# IV. PLANETARY NEBULAE CONNECTION: EVOLUTION FROM THE AGB

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# THE THIRD DREDGE-UP: STATUS AND PROBLEMS

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ABSTRACT. In this paper I review our understanding of the third dredge-up phenomenon and the nucleosynthesis which occurs during thermally-pulsing AGB evolution.

## 1. Introduction

Asymptotic Giant Branch (AGB) stars are among the most complex and most interesting of all stars. Yet this complexity makes understanding them very difficult because they exhibit the very phenomena which stellar physicists find the hardest to model, such as convection and mass loss. Still, much progress has been made in understanding these stars (Iben and Renzini 1983, Lattanzio 1989a). In this paper we are concerned primarily with their nucleosynthesis and the periodic "dredge-up", or penetration of the convective envelope into regions of nuclear processing. This results in mixing to the surface of the nuclear burning products. Note that dredge-up plays a crucial role, linking theory to observations, *i.e.* the interior to the photosphere. As such, one may expect that trying to determine characteristics of dredge-up would be restricted by errors and uncertainties in both theory and observations. This is indeed true, especially since the extent and occurrence of dredge-up itself is very sensitive to changes in modelling parameters etc. Yet we will see that much can still be done.

## 2. Anatomy of a Shell Flash

Figure 1 shows the four phases of a shell flash, or thermal pulse, as defined by Iben (1981a). Cross-hatched regions denote convection, and wavy lines indicate radiative energy transport. During the "on" phase the high ($\sim 10^8 L_\odot$) luminosity of the helium shell drives a convective zone, hereafter called the Inter-Shell Convective Zone (ISCZ), which consists of roughly 23% $^{12}$C and 75% $^4$He. In the "power-down" phase the ISCZ disappears as the He-shell decreases in its output. The legacy of the ISCZ is the enhanced $^{12}$C abundance in the region between the H and He shells. Finally, during the "dredge-up" phase, the inward advance of the convective envelope eventually penetrates the erstwhile ISCZ and mixes freshly produced $^{12}$C to the surface. The convection then recedes, and the cycle repeats every $\sim 10^4$ years or so (depending on the core mass), after a period of quiescent H burning.

Figure 2 shows two consecutive thermal pulses, and defines some parameters. The mass of material processed by the H shell between pulses is $\Delta M_H$, and the amount dredged to the surface is $\Delta M_{dredge}$. Two very important parameters are the mass of the hydrogen exhausted core, $M_H$, and the dredge-up parameter, $\lambda = \Delta M_{dredge}/\Delta M_H$. The results of many

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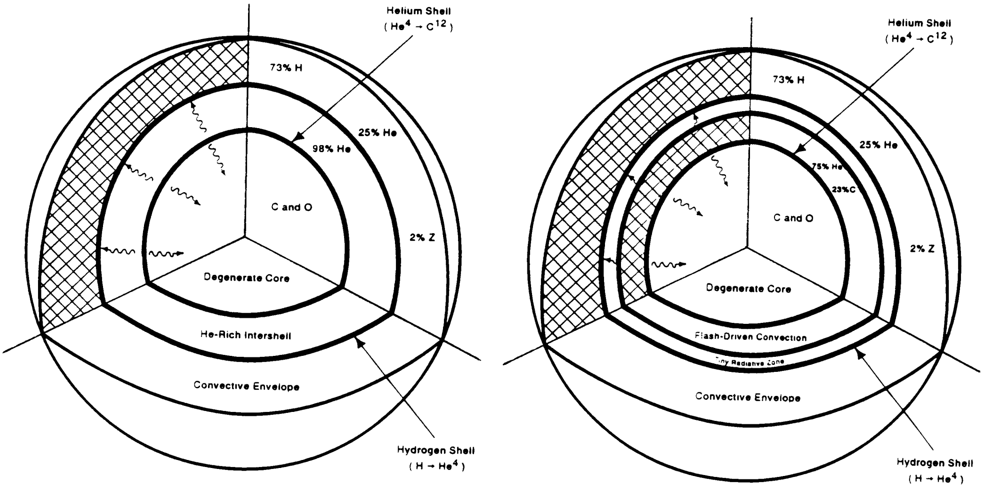
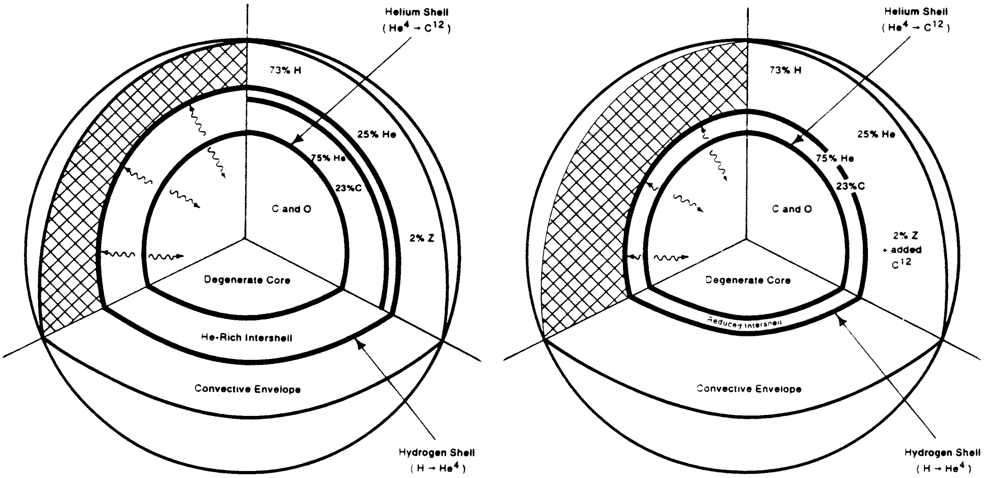


"Off" Phase

"On" Phase



"Power-Down" Phase

"Dredge-Up" Phase

Figure 1: The four phases of a thermal pulse.

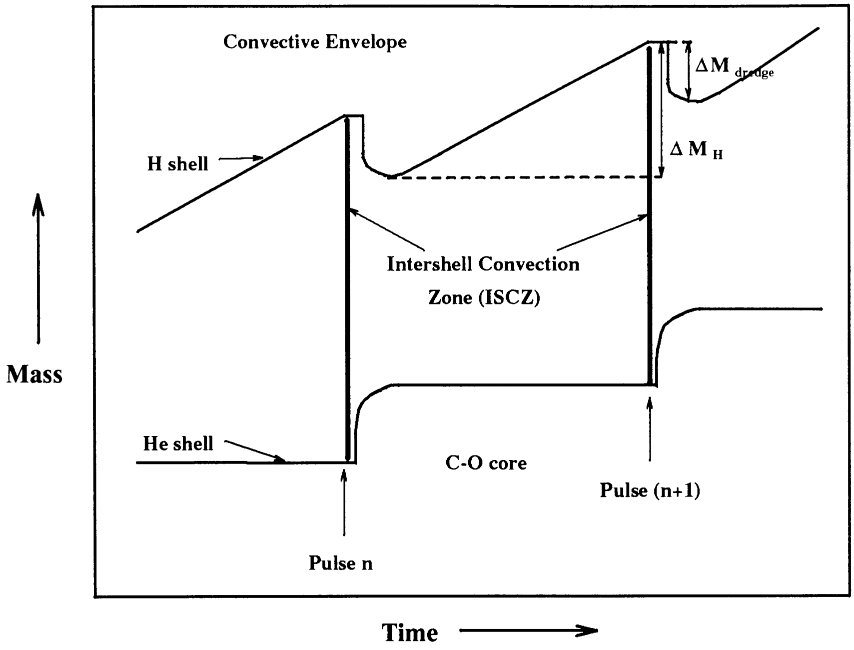


Figure 2. Schematic diagram showing the time evolution of important mass boundaries in two consecutive thermal pulses.

calculations (*e.g.* Wood 1981, Iben and Renzini 1983, Lattanzio 1986, 1989b, 1991) show that dredge-up becomes easier when $M_H$ increases, $M_e = M - M_H$ increases, $Z$ decreases, $Y$ decreases, or $\alpha = \ell / H_P$ = mixing-length parameter increases.

## 3. Making $^{12}$C in Shell Flashes

The simplest nucleosynthesis which occurs in thermally pulsing AGB stars is the production of $^{12}$C, which was outlined in the previous section. Unfortunately, a direct study of this phenomenon is very expensive in computer time. But results of those calculations which have been performed show that most of the AGB evolution can be parametrized in terms of the core-mass. For example, the peak quiescent luiminosity reached before a pulse isgiven by $L = aM_H + b$, where $a$ and $b$ are constants (see Paczynski 1971). Using such expressions we can simulate detailed evolutionary calculations for far more cases than are possible by direct methods. Such calculations are called "synthetic" evolutionary calculations, and were used by Iben (1981b) and Renzini and Voli (1981) to show that theory produces too many high luminosity C-stars and not enough of low luminosity (when compared to the observed luminosity functions in the Magellanic Clouds). The problem with these calculations was that in 1981 there were no models available for the range of 1–3 $M_\odot$, which is appropriate for most of the Cloud stars. Thus the parametrized evolutionary models were based on calculations then available ($M \leq M_\odot$ and $M \geq 3M_\odot$). Now the most important parameter is the core mass at the first thermal pulse, and this is a sensitive function of initial mass (and metallicity) in this mass range (see Lattanzio 1986, Boothroyd and Sackmann 1988d). This limits the quantitative accuracy of these early calculations.

With new detailed evolutionary calculations available in the appropriate mass range (Lattanzio 1986,1989b; Lattanzio and Malaney 1989; Boothroyd and Sackmann 1988a,b,c,d) the synthetic calculations were repeated by Bryan *et al.* (1990) with updated parametrizations. They were able to match the observed luminosity functions of AGB stars, as well as the O-rich to C-rich number ratio, by adopting a new mass loss formula. The dredge-up was taken as constant, with $\lambda \simeq 0.25$, and assumed to occur at each pulse, whereas the models experience quite a few pulses before dredge-up begins. Indeed, there is a minimum core mass for dredge-up, which depends on the total (initial) mass and the composition. Part of the agreement found by Bryan *et al.* between models of C stars and observations must, unfortunately, be due to this assumption, which is *not* consistent with the models. (Note that this only affects when stars become C-stars, and not the initial-final mass relation, etc., which is also discussed by Bryan *et al.* )

There are also three further refinements which should be included in synthetic models. The recent evolutionary calculations revealed some dependence on metallicity, which has so far been neglected. Also, as pointed out frequently by Iben, there is actually a sizeable variation in luminosity during the pulse cycle, with a significant fraction of the interpulse period spent at a luminosity which is lower than that given by the core-mass–luminosity relation. Finally, the variation of physical parameters with $M_H$ is much more rapid during the first "few" pulses ($\sim 10$) than it is in the later, so-called "full amplitude" pulses. All of these effects will alter the predicted AGB star luminosity distributions if included in the synthetic calculations. Indeed, at this meeting, a poster was presented by Groenewegen and de Jong which included these effects (see elsewhere in this volume).

The calculations of Groenewegen and de Jong (1992) assumed $\lambda$ = constant, and that dredge-up begins when $M_H$ exceeds $M_H^{min}$. Using values for these parameters from recent calculations they are unable to match the observed C-star luminosity functions in the Large Magellanic Cloud (LMC) or the Galaxy. A good fit is found for $\lambda = 3/4$ and $M_H^{min} = 0.58M_\odot$, in contrast to the theoretically determined values of $\lambda \simeq 1/3$ and $M_H^{min} = 0.62$–$0.63M_\odot$ (Lattanzio 1989b, Lattanzio and Malaney 1989). So we are forced to a conclusion very similar to that of Iben (1981b): dredge-up occurs at smaller core masses than indicated by models, and at higher (average) efficiency (at least at these small core masses: note that Vassiliadis and Wood (1992, at this meeting) find $\lambda$ approaching the maximum possible value of unity in their calculations of a $5M_\odot$ model). In this context it remains to be seen what will be the effects of the recent OPAL opacities (Rogers and Iglesias 1992) on dredge-up calculations. Likewise, the dredge-up parameter is actually an unknown (!) function of total mass, core mass, envelope mass as well as composition. The determination of this dependence is a laborious task, but one which we need to complete.

Finally a small warning. As pointed out by Bryan *et al.* (1990), the mass loss formula used in synthetic calculations has a significant effect on the results, through the termination of AGB evolution. This is another uncertainty in all the synthetic models calculated so far.

## 4. Making *s*-Process Elements in Shell Flashes

The unambiguous observational evidence for a correlation between C/O and mean abundances of *s*-process elements in AGB stars (*e.g.* Smith and Lambert 1990a) is direct evidence for the association of *s*-process enhancements with shell-flashes and dredge-up, since these are clearly responsible for the increase in C/O. There are two suspected neutron sources for this *s*-processing: $^{22}$Ne($\alpha$,n)$^{25}$Mg and $^{13}$C ($\alpha$,n)$^{16}$O. We will deal with these separately below.

### 4.1 $^{22}$NE AS THE NEUTRON SOURCE

4.1.1 *Getting the $^{22}$Ne.* During H shell burning the CN(O) cycle converts virtually all of the $^{12}$C and $^{16}$O present into $^{14}$N. Later, during He burning, we find the sequence of alpha captures $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+}\nu)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$ converts all $^{14}$N to $^{22}$Ne.

4.1.2 *Getting the neutrons.* At the next thermal pulse the hot He burning can process the $^{14}$N (from H burning) into $^{22}$Ne, and if the temperature at the base of the ISCZ exceeds about $300\times10^{6}$K then we get $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ releasing neutrons.

4.1.3 *Problems.* The high temperature required for this reaction limits its applicability to stars of large core masses ($M_H \gtrsim 0.9M_{\odot}$) and (hence) total masses ($M \gtrsim 7M_{\odot}$). But the majority of LMC (and Galactic) stars are thought to have masses in the range of 1–3 $M_{\odot}$, based on many different lines of reasoning (e.g. kinematics, spatial distibution, pulsation). Also, no enhancements of $^{25}\mathrm{Mg}/^{24}\mathrm{Mg}$ have been observed (Lambert 1989, 1991) which would be expected if $^{22}$Ne were the neutron source in these stars (but see §6 below).

### 4.2 $^{13}$C AS THE NEUTRON SOURCE

4.2.1 *Getting the $^{13}$C.* Sackmann (1980) suggested that the large expansion following a strong pulse could propel the erstwhile ISCZ, rich in $^{12}$C, to temperatures low enough for recombination to begin. This, she suggested, could be an important source of extra opacity in the models. Calculations by Iben and Renzini (1982a,b) found that this extra opacity led to the formation of a semiconvective zone at the base of the convective envelope during what would be the dredge-up phase. The main effect of this semiconvection is to mix a small quantity of H downward into the C-enriched regions. When the H shell is re-ignited these protons are then captured by the $^{12}$C to form $^{13}$C. (An important feature of this mechanism is that there is not enough H to continue the CN cycle through to the formation of $^{14}$N.)

4.2.2 *Getting the neutrons.* During the next thermal pulse the ISCZ engulfs the layer of $^{13}$C, mixing it with He, and initiating $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$. This reaction is quite efficient, requiring temperatures no higher than $\sim 150\times10^{6}$K, which are easily found in the ISCZ of models of low mass stars.

4.2.3 *Problems.* The largest uncertainties in the above scenario are the details of the semiconvection. Different authors find different amounts (*e.g.* Boothroyd and Sackmann 1988d, Hollowell 1988, Hollowell and Iben 1989) or none at all (Lattanzio 1991). This is possibly due to the use of different opacities (and interpolation schemes *etc.* ). Also, it seems that this mechanism only works for low $Z$ and small envelope masses (Iben and Renzini 1984). This may be a problem, since $s$-process enhancements are clearly seen in stars of solar composition.

4.2.4 *A Further Complication.* Bazan and Lattanzio (1992) have drawn attention to the fact that all extant evolutionary calculations have ignored the energy released by the $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ reactions, as well as the associated $s$-processing. By including this, in an approximate manner, they found some significant changes in the evolution. Firstly, the peak neutron density achieved in the ISCZ increases, but seems to be limited by the fact that the base of the ISCZ moves outward in mass, which decreases the maximum temperature in the convective zone. Without this, the peak neutron density could create problems for certain $s$-elements. But a further effect of this change in the shape of the convective boundary is the near quenching of the ISCZ ! This raises the possibility of mini-pulses of convection within a single thermal pulse. This could have profound effects on the nucleosynthesis, and will be discussed further in §7.5

## 5. Making $^{19}$F in Shell Flashes

Recent observations by Jorissen *et al.* (1992) have shown that F/O correlates with C/O in AGB stars. Again, as was the case with *s*-process elements, this implicates thermal pulses and dredge-up in the production of $^{19}$F. Forestini *et al.* (1992) investigated many possible reaction chains and sites for the $^{19}$F production, and concluded that the most likely is $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+}\nu)^{18}\mathrm{O}(\mathrm{p},\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ occurring in the He shell. The catch here is that protons are needed for the p-captures on $^{18}$O. Possible sources of protons are $^{14}$N(n,p)$^{14}$C or $^{26}$Al(n,p)$^{26}$Mg, both of which require neutrons. And the neutron source ? It "must" be $^{13}$C again. The CN cycle does not seem to produce enough $^{13}$C for this purpose, so again we are forced to conclude that some extra $^{13}$C is present (see §4). But the problem here is getting enough $^{19}$F without over-producing $^{18}$O. The models seem to require more $^{13}$C than the semiconvective scheme, discussed earlier, is capable of producing (by about a factor of 5). In any case, this requires much more H be mixed down to produce the $^{13}$C, but without producing $^{14}$N (which is the next step in the CN cycle when there is abundant H). There are clearly quantitative problems with explaining the observed $^{19}$F abudances, but the possibility of using this to determine the distribution of $^{13}$C is exciting.

## 6. Hot Bottom Burning

A final complication is hot bottom burning, where the base of the convective envelope is hot enough for nucleosynthesis to occur. This has been invoked to explain the lack of high luminosity C-stars by assuming that the $^{12}$C dredged to the surface is then cycled to $^{14}$N by CN reactions at the base of the envelope. Hot bottom burning has been suggested as the mechanism resposible for the production of Li in the Li-rich LMC AGB stars discovered by Smith and Lambert (1989, 1990b), which are indeed bright AGB stars which are O-rich rather than C-rich. Recent calculations by Sackmann and Boothroyd (1992) showed that these stars can indeed be explained by this mechanism. Note that temperatures of 50–100 $\times 10^{6}$K are often found (Blocker and Schonberner 1991, Forestini *et al.* 1992, Lattanzio 1992). This is hot enough for $^{25}$Mg(p,$\gamma$)$^{26}$Al, with two important consequences. Firstly, it would destroy any $^{25}$Mg produced by the $^{22}$Ne neutron source (see §4.1), and secondly this could be the source of $^{26}$Al enhancements seen in SiC grains (see the recent meeting "Nuclei in the Cosmos", held in Karlsruhe 1992).

In a broader context, however, hot bottom burning must be seen as an unfortunate occurrence. It is already difficult using interior models, linked by dredge-up, to predict the composition of AGB star photospheres. To this we must now add the possibility of nuclear processing of the envelope, which consists of the initial envelope, and the products of earlier nuclear burning in the interior. A very complicated problem in nucleosynthesis and mixing.

## 7. Summary

Just as parametrized models of $^{12}$C production can be used to determine the dredge-up parameter, a *simultaneous* fit of $^{12}$C, *s*-process elements and $^{19}$F production would be a powerful constraint on dredge-up. Unfortunately we are nowhere near advanced enough in our understanding of the $s$-processing or $^{19}$F production to make such calculations possible. Instead, we must look at each separately.

### 7.1 $^{12}$C PRODUCTION

We are getting closer to reality, but we still need more efficient dredge-up, beginning at lower core masses.

### 7.2 $s$-ELEMENT PRODUCTION

It seems that $^{22}$Ne can be the neutron source only in massive stars. Lower masses ($M \lesssim 7M_\odot$) require the $^{13}$C source, which has many quantitative problems. Specifically, it is yet to be found to operate in stars near solar metallicity, or with significant envelope masses.

### 7.3 $^{19}$F PRODUCTION

Clearly this is associated with dredge-up and shell flashes. Can we use this to determine the distribution and amount of $^{13}$C present ? How can we avoid over-producing $^{18}$O ? Are the $^{18}$O rich planetary nebulae also rich in $^{19}$F ?

### 7.4 HOT BOTTOM BURNING

We need models of hot bottom burning if we are to understand how the observed photospheric composition is related to the composition of the dredged-up material.

### 7.5 FANTASY ?

I discussed earlier the exploratory calculations of Bazan and Lattanzio (1992) which showed that previously ignored energy sources associated with $^{13}$C ingestion and $s$-processing could lead to changes inthe evolution of the boundaries of the ISCZ. Although sensitive to the details of the $^{13}$C ingestion, the possibility arose of mini pulses of convection within a single thermal pulse. It seems that the shape of the ISCZ may be critically dependent on the uncertain distribution of $^{13}$C in the model. It is possible to imagine a distribution which could cause the ISCZ to split into two regions, an outer one which produces the $^{19}$F, and an inner zone for the $s$-processing. By separating the sites of this nucleosynthesis, it may be possible to satisfy the observational constraints on the neutron density and the $^{18}$O abundance. Perhaps some overlap is required between these zones, say at the start (or finish ?) of a thermal pulse. It is also quite possible that some details of convection, not reproduced by the mixing-length theory, may be required to solve all of the above problems.

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