}C) are mixed to the surface in the first dredge-up, just as seen at lower masses, and sketched in inset (c) of Figure 2.

For these more massive stars the ignition of ^{4}He occurs in the centre and under non-degenerate conditions, and the star settles down to a period of quiescent ^{4}He-burning in a convective core, together with H-burning in a shell (see inset (d) in Figure 2). The competition between these two energy sources determines the occurrence and extent of the subsequent blueward excursion in the HR diagram (*e.g.* Lauterborn *et al.* 1971), when the star crosses the instability strip and is observed as a Cepheid variable (points 10–14). Following core ^{4}He exhaustion the structural re-adjustment to shell ^{4}He burning results in a strong expansion, and the H-shell is extinguished as the star begins its ascent of the AGB. With this entropy barrier removed, the inner edge of the convective envelope is free to penetrate the erstwhile H-shell. Thus the products of complete H-burning are mixed to the surface in what is called the "second dredge-up" (point 15). This again alters the surface compositions of ^{4}He, ^{12}C, ^{13}C and ^{14}N, and actually reduces the mass of the H-exhausted core, because in the process of mixing ^{4}He outward we also mix H inward (see inset (e) in Figure 2). Note that there is a critical mass (of about $4M_\odot$, but dependent on composition) below which the second dredge-up does not occur. Following dredge-up the H-shell is re-ignited and the first thermal pulse occurs soon after: the star has reached the thermally-pulsing AGB, or TP-AGB. Note that at this stage the structure is qualitatively similar for all masses.

3 Thermal Pulses on the AGB: Making Carbon Stars

This phase has been reviewed extensively, and we present here only a very brief summary (for further details, see Iben and Renzini 1983, Lattanzio 1989, Sackmann and Boothroyd 1991, and Iben 1991). The ^{4}He-burning shell is thermally unstable (*e.g.* Schwarzschild and Härm 1965, Sackmann 1977, Sugimoto and Fujimoto 1978), and experiences periodic outbursts called "shell flashes" or "thermal pulses". The four phases of such a thermal pulse are: (a) the off phase, where the structure is basically that of an early-AGB star. During this phase almost all of the surface luminosity is provided by the H-shell. This phase lasts for 10^4 to 10^5 years, depending on the core-mass; (b) the "on" phase, when the ^{4}He-shell burns very strongly, producing luminosities up to $\sim 10^8 L_\odot$. The energy deposited by these ^{4}He-burning reactions is too much for radiation to carry, and a convective shell develops, which extends from the ^{4}He-shell almost to the H-shell. This convective zone is comprised mostly of ^{4}He (about 75%) and ^{12}C (about 22%), and lasts for about 200 years; (c) the "power down" phase, where the ^{4}He-shell begins to die down, and the intershell convection is shut-off. The previously released energy drives a substantial expansion, pushing the H-shell to such low temperatures and densities that it is extinguished (or very nearly so); and (d) the "dredge-up" phase, where the convective envelope, in response to the cooling of the outer layers, extends inward and, in later pulses, beyond the H/He interface (which was previously the H-shell) and can even penetrate the erstwhile flash-driven convective zone. This results in the ^{12}C which was produced by the ^{4}He-shell, and mixed outward by the flash-driven convection, now being mixed to the surface by the envelope convection. This is the "third dredge-up", and it qualitatively (and almost quantitatively) accounts for the occurrence of Carbon stars at higher luminosities on the AGB. Figure 3 shows these four phases during one pulse (top) and during two consecutive pulses (bottom). From this figure we see the definition of the so-called "dredge-up parameter", λ. This is defined as $\lambda = \Delta M_{dredge}/\Delta M_H$ where ΔM_{dredge} is the amount of mass dredged-up by the convective envelope, and ΔM_H is the amount

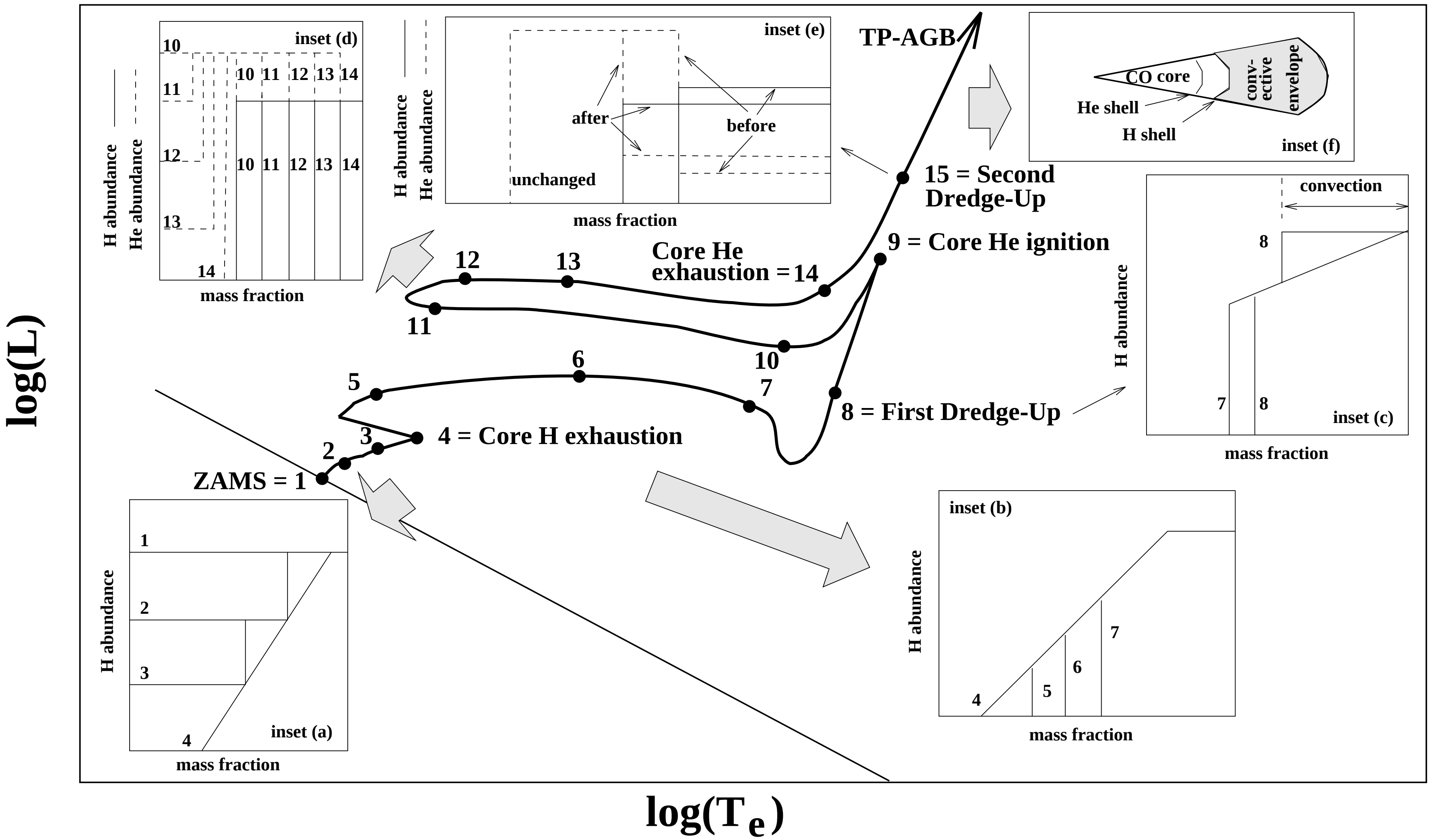

Figure 2: Schematic of evolution at $\sim 5 M_{\odot}$.

of mass through which the H-shell has moved during the interpulse phase. Typical evolutionary calculations show that $\lambda \simeq 0.3$ (at least for lower masses, although we find $\lambda \sim 0.9$ for $M \sim 6M_\odot$). Also shown in the bottom panel is the variation of the total radiated luminosity and the two nuclear energy sources (i.e. the luminosities from H and ^{4}He burning) during a pulse cycle.

4 Interior Nucleosynthesis on the AGB

4.1 ^{13}C and the s-process

It is now well established observationally that many AGB stars show an overabundance of the s-process elements. This is easily understood within the picture given above. It was initially envisaged (*e.g.* Iben 1975a) that the H-shell, which burns primarily by the CNO cycles, would leave behind significant amounts of ^{14}N. During the next flash cycle this ^{14}N is mixed downward to regions where the temperature is higher (the exact value depending mainly on the star's core mass) and then the sequence of reactions

$$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^+\nu)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$$

occurs. If the core mass is greater than about $0.9M_\odot$ then this is followed by $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ which releases neutrons that are then captured by many species, including ^{56}Fe and its progeny, producing a distribution of s-process elements which is close to that seen in the solar system (Iben 1975b, Truran and Iben 1977).

Various observations (see Smith *et al.* 1987) indicate that the s-process enriched stars have masses $\sim 1-3M_\odot$, which means they have smaller cores and consequently cooler intershell convection zones. Thus the ^{22}Ne source would never be activated (or, at least, not at a sufficient rate to provide enough neutrons for the observed s-processing to occur). Hence it appears that ^{22}Ne is not the neutron source, and we are forced to find another. One rather obvious source is $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$, which ignites at much lower temperatures. The problem here is to produce enough ^{13}C to provide sufficient neutrons. The obvious source is CN cycling in the H-shell, but this leaves behind only very small amounts of ^{13}C: $X(^{13}\mathrm{C}) \sim 10^{-2}X(\mathrm{CNO})$.

Sackmann (1980) and Iben (1982) discussed the possibility of post-pulse expansion causing the carbon rich region to be exposed to very low temperatures, with a consequent increase in the opacity due to Carbon recombination, and possibly leading to some mixing. Iben and Renzini (1982a) indeed showed that following a pulse the bottom of the convective envelope can become semiconvective. This results in the diffusion of some protons downward beyond the formal maximum inward extent of the convective envelope during the third dredge-up phase. This is shown schematically in Figure 4. The protons which are deposited by this semiconvection are in a region comprising about 75% ^{4}He and 22% ^{12}C, so when the H-shell is re-ignited they are burned into ^{13}C (and ^{14}N). In this scenario, which we shall call the "classical ^{13}C scenario", when the next thermal pulse occurs the ^{13}C is engulfed by the flash-driven convection, and then in this ^{4}He-rich environment neutrons are released by the $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$. These neutrons are then captured by ^{56}Fe and its progeny to produce the observed s-process elements (see Iben and Renzini 1982b, Gallino *et al.* 1988).

This scenario has many attractive features, but it has always had some problems (Lattanzio 1989), the most serious of which is that not all calculations reproduce this semiconvective mixing. Of course, a small amount of overshoot[1] inwards could produce the same results, as could almost any form of mixing which will distribute some H below the convective envelope and into the previously flash-driven convective zone. In any event, to calculate the effects of this proposed mixing, it has been common to artificially add a ^{13}C profile just before a pulse. This is how subsequent nucleosynthesis was calculated in the classical scenario.

[1] Note that it is incorrect to refer to this as "undershoot". Overshoot refers to the mixing *beyond* the formal convective boundary, and undershoot would mean that the mixing ended *before* reaching the normal boundary. Thus the phenomenon of overshooting in the inward direction is quite distinct from undershoot.

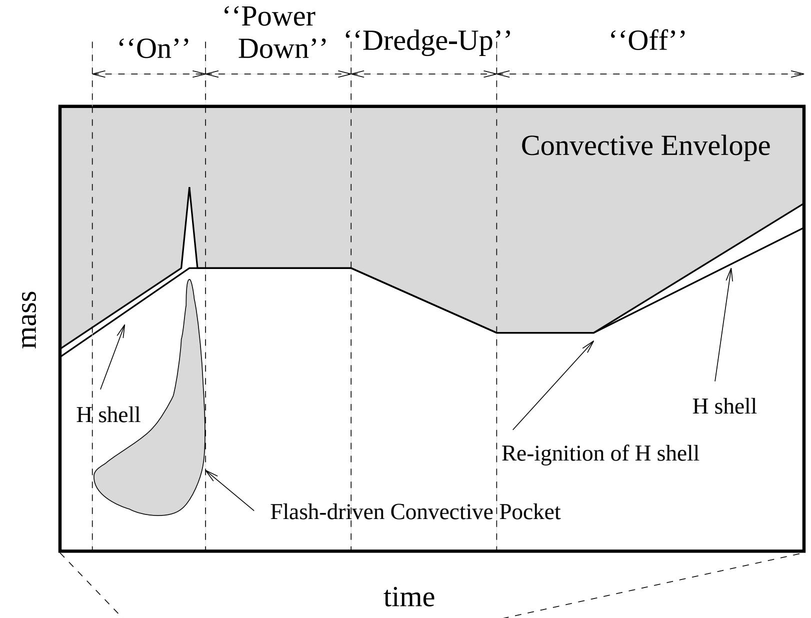

Figure 3 (a). One thermal pulse.

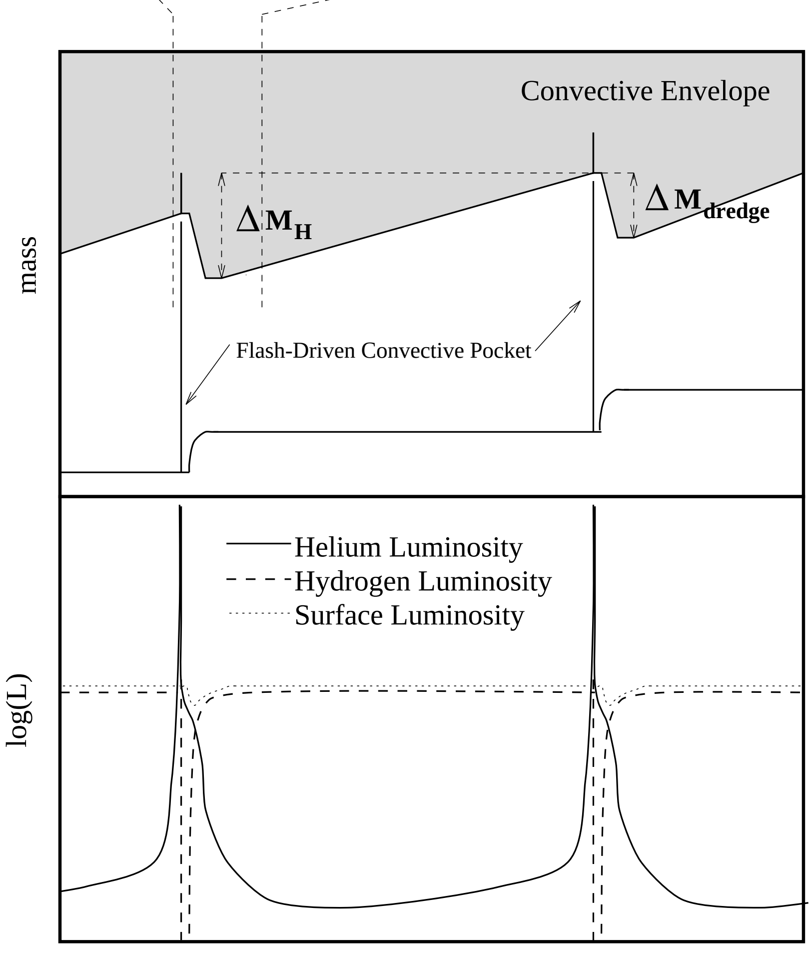

Figure 3 (b). Two consecutive thermal pulses

Figure 3: Details of interior evolution during one thermal pulse (top) and for two consecutive pulses (bottom).

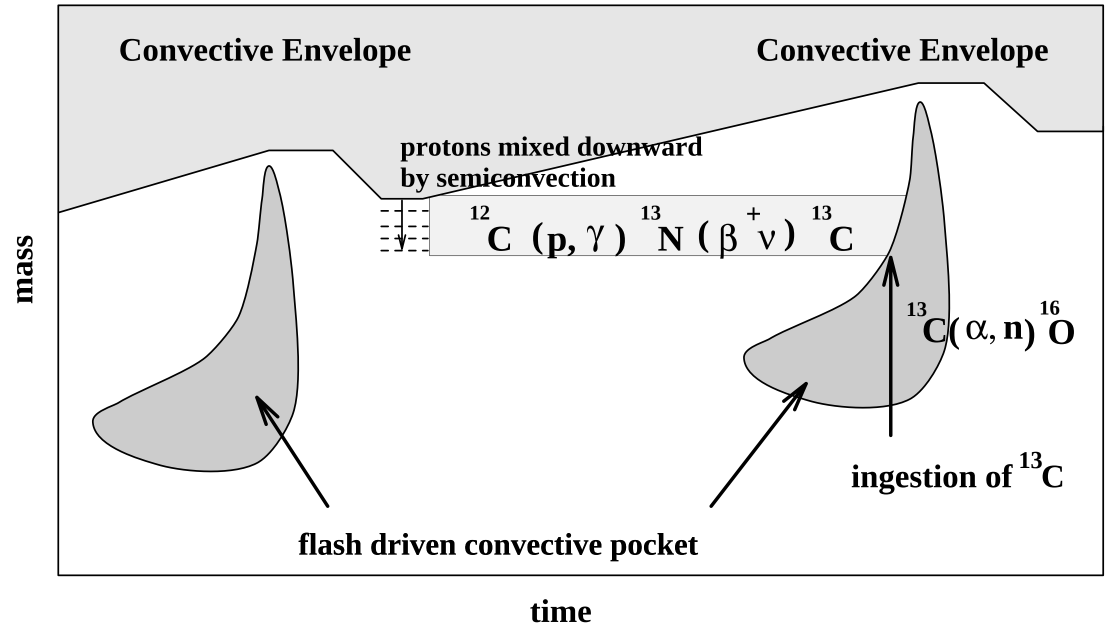

Figure 4: Schematic of the "classical" scenario describing how ^{13}C acts as a neutron source in low mass AGB stars.

A modification to this scenario appears to have been found by Straniero *et al.* (1995a,b) who discovered that any ^{13}C present will burn under *radiative* conditions during the interpulse phase. They observed this to happen in their calculation of a $3M_\odot$ model with $Z = 0.02$. The temperature of the intershell region is usually lower during the interpulse phase than when this zone becomes convective during the next pulse. But it does increase during the interpulse phase, reaching values of $T_6 \sim 90$ just before the later pulses. With an interpulse period of about 50,000 years there is plenty of time for the ^{13}C to be consumed by alpha captures between pulses and hence under radiative conditions. Thus all the ^{13}C is burned into ^{16}O before the next pulse, by the same ^{13}C(α,n)^{16}O reaction as in the classical scenario. But now this occurs at lower temperatures, and with the release of neutrons *in situ*, so that the neutron density remains very low, with n_n at most a few $\times 10^7$, compared with $\sim 10^9$ in the classical picture. It now appears that an asymptotic distribution of s-elements is achieved after fewer pulses (about 5, see Gallino and Arlandini 1995) than in the classical scenario. The resulting s-element distribution looks similar to that in the classical scenario only for the heavier elements, with significant differences appearing for the isotopes with $A < 90$. For further details refer to Gallino and Arlandini (1995).

It is worth noting, finally, that the radiative burning of ^{13}C has been confirmed by Mowlavi *et al.* (1995) and in unpublished calculations by the authors.

4.2 The Production of ^{19}F

Jorissen *et al.* (1992) discovered that the ^{19}F/^{16}O ratio in AGB stars increases with the ^{12}C/^{16}O ratio implicates thermal pulses in the origin of this ^{19}F. Little theoretical work has been done at this stage. The paper by Jorissen *et al.* investigated many possible scenarios, and this was followed by Forestini *et al.* (1992) who investigated the most promising scenario in more detail. This is shown in Figure 5. Here, some ^{13}C produces neutrons via the ^{13}C(α,n)^{16}O reaction discussed above, 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}O(p,α)^{15}N(α,γ)^{19}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. This may be important in view of the fact that ^{13}C is now believed to burn

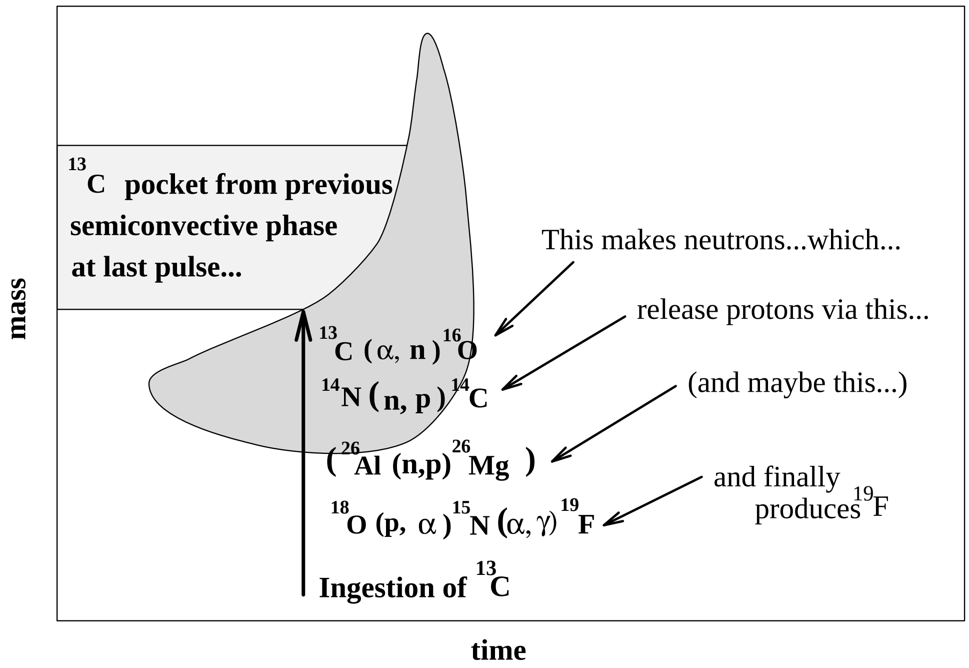

Figure 5: Schematic of the ^{19}F production mechanism as envisaged by Jorissen *et al.* (1992) and Forestini *et al.* (1992)

between pulses, and may indicate that small overabundances of ^{19}F are easily explained without the extra ^{13}C provided by the semiconvection of Iben and Renzini (1982a,b). Yet for those stars showing more enhanced ^{19}F we may need to invoke some extra-mixing (semiconvection, overshoot, diffusion, or whatever) to distribute some H into the carbon-rich intershell region.

Recent models by Mowlavi *et al.* (1995) show that the scenario described above can work only for the first few pulses (for low masses). After that the high temperature in the intershell destroys ^{19}F via ^{19}F(p, α)^{16}O. Furthermore, with the new (and much higher) rate for the ^{18}O(α,γ)^{22}Ne reaction, the survival of sufficient ^{18}O is not assured. To complicate matters further, during these thermal pulses the lifetime of (neutrons and) protons can actually decrease below the convective timescale, so that the usual homogeneous mixing approximation breaks down and one must include some time-dependent mixing algorithm, such as the diffusion approximation or perhaps something else (*e.g.* Cannon *et al.* 1995). Clearly we have not yet heard the last word about ^{19}F and much work still needs to be done to clarify the situation.

4.3 Producing heavier elements

Stellar evolutionary calculations include all nuclear reactions necessary to calculate the energy production in stellar models. They usually ignore the many other reactions which are energetically negligible. However, with improved observations and the emerging science of isotopic analysis in meteorites (see below), it is now necessary to include many other species if we wish to make a detailed comparison with real AGB stars. Calculations including species beyond the CNO group are just becoming available now (but have been available for massive stars for quite some time), and although we will deal with this in more detail below, the case of ^{26}Al has been considered in the literature and is worthy of particular attention at this point.

The beta decay of ^{26}Al produces 1.8 Mev γ-rays (see Schönfelder and Varendorff 1991). These can be analysed to determine the approximate amount of ^{26}Al present in the galaxy, with current estimates giving $\sim 3-5M_\odot$ (Clayton and Leising 1987). Since ^{26}Al has a half-life of $\tau_{26} \sim 10^6$ years, this means there is about $2M_\odot$ of ^{26}Al ejected into the Galaxy every τ_{26} (Prantzos 1995). Many sources have been postulated for this ^{26}Al, and the analysis by Prantzos shows that the distribution of ^{26}Al follows the

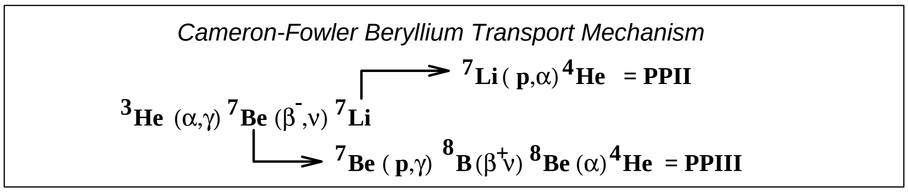

Figure 6: The Cameron-Fowler Beryllium Transport Mechanism.

spiral structure of the galaxy, thus implying that it is associated with massive stars. This is consistent with production by massive AGB stars as well as Type II supernovae and Wolf-Rayet stars.

Restricting our attention to AGB stars, there are two proven sites of formation of ^{26}Al; these are the H-shell itself, and the bottom of the convective envelope. The latter will be discussed below in the section on HBB, but it is important to note that the H-shell produces some ^{26}Al via the Mg-Al cycle by transforming any initial ^{25}Mg into ^{26}Al. This was investigated by Forestini *et al.* (1991), who found that small amounts of ^{26}Al can be made and then dredged to the surface (although they had to force the dredge-up, which does not occur in their models). More recently, Guélin *et al.* (1995) have observed IRC+10216 for Mg and Al isotopes. They also present models of AGB stars with HBB, and we defer a discussion of these models until Section 6.2

5 Hot Bottom Burning in AGB Stars

It has been known for some time that it was theoretically possible for the convective envelope of a star to reach so close to the H burning shell that some nuclear processing could occur at the bottom of the envelope. Cameron and Fowler (1971) suggested a mechanism for the production of ^{7}Li which required HBB. In this picture, the ^{3}He left in the star from earlier H-burning can capture an alpha particle at the base of the convective envelope to form ^{7}Be. If this ^{7}Be remains exposed to high temperatures then it can capture a proton, and go on to complete the PPIII sequence (see Figure 6). Alternatively, if the ^{7}Be decays into ^{7}Li then the ^{7}Li can capture a proton to complete the PPII sequence. If, however, we are to make much ^{7}Li without completing the PP chains, then the ^{7}Be must be moved away from the hot region so that it can decay into ^{7}Li. This ^{7}Li is also very fragile, and must spend most of its time in cool regions or it will be destroyed by the PPII chain. Clearly a convective envelope with a thin, hot base, can fulfill these criteria, and this is exactly what was proposed by Cameron and Fowler. Indeed, there were some calculations carried out in the 70s by Sackmann *et al.* (1974) and Scalo *et al.* (1975), but with no observational motivation the models were not further studied until recently.

5.1 Observational Motivation

Perhaps the first serious consideration of the possibility of HBB was in the paper by Wood *et al.* (1983), looked at the very brightest AGB stars in the Magellanic Clouds and found that they were not Carbon stars. In this picture the brightest stars would have experienced many thermal pulses, and hence dredge-up episodes, as they ascended the AGB. So how could the brightest not have dredged enough ^{12}C to become Carbon stars? Wood *et al.* suggested that HBB was responsible: with a sufficiently hot envelope some CN cycling could occur, and conceivably process the added ^{12}C into ^{14}N (predominantly).

Later, Smith and Lambert (1990) checked these stars for ^{7}Li, an expected by-product of HBB via the Cameron-Fowler mechanism mentioned above. They found that all of these bright AGB M-stars showed extremely strong Li lines[2]. At about the same time there appeared some calculations

[2]The suggestion that perhaps these are supergiants rather than AGB stars is easily refuted, because they show excesses of *s*-process elements (Smith and Lambert 1986) which we have seen are also produced by thermal pulses on the AGB.

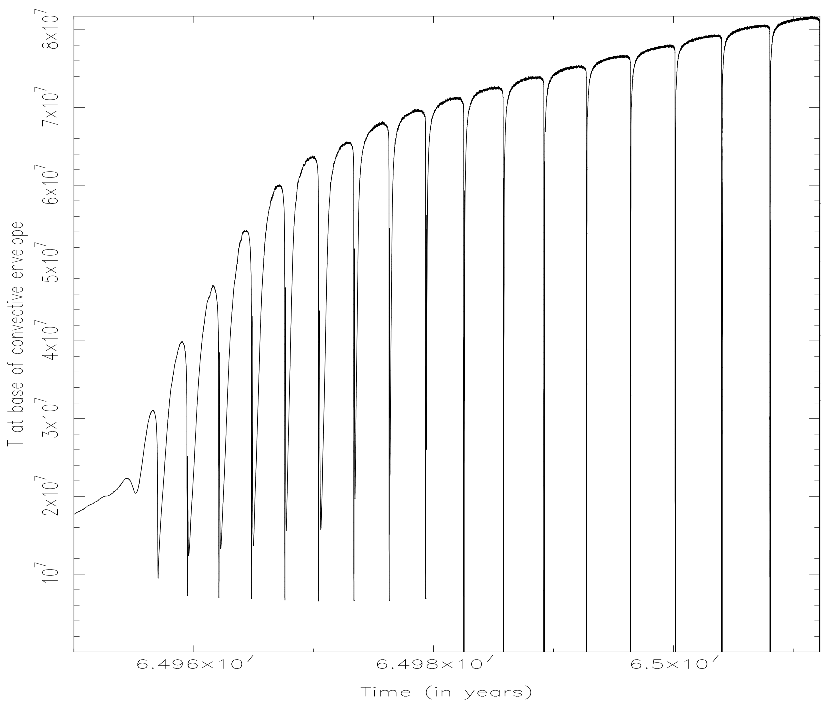

Figure 7: Temperature at the base of the convective envelope during the first few pulses of a $6M_\odot$ model with $Z = 0.02$.

which indicated that the correct conditions did occur in some stars (see, for example, Blöcker and Schönberner 1991; Lattanzio 1992). In models of relatively large masses, above $\sim 5M_\odot$, the convective envelope was seen to reach into the top of the H-burning shell, and hence the material in the envelope was exposed to very high temperatures, reaching up toward $T_6 = 100$! An example, for a $6M_\odot$ model with $Z = 0.02$ is shown in Figure 7. (This model will be used throughout the rest of this paper to illustrate the various topics we discuss.) Note that the temperature rises rapidly at first, as the pulses reach "full amplitude", after which the growth is slowed somewhat. However, we see that even after 18 pulses the peak temperature during the interpulse phase is still growing, and is already above $T_6 = 80$.

5.2 The Production of Lithium

Although there were early calculations of HBB and possible ^{7}Li production (Sackmann *et al.* 1974, and Scalo *et al.* 1975) the calculations of Boothroyd and Sackmann (1992a) showed quantitatively that such a scenario can work in the required stars. The peak abundances of ^{7}Li found by the models agreed very well with the observations, showing $\log\epsilon(^7\mathrm{Li}) \simeq 4.5$ [3]. After rapidly reaching the peak, however, the ^{7}Li is destroyed as it is repeatedly cycled through the hot bottom of the convective envelope. Also, the initial ^{3}He supply is finite, and once it is used there is no more to form the required ^{7}Be. This behaviour is shown in Figure 8 for the $6M_\odot$ model discussed above. These two effects combine to limit the lifetime of the so-called "super-Li-rich giants", so that they only appear in a small range of $M_{bol} \simeq -6.2$ to -6.8. This predicted range of luminosities agrees well with the observations for the Magellanic Clouds which showed Li-rich stars confined to a range $M_{bol} \simeq -6$ to -7 (Smith and Lambert 1989, 1990).

A key ingredient in these calculations is the inclusion of some time-dependent mixing algorithm. Boothroyd and Sackmann (and earlier authors) have used the diffusion equation to calculate the

[3] $\log\epsilon(\mathrm{E}) = \log_{10}(n(\mathrm{E})/n(\mathrm{H}))+12$ where $n(\mathrm{E})$ is the number abundance of element E and $n(\mathrm{H})$ is the number abundance of hydrogen.

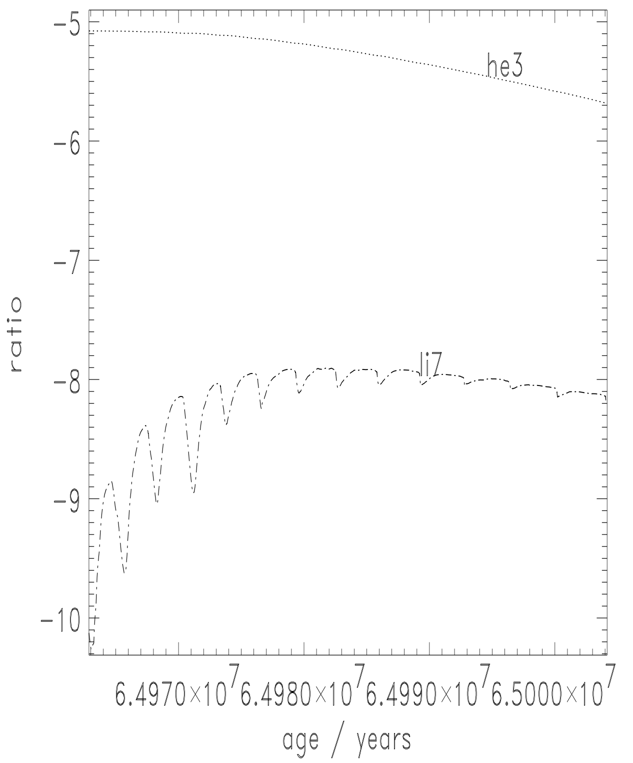

Figure 8: Surface ^{7}Li and ^{3}He abundances in the $6M_\odot$ model discussed in the text.

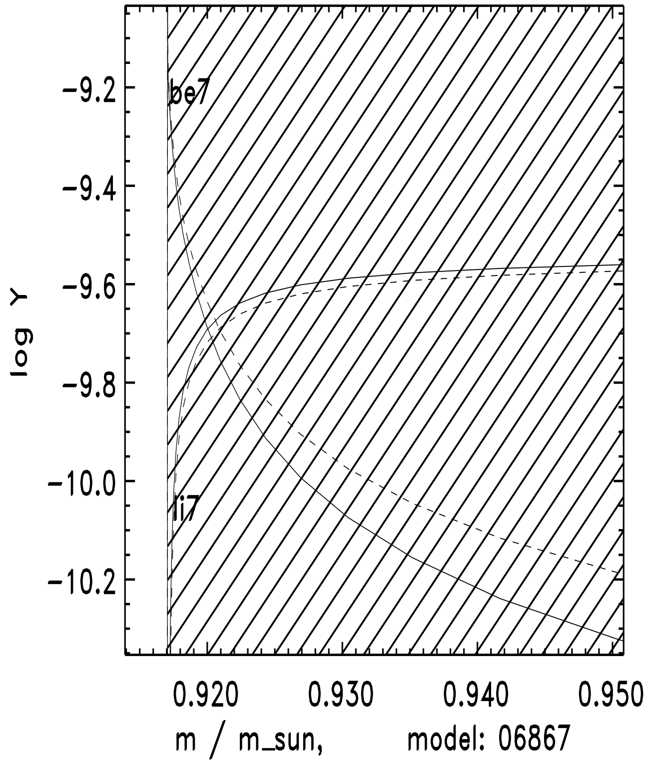

Figure 9: ^{7}Be and ^{7}Li abundances in the envelope of the $6M_\odot$ model discussed in the text. The hatched region denotes convection.

distribution of ^{7}Be and ^{7}Li in the convective regions. (They also quite nicely illustrated that the instantaneous mixing assumption is incorrect for these species, and results in a decrease of ^{7}Li rather than an increase.) In the calculations of Cannon *et al.* (1995) a slightly different algorithm was used, which allows for different compositions in the upward and downward moving streams, and some horizontal diffusion at a given level. This reduces to the diffusion approximation in the case of infinitely quick horizontal diffusion between the two streams, but it does allow us to calculate the different compositions in the upward stream, which has just been exposed to high temperatures, and the downward stream, which has been through the entire envelope and is now returning to the high temperature regions. The effect of this can be seen in Figure 9, where the same algorithm as Cannon *et al.* is applied to the $6M_\odot$ model with $Z = 0.02$. The dashed lines represent the upward moving stream, which is richer in ^{7}Be (having been produced at the bottom of the envelope) and poorer in ^{7}Li (which has just been destroyed at the bottom of the envelope by the conclusion of the PPII chain). The solid line shows the downward stream, which is richer in ^{7}Li and poorer in ^{7}Be (due to the decay of the ^{7}Be into ^{7}Li in the outer, cooler parts of the envelope).

5.3 Preventing Carbon Star Formation

The original motivation for HBB by Wood *et al.* (1983) was that it may process sufficient ^{12}C for the formation of a Carbon star to be avoided, despite the expected large amounts of ^{12}C dredged to the surface. This was quantitatively shown to occur by Boothroyd, *et al.* (1993). They found that HBB begun at $M \simeq 5M_\odot$ for $Z = 0.001$. Models of $4M_\odot$ became Carbon stars quite easily, but $5M_\odot$ models of this composition *just* failed to become Carbon stars due to the CN cycling at the bottom of the envelope. This is able to destroy all the ^{12}C added by each pulse. In fact, the envelope quickly reaches the equilibrium value of $^{12}C/^{13}C \simeq 3$. That is, the entire envelope is processed through the bottom of the envelope sufficiently often during the interpulse phase that equilibrium abundances of ^{12}C and ^{13}C result. There is also, of course, some processing into ^{14}N, but the key result is that HBB prevents the formation of Carbon stars for relatively massive AGB stars.

The composition dependence of their results is very interesting. For $Z = 0.001$ there is negligible CN cycling by HBB at $4M_\odot$, which indeed becomes a Carbon star. However HBB in the $5M_\odot$ model prevents it from becoming a Carbon star. At $6M_\odot$ the HBB is so efficient that from the first pulse the C/O ratio declines, and N/O rises dramatically, even exceeding unity. The behaviour at $Z = 0.02$ is similar. There is minimal dredge-up seen at $4M_\odot$, reflecting the well-known phenomenon that dredge-up is more easily obtained at lower metallicities. And where there is dredge-up, the increase in C/O is slower due to the higher ^{16}O abundance initially present. HBB begins at about $5M_\odot$ again, but it mainly affects the $^{12}C/^{13}C$ abundance, with a negligible change in the C/O ratio. In fact, the $^{12}C/^{13}C$ does not even reach equilibrium before mass-loss has removed the entire envelope. The $5M_\odot$ model shows very substantial HBB, as did the same mass at $Z = 0.001$. Similar results are found for the $6M_\odot$ case discussed in this paper, and the ratios of these surface abundances are shown in Figure 10.

Before leaving this subject, we mention briefly some problems associated with synthetic evolutionary calculations. In these, one parametrises the results of detailed evolutionary calculations (*e.g.* Iben 1981, Renzini and Voli 1981, Groenewegen and de Jong 1993, Marigo *et al.* 1995a,b) and then constructs stellar populations for comparison with observations. Such calculations have led some to conclude that M_c^{min}, the minimum core-mass for dredge-up of ^{12}C, is closer to $0.58M_\odot$ than the values of $\sim 0.65M_\odot$ obtained in detailed evolutionary calculations. Also, they conclude that the dredge-up parameter, $\lambda = \Delta M_{dredge}/\Delta M_H$ (see Figure 3b), is closer to 0.6 than the value of 0.3 returned by evolutionary calculations. We warn here against a literal interpretation of these results: both λ and M_c^{min} are functions of composition, mass, and mass-loss history (and mass-loss is not properly understood at present). However, there is another problem associated with the input for these models. At present we do not know when HBB ceases, or when dredge-up ceases. Both of these require a reasonably massive envelope mass, but with almost any combination of core-mass and envelope mass possible, due to differing mass loss formulae, it is almost impossible to determine when these effects cease. The predictive power of these models is weakened by their dependence on which assumptions are made here.

5.4 Core-Mass Luminosity Relation

Finally, another consequence of HBB is that it results in departure from the well established core-mass—luminosity relation, which was discovered by Paczynski (1970a,b), and relates the maximum pre-flash surface luminosity to the mass of the H-exhausted core. Although the original relation as quoted by Paczynski was independent of composition, numerous authors have refined his calculations and now the most accurate relations include the effects of composition. It is the utility of this equation which stands at the base of all the synthetic calculations, discussed above.

However, Blöcker and Schönberner (1991) showed that once HBB begins the stars no longer obey this relation. They followed a different relation with a gradient at least a factor of 10 steeper. This were confirmed by Boothroyd and Sackmann (1992) and Lattanzio (1992). Blöcker and Schönberner found that the reason for departure from the erstwhile relation was that a very deep convective envelope does not allow for a radiative zone which decouples the envelope from the H-shell. There are two obvious consequences of this discovery. Firstly, new synthetic evolutionary calculations will have to include this effect. Although the duration may be short-lived, it can generate very high luminosities, and since mass-loss[4] is tied to the luminosity, the mass loss increases also. Of course, as the envelope mass decreases, the HBB will eventually cease, and the model will then return to

[4]We do not discuss the thorny issue of mass-loss in this paper. For a discussion particularly relevant to AGB stars see Blöcker (1995).

the normal core-mass—luminosity relation. The second important consequence is that the previously assumed maximum luminosity on the AGB will be incorrect. It was assumed that once the core-mass reached the Chandrasekhar limit, then the core would collapse and the star would leave the AGB as a supernova. So inserting this core-mass into the core-mass—luminosity relation yields a maximum luminosity for stars on the AGB. This is no longer correct, which means that observational surveys may have *missed* the brightest AGB stars !

We defer the discussion of HBB and oxygen ratios to Section 6.2.

6 Constraints on Nucleosynthesis from Meteorite Grains

In recent years we have seen the advent of a new source of information about the composition of stellar material. This has been provided by measurements of isotopic and elemental abundances in individual grains found in meteorites. A significant advantage of these measurements is that they can provide information about many elements for each grain, and since each grain has condensed in the outflow from a single star, we obtain much compositional information from a *single* stellar source. A further advantage is that abundances can be found for species which are simply not visible in spectra. The disadvantage[5] is that we do not know *a priori* which kind of star produced which grain. Although a young field (the first grain isolation occurred in 1987 ! see Lewis *et al.* 1987) there is far too much literature to be reviewed here. We will just try to give a flavour for the kinds of constraints which the measurements place on the models, and then discuss some of the recent models which attempt to address the problems. Further information is found in Anders and Zinner (1993), Ott (1993) and the many papers in Section V of the 1994 *Nuclei in the Cosmos III* meeting, edited by Busso, Gallino and Raiteri.

The grains of interest to us come from carbonaceous chondrites, and are called "exotic" by meteoriticists, because of their isotopic anomalies compared to the solar system abundance distribution. These are the silicon carbide (SiC) grains and the oxide grains, especially corundum (Al_2O_3). The other main category, the graphite grains, are probably formed mainly in very massive stars, as discussed by Travaglio and Gallino (1995). Hence we do not discuss them here.

6.1 SiC Grains: Carbon and Nitrogen abundances

Because the SiC grains must form in a carbon-rich environment it is believed that these grains originated in the envelopes of Carbon stars. Further evidence comes from the distribution of $^{12}C/^{13}C$ ratios in the grains, which is similar to that seen in Carbon stars, and the fact that SiC is observed in the spectra of the dusty envelopes of many Carbon stars.

Basically, the abundances of the carbon and nitrogen isotopes in these grains agree quite well with predictions from stellar models. Nevertheless, there are some grains showing $^{12}C/^{13}C$ ratios less than the value expected from first dredge-up (~ 20), even going as low as 2 or 3, appropriate to CN equilibrium. Yet these grains do not show $^{14}N/^{15}N$ ratios expected from CN burning: they show ratios which are up to a factor of ten lower than expected from first dredge-up (*e.g.* El Eid 1994), and if CN cycling is to reduce the $^{12}C/^{13}C$ ratios to the equilibrium values, then these grains should be even richer in ^{14}N. We have seen that HBB can produce $^{12}C/^{13}C$ ratios appropriate to equilibrium CN cycling, but these models fail to account for the low $^{14}N/^{15}N$ ratios (*e.g.* Sackmann and Boothroyd 1992, Boothroyd *et al.* 1994). Further, HBB is expected to prevent the formation of Carbon stars by cycling the ^{12}C into ^{13}C and ^{14}N, so how could SiC grains form in this environment? Is it possible that the J-stars could be the sources of these SiC grains with low $^{12}C/^{13}C$ ratios? And the $^{28,29,30}Si$ isotopes themselves are not seen in the ratios expected for neutron captures in the intershell zone of thermally pulsing AGB stars, and seem to indicate a spread of Si abundances in the initial composition. Much more quantitative work needs to be done on stellar models to explain all the data from these grains.

[5] There is always a disadvantage...

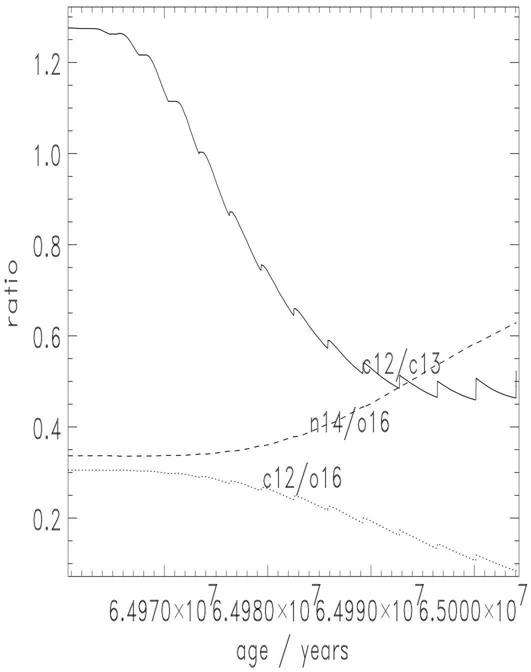

Figure 10: Variation of surface ratios in the envelope of the $6M_{\odot}$ model discussed in the text. Note that the curve labelled c12/c13 is actually $\log(^{12}C/^{13}C)$.

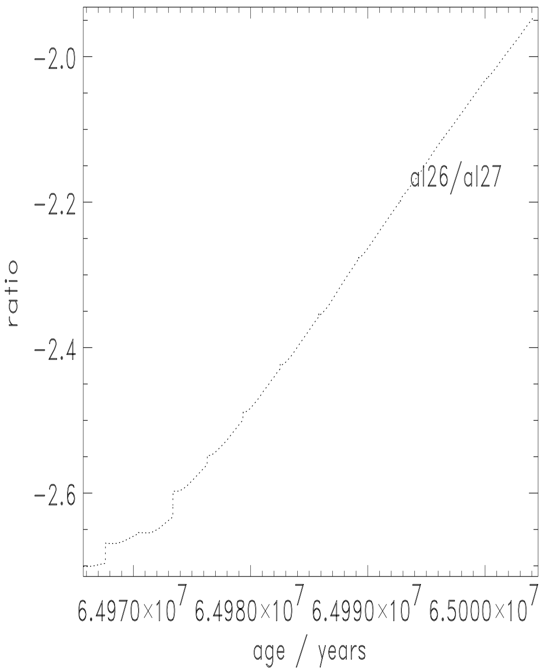

Figure 11: The increase of $\log(^{26}Al/^{27}Al)$ during the thermally pulsing evolution of the $6M_{\odot}$ model discussed in the text.

6.2 Corundum Grains: Oxygen and Aluminium abundances

The most studied of the various oxide grain is corundum, Al_2O_3. The interest in these is due to their oxygen and aluminium isotopic ratios, which show evidence of the three dredge-up episodes, together with HBB.

Nittler *et al.* (1994, 1995) divide these grains into 4 groups, according to their oxygen isotopic ratios. The largest is Group 1, which shows $^{18}O/^{16}O$ and $^{17}O/^{16}O$ ratios that are consistent with the first and second dredge-up: namely that $^{18}O/^{16}O$ is reduced by a modest amount (less than a factor of two), while the $^{17}O/^{16}O$ ratio increases by a factor of up to twenty, compared to the initial values of $^{18}O/^{16}O \simeq 0.002$ and $^{17}O/^{16}O \simeq 0.00038$. It appears that a satisfactory explanation of all these grains requires us to consider stars of varying initial masses and a spread in the initial oxygen isotopic ratios, as discussed by Boothroyd *et al.* (1994).

The effect of HBB has been calculated by Boothroyd *et al.* (1995). Initially there is a rapid destruction of the ^{18}O in the envelope, with a slower increase in the ^{17}O as the temperature at the base of the convective envelope increases with the subsequent pulses. This would appear to explain many of the Group 2 grains, which have much lower $^{18}O/^{16}O$ ratios, and which simply cannot result from the first or second dredge-up episodes. Nevertheless, there are some Group 2 grains that could only be explained by HBB if the lowest mass for HBB is substantially lower than is found in detailed models. For these, Boothroyd *et al.* (1995) suggested that some deep mixing could be the explanation, a phenomenon they called "cool bottom burning", and which is discussed below. The Group 3 grains are a separate problem, showing $^{17}O/^{16}O$ less than solar. No satisfactory stellar site has been found for these grains yet, and they are likely not from AGB stars. The newly identified (Nittler *et al.* 1995) Group 4 grains show enhancements of both ^{18}O and ^{17}O. These could be due to AGB stars, as early thermal pulses can produce large amounts of ^{18}O, and if the stellar mass is less than about $5M_{\odot}$, there is no HBB to destroy it. But the origin of these grains is still unclear at present.

Corundum grains can be used for extracting information about heavier species as well. For example, many of the oxide grains of Nittler *et al.* (1995) have been analysed for Al-Mg and show excesses of ^{26}Mg but have normal ^{25}Mg/^{24}Mg. This indicates that live ^{26}Al has decayed *in situ* to produce the ^{26}Mg. The inferred initial ^{26}Al/^{27}Al ratios are as large as 0.016. In Figure 11 we show the variation in this ratio for our $6M_\odot$ model discussed earlier. The second dredge-up raises the ratio from essentially zero to $\sim 10^{-3}$, and once HBB begins the ratio climbs steadily, with no sign of levelling off when the calculations were terminated. It still shows normal ratios of ^{24}Mg/^{25}Mg, as required. We should note that the largest values for ^{26}Al/^{27}Al which can be obtained by dredging-up the products of the Mg-Al cycle from the H-shell are $\sim 2 \times 10^{-3}$ (Forestini *et al.* 1991). It appears that the $6M_\odot$ model presented here would give rise to extreme Group 2 grains, with the current values of ^{16}O/^{18}O $\sim 10^6$ and ^{16}O/^{17}O $\simeq 100$. Note that these values agree well with the $5M_\odot$ models of Guélin *et al.* (1995), as well as their observations of IRC+10216.

There is also a wealth of data available for other species, such as Ti, Xe, etc (see, for example, Gallino *et al.* 1994) but this will not be addressed here, except to remind us that we ignore this new source of highly accurate and wonderful data at our peril.

6.3 Cool Bottom Burning

We mentioned above that some of the Group 2 corundum grains seem to imply that HBB occurs in masses which are too small to be consistent with the extant models. A possible solution to this was proposed by Boothroyd *et al.* (1995) and followed up by Wasserburg *et al.* (1995). In this model there is some extra mixing from the bottom of the convective envelope down toward the H-shell. This is called "Cool Bottom Burning", and seems to produce the low values of ^{18}O/^{16}O required by the grains (and also many observations of Carbon stars, which also show similar isotopic ratios). Wasserburg *et al.* (1995) showed that the isotopic ratios depend critically on the temperature (of course!) to which the material is mixed, but there was very little dependence on the rate of mixing. For best results the mixing reaches down to $\Delta \log T \simeq 0.17$ from the base of the H-shell on the AGB.

Note that Charbonnel (1994) has suggested a similar mechanism to explain the anomalously low ^{12}C/^{13}C ratios for low mass stars, when compared to the predictions from first dredge-up calculations. Wasserburg *et al.* (1995) found that an identical mixing on the first giant branch, with the same $\Delta \log T$, produced ^{12}C/^{13}C ratios in the required range. Further studies are needed.

7 The Future: What Should Be Done ?

So, after that lengthy introduction, we come to the main topic of this review! We will break this into two subsections.

7.1 Evolution

There remain many uncertainties in modeling of AGB stars. First and foremost is the lack of a good theory of convection (still). For AGB stars the thing which we most need is an accurate way to determine the boundaries of the various convective zones, and any associated overshoot. Note that changes in the assumptions one uses to treat convection can make large differences in the amount of dredge-up obtained (Frost 1995). Various authors may use different ways of treating a discontinuity in ∇_{rad}/∇_{ad} at the edge of a convective zone. These may all be physically motivated, and phenomenologically reasonable, yet yield different results.

Sometimes during dredge-up we can obtain convergence problems. If one iterates on the physical variables until converged, and then mixes in the convective zone, one has a model which is internally inconsistent: the composition used for convergence is not that which resulted from the implied mixing. Alternatively, one could alternate iterations on the physical variables with mixing over the current convective zone. (This is what we do.) When this works, one has an internally consistent model.

Yet sometimes this procedure will not converge, and some other recourse must be taken and, to some extent, the amount of dredge-up obtained depends on how these problems are handled (see Frost 1995). Of course, there are various other schemes, such as mixing first and then iterating (Sweigart 1995). In short, these differences in treatment of details in the convection, as well as treatment of convective boundaries, can explain the differences in the size of the dredge-up parameter found by various authors.

Probably related to this is the expected (but rarely seen) semiconvective mixing of H down beyond the formal convective boundary during dredge-up. It is this which produces the (apparently) required ^{13}C pocket responsible for the neutrons that enable the *s*-processing to occur on the AGB. We need to know how this pocket is formed, and its size. All of this seems to require a greater knowledge of convection and mixing (again, especially at boundaries, and probably involving semiconvection) than we have at present.

Another convection problem is that we need to know how the dredge-up varies with mass, composition and mass-loss history. Yet, as outlined above, we cannot even agree on how to calculate it, let alone embark on a computing job of such magnitude (Renzini 1989).

7.2 Nucleosynthesis

With such a wealth of data now available, both from stars and meteorite grains, it has become clear that for quantitative comparisons we must use codes which contain many more nuclear species than are usually included in evolutionary calculations. It is now relatively common to see calculations now including 20 to 40 species, and our nucleosynthesis calculations reported in this paper for a $6M_\odot$ model use a network of 74 species and some 506 reactions. It seems that calculations of this size are now the minimum we need for comparison with the avalanche of data coming our way.

Of course, all calculations of nucleosynthesis are only as accurate as the rates used. Some of the most important rates for these calculations (*e.g.* the Ne-Na and Mg-Al cycles) are not very well known yet, as reviewed by Arnould (1995). These data are required urgently.

The consequences of the radiative burning of ^{13}C need to be investigated. How does this affect the *s*-processing? How will it affect other nucleosynthesis? Indeed, how does the ^{13}C pocket come into existence?

It also appears that we can no longer assume that all mixing occurs instantaneously. We have seen that this assumption must be removed to produce the Li-rich stars. A similar situation is likely to exist for some species in the intershell convective zone. Although this time-dependent mixing is likely to have little effect on the stellar structure (as most of the reactions involved are energetically negligible), it may well be crucial for accurate calculations of the nucleosynthesis. In lieu of a suitable theory of time-dependent convective mixing, we must use the diffusion equation (*e.g.* Boothroyd *et al.* 1995) or some variant (Cannon *et al.* 1995, Wasserburg *et al.* 1995).

Related to this is the postulated "cool bottom burning", where material burns while moving (slowly) through radiative zones. This should be investigated in two ways: firstly phenomenologically, to see if it can account for the observed abundances, and secondly from a purely physical view, so that the mechanism which drives the mixing can be understood!

8 Conclusion

We hope we have conveyed some of the excitement, and frustration, of AGB stellar modeling. We are on the verge of a new level of quantitative understanding, produced by accurate observations and meteoritic measurements, which have spurred the theorists to include more and more species and even try to calculate time-dependent mixing. Almost all of the areas we listed for future research are indeed being investigated by various workers at present, but the most serious problem remains that of determining convective boundaries under the complex conditions found in these stars. The extant hydrodynamical studies of convection (*e.g.* Nordlund 1995, Zahn 1995) cannot cover the dynamical range of densities required, nor match the other conditions (such as viscosities) seen in the stellar context. Sadly, we see no reason for optimism in this area in the near future.

But we cannot end on a sad note. We have made enormous strides in the last few years, and we now have a new source of information concerning abundances. The next few years should be exciting.

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References

Anders, E., and Zinner, E.: 1993, *Meteoritics*, **28**, 490.
Arnould, M.: 1995, this volume.
Blöcker, T.: 1995, *A. & A.*, in press.
Blöcker, T., and Schönberner, D.: 1991, *A. & A.*, **244**, L43.
Boothroyd, A. I. and Sackmann, I.-J.: 1992, *Ap. J. Lett.*, **393**, L21.
Boothroyd, A. I. *et al.*: 1993, *Ap. J.*, **416**, 762.
Boothroyd, A. I. *et al.*: 1994, *Ap. J. Lett.*, **430**, L77.
Boothroyd, A. I. *et al.*: 1995, *Ap. J. Lett.*, **442**, L21.
Cameron, A. G. W., and Fowler, W. A.: 1971, *Ap. J.*, **164**, 111.
Cannon, R. C., *et al.*: 1995, in *Nuclei in the Cosmos III*, Eds. M. Busso, R. Gallino, C .M. Raiteri, (AIP: New York), p. 469.
Castellani, V., *et al.*: 1971a, *Astr. Sp. Sci.*, **10**, 340.
Castellani, V., *et al.*: 1971b, *Astr. Sp. Sci.*, **10**, 355.
Charbonnel, C.: 1994, *A. & A.*, **282**, 811.
Clayton, D. D., and Leising, M.: 1987, *Phys. Rep.*, **144**, 1.
Deupree, R. G.: 1984, *Ap. J.*, **287**, 268.
El Eid, M.: 1994, *A. & A.*, **285**, 915.
Forestini, M., *et al.*: 1991, *A. & A.*, **252**, 597.
Forestini, M., *et al.*: 1992, *A. & A.*, **261**, 157.
Frost, C. A.: 1995, Monash University Internal Report.
Gallino, R., and Arlandini, C.: 1995, this volume.
Gallino, R., *et al.*: 1988, *Ap. J. Lett.*, **334**, L45.
Gallino, R., *et al.*: 1994, *Ap. J.* , **430** ,858 .
Groenewegen, M. A. T., and de Jong, T,: 1993, *A. & A.*, **267**, 410.
Guélin, M., *et al.*: 1995, preprint.
Iben, I., Jr.: 1975a, *Ap. J.*, **196**, 525.
Iben, I., Jr.: 1975b, *Ap. J.*, **196**, 549.
Iben, I., Jr.: 1981, *Ap. J.*, **246**, 278.
Iben, I., Jr.: 1982, *Ap. J.*, **260**, 821.
Iben, I., Jr.: 1991, in *Evolution of Stars: The Photospheric Abundance Connection*, p. 257.
Iben, I., Jr., and Renzini, A.: 1982a, *Ap. J.*, **259**, L79.
Iben, I., Jr., and Renzini, A.: 1982b, *Ap. J.*, **259**, L79.
Iben, I., Jr., and Renzini, A.: 1983, *A. R. A. & A.*, **21**, 271.
Jorissen, A, *et al.*: 1992, *A. & A.*, **261**, 164.
Lattanzio, J. C.: 1984, *MNRAS*, **207**, 309.

Lattanzio, J. C.: 1989, in *Evolution of Peculiar Red Giants*, Eds. H. R. Johnson and B. Zuckerman, CUP, p. 161.
Lattanzio, J. C.: 1992, *Proc. Astron. Soc. Aust.*, **10**, No. 2., 120.
Lauterborn, D., *et al.*: 1971, *A. & A.*, **10**, 97.
Lewis, R. S., *et al.*: 1987, *Nature*, **326**, 160.
Marigo, P., and Chiosi, C.: 1995a, this volume.
Marigo, P., and Chiosi, C.: 1995b, *A. & A.* , submitted.
Mowlavi, N., *et al.*: 1995, this volume.
Nittler, L. R., *et al.*: 1994, *Nature*, **370**, 443.
Nittler, L. R., *et al.*: 1995, this volume.
Nordlund, A.: 1995, this volume.
Ott, U: 1993, *Nature*, **364**, 25.
Paczyński, B.: 1970a, *Acta Astron.*, **20**, 47.
Paczyński, B.: 1970b, *Acta Astron.*, **20**, 287.
Prantzos, N.: 1995, in *Nuclei in the Cosmos III*, Eds. M. Busso, R. Gallino, C .M. Raiteri, (AIP: New York), p. 553.
Renzini, A.: 1989, in *Evolution of Peculiar Red Giants*, Eds. H. R. Johnson and B. Zuckerman, CUP, p 413ff.
Renzini, A., and Voli, M.: 1981, *A. & A.*, **94**, 175.
Sackmann, I.-J.: 1977, *Ap. J.*, **212**, 159.
Sackmann, I.-J.: 1980, *Ap. J. Lett.*, **241**, L37.
Sackmann, I.-J., and Boothroyd, A. I.: 1991, in *Evolution of Stars: The Photospheric Abundance Connection*, p. 275
Sackmann, I.-J., and Boothroyd, A. I.: 1992, *Ap. J. Lett.*, .
Sackmann, I.-J., *et al.*: 1974, *Ap. J.*, **187**, 555.
Scalo, J. M., *et al.*: 1975,*Ap. J.*, **196**, 809.
Schöenfelder, V., and Varendorff, M.: 1991, in *Gamma-Ray Line Astrophysics*, Eds. Ph. Durouchoux and N. Prantzos.
Schwarzschild, M., and Härm, R.: 1965,*Ap. J.*, **142**, 855.
Smith, V. V., and Lambert, D. L.: 1986, *Ap. J.* , **311**, 843.
Smith, V. V., and Lambert, D. L.: 1989, *Ap. J.*, **311**, 843.
Smith, V. V., and Lambert, D. L.: 1990, *Ap. J. Lett.*, **361**, L69.
Smith, V. V., *et al.*: 1987, *Ap. J.*, **320**, 862.
Straniero, *et al.*: 1995a, in *Nuclei in the Cosmos III*, Eds. M. Busso, R. Gallino, C .M. Raiteri, (AIP: New York), p. 407.
Straniero, O. *et al.*: 1995b, *Ap. J. Lett.*, **440**, L85.
Sugimoto, A., and Fujimoto, M. Y.: 1978, *Pub. Astron. Soc. Japan*, **30**, 467.
Sweigart, A. V.: 1995, personal communication.
Travaglio, C., and Gallino, R.: 1995, this volume.
Truran, J. W., and Iben, I., Jr.: 1977, *Ap. J.*, **216**, 797.
Wasserburg, G. J., *et al.*: 1995, *Ap. J. Lett.*, **447**, 37L.
Wood, P. R., *et al.*: 1983, *Ap. J.*, **272**, 99.
Zahn, J. P.: 1995, this volume.