Nucleosynthesis in Intermediate-Mass Asymptotic Giant Branch Stars

JOHN C LATTANZIO$^{1,2}$

$^1$ Department of Mathematics and Statistics, Monash University, Clayton, 3168, Victoria, Australia
$^2$ Institute of Astronomy, Madingley Rd, Cambridge, CB3 0HA, England

Abstract. We summarise the main properties of Asymptotic Giant Branch stars, including their structure, evolution and nucleosynthesis. The main physical mechanisms are outlined, as are the uncertainties. In keeping with the multi-disciplinary nature of this meeting, this paper is designed for those who are not experts in stellar structure.

1 What Is An AGB Star?

Most stars will pass through the Asymptotic Giant Branch (AGB) phase. Although only a brief phase compared to the overall stellar lifetime, these stars experience substantial nucleosynthesis during this phase. Further, they find ways of mixing the results of this synthesis to the surface, where stellar winds expel the material into the interstellar medium.

The AGB phase is the last phase of evolution for low and intermediate mass stars (about 1–8$M_\odot$). The evolution leading up to this phase has been discussed in detail in [16] and [15]. Briefly, stars begin by burning hydrogen in their cores, on the main sequence. Following the exhaustion of their central hydrogen supply, they become red-giants. During this phase the stars develop a deep convective envelope which extends inwards and can reach into regions where partial hydrogen burning has taken place. This is called the “first dredge-up” event, and it results in polluting the stellar surface with the products of hydrogen burning.

The ascent of the giant branch is terminated by ignition of the central helium supply, either degenerately in a core flash (in the case of low mass stars, below about 2.5$M_\odot$) or non-degenerately (for higher masses). The subsequent evolution is characterized by helium burning in a convective core and a steadily advancing hydrogen burning shell. For low mass stars the evolution is complicated by semiconvection, but this a detail we do not need for our present purposes. The fusion of helium produces $^{12}$C, and this carbon is in turn subject to alpha capture to form $^{16}$O. Eventually the helium supply is totally consumed, leaving a core of carbon and oxygen (the exact proportions of which depend on the infamously uncertain rate for the $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction. In any event, following the exhaustion of central helium the star begins to ascend the giant branch again. It is now called the “second” or “asymptotic” giant branch, because of the way the evolutionary tracks seem to approach the (first) giant branch asymptotically (for some masses, at least).

So when a star reaches the AGB it has the structure shown in Figure 1. If its mass is above about 4$M_\odot$ the shifting of helium burning from the core to a shell causes the extinguishing of the hydrogen shell. In lower mass stars this nuclear burning stops the inward advance of the convective envelope, but in more massive stars the envelope penetrates the erstwhile hydrogen shell, and the products of hydrogen burning are
Figure 1: Schematic structure of an AGB star.

again mixed to the stellar surface, in what is known as the “second dredge-up” episode. Note that low mass stars do not experience the second dredge-up.

2 Why Care About AGB Stars?

The importance of AGB stars lies in the nucleosynthesis which occurs during their evolution along the AGB. During this phase they show an electron degenerate carbon-oxygen core, and two nuclear shells: one burning helium and one burning hydrogen. The subsequent nucleosynthesis comes from two sources: the thermal instability of the helium shell (known as “thermal pulses” or “shell flashes”) and nuclear burning at the bottom of the convective envelope (known as “hot bottom burning”).

For most of the evolution on the AGB, the helium shell is largely inactive. But periodically the shell suffers a thermal runaway and generates enormous quantities of energy, at rates up to \(10^8L_\odot\) or so, for short periods of time (of order a year). This energy release results in a “flash-driven convection zone” which extends from the helium shell almost to the hydrogen shell, as shown in Figure 1. This mixes the \(^{12}\text{C}\) produced by the helium shell throughout this convective region. As the helium flash dies down, the energy deposited in the star causes a substantial expansion and cooling. The hydrogen shell is extinguished and the convective envelope reaches in beyond its old location, and (for later pulses) into the carbon-rich region left behind by the flash convection. This mixes carbon to the surface of the star, and is known as the “third dredge-up”. As the star now contracts again, the hydrogen shell is re-ignited and the star begins an extended “interpulse” phase (of order \(10^4\) years) during
which the hydrogen shell provides essentially all of the star’s luminosity. Eventually there is another flash, and the cycle repeats.

For stars above about 4\(M_\odot\) a second important phenomenon is the occurrence of hot bottom burning. Here the convective envelope is so deep that it penetrates into the top of the hydrogen burning shell, so that nucleosynthesis actually occurs in the envelope of the star. Temperatures can reach as high as almost \(10^8\)K. We will deal with the consequences of these phenomena below.

3 Nucleosynthesis on the AGB

3.1 Thermal Pulses

Thermal pulses, and their associated dredge-up, were the first known site for nucleosynthesis in AGB stars (see, for example, \(\underline{[2]}\), \(\underline{[3]}\)). In describing how thermal pulses work (above) we saw how (primary) \(^{12}\)C is produced and mixed to the surface. This is responsible for changing the star from a normal, oxygen-rich composition, to one which is carbon-rich (i.e. the number ratio C/O \(> 1\)) and is known as a Carbon star (spectral type N; the R and J stars probably form by a different mechanism). But carbon production is not the end of the story.

Arguably the most important synthesis to occur in AGB stars is the production of \(s\)-process elements (see \(\underline{[9]}\) for a more complete summary). This is outlined in Figure 2. Basically, we believe that somehow there is contact made between the hydrogen-rich envelope and the carbon-rich intershell zone. The mixing in this region is partial, leaving behind a varying composition profile. Then, as the star contracts, proton captures on \(^{12}\)C produce \(^{13}\)C. During the interpulse phase this reaction is followed by \(^{13}\)C\((\alpha,\text{n})^{16}\)O which releases neutrons for capture on iron and similar elements.

There are two important aspects of this to discuss. Firstly, until 1995 it was believed that the pocket of \(^{13}\)C remained in place until it was engulfed by the next flash-driven convective zone. But in 1995 it was shown by \(\underline{[23]}\) that the \(^{13}\)C burns \textit{in situ} during the interpulse phase. Hence the neutrons are both released and captured locally, at lower temperatures than found in the convective shell at the next pulse, and the resulting neutron densities are lower. Studies of the subsequent \(s\)-processing assume hydrogen penetrates only a few \(10^{-4}\)\(M_\odot\) which is enough to provide a good match to the observations in AGB stars (\(\underline{[8]}\)).

The second important point is that we are not sure exactly how this \(^{13}\)C is produced. The problem is that we must mix small amounts of hydrogen into the carbon-rich region. If there is too much hydrogen then the CN cycle makes the \(^{13}\)C that we want, but there are plenty of protons left for the \(^{13}\)C to capture another proton to produce \(^{14}\)N, i.e. we complete the CN cycle. So it is crucial that there be only small amounts of hydrogen present. Initially it was believed that the high opacity caused by the recombination of \(^{C6+}\) to \(^{C5+}\) caused a semiconvective zone to form, which resulted in the partial mixing of the two zones (\(\underline{[4]}\)). Another mechanism has been outlined by \(\underline{[1]}\), who has shown that a combination of convective overshooting and partial mixing (implemented via a diffusion equation) can produce both extensive dredge-up and a \(^{13}\)C pocket. This is very promising, although it does introduce another parameter which must be calibrated somehow. Another possibility is that shear mixing could occur at the bottom of the convective envelope. For rotating stars we would expect a significant shear layer at the bottom of the convective envelope,
which is exactly where this mixing must occur. In summary, it seems clear that some hydrogen is mixed into the intershell region, but we are still unsure how.

AGB stars can also make $^{19}$F through thermal pulses, although the details are rather complicated. There is a delicate interplay between many reactions, primarily concerning the fate of the abundant $^{14}$N and the production of $^{15}$N in the flash-driven convection zone ([4],[19]). The basic production scheme is shown in Figure 3. Some $^{13}$C produces neutrons via the $^{13}$C($\alpha$,n)$^{16}$O reaction described 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,$\alpha$)$^{15}$N($\alpha$,$\gamma$)$^{19}$F produces the observed $^{19}$F, which is then dredged to the surface in the usual way following the next pulse. Note that the neutron captures on $^{14}$N must compete with $\alpha$-captures, and likewise the production of $^{15}$N is very dependent on the temperature (and hence the stellar mass). It appears that the amount of $^{13}$C left over from hydrogen burning is dramatically short of the amount required for $^{19}$F production ([20]) and hence this is further evidence for the existence of a $^{13}$C pocket.

### 3.2 Hot Bottom Burning

For stars more massive than about $4M_\odot$ the temperature at the bottom of the convective envelope becomes high enough for some reactions to occur. The first effect of this “hot bottom burning” (hereafter HBB) is that the star produces $^7$Li via the Cameron-Fowler mechanism. At the bottom of the envelope, $^3$He (left over from earlier hydrogen burning on the main-sequence) captures an alpha particle to make $^7$Be, which decays into $^7$Li. However, at the high temperatures necessary for the first step of this reaction, the $^7$Be is destroyed by the PPIII chain, and the $^7$Li itself is destroyed by the PPII chain. So if the abundance of $^7$Li is to increase, we must produce the $^7$Be and then mix it away to regions of lower temperature, where it can decay into $^7$Li. Detailed calculations by [2] showed that $^7$Li was produced as soon as the temperature at the bottom of the convective envelope exceeded $50 \times 10^6$K, and produced abundances up to $\log \varepsilon(^7\text{Li}) \sim 4.5$ in stars with $M_{\text{bol}} \simeq -6$ to $-7$ (note...
that \( \log \varepsilon(\text{Li}) \equiv \log \{ n(\text{Li})/n(\text{H}) \} + 12 \). This is in excellent agreement with the observations ([21] and [22]).

The next consequence of HBB is that the \( ^{12}\text{C} \) which has been added to the envelope after each dredge-up event is now processed by the CN cycle into \( ^{13}\text{C} \) and \( ^{14}\text{N} \). It turns out that the entire envelope is processed many times during the interpulse phase, and the surface ratio of \( ^{12}\text{C}/^{13}\text{C} \) can reach its equilibrium value of about 3-3.5. Further, as \( ^{12}\text{C} \) is destroyed in the process, the star can be prevented from becoming a C-star by HBB ([3]), and it can even produce significant amounts of (primary) \( ^{14}\text{N} \) by this process ([7]).

Two other important consequences of HBB are the production of \( ^{26}\text{Al} \) and the destruction of \( ^{19}\text{F} \) ([16]). This is important for our understanding of meteorite grains (see [1]) and for the overall galactic enrichment of \( ^{19}\text{F} \), but we will defer the details to elsewhere.

### 3.3 But...

But this picture has to be modified slightly. Both HBB and dredge-up require a reasonably large envelope mass. Until recently we did not know how large. The continued effect of mass-loss on the AGB is to reduce the envelope mass. So both dredge-up and HBB will eventually cease, before the stars leaves the AGB as a planetary nebula. But which ceases first? Dredge-up or HBB? It was recently shown by [7] that HBB is the first to end, while dredge-up continues. Hence the carbon continues to be added to the envelope without it being burned, and the star does indeed become a carbon star near the end of its life, despite earlier HBB. At this time, however, the mass loss rate is so large that the star is not visible optically, which explains recent infra-red surveys which show that of order of 50% of the obscured AGB stars are in fact C-stars ([17]).
4 Do We Really Understand It All?

Lest the reader think that all is understood, there are some significant uncertainties in the details, which I have not discussed at all. Some of these include the form of the mass-loss, the value of the mixing length, various reaction rates, as well as the ever-present (and mostly ignored) unknown effects of rotation. But the one uncertainty which I do wish to elaborate on (slightly) is that of dredge-up.

There has been, and continues to be, a large disparity in the extent (or even occurrence) of dredge-up found by various authors. The importance of differences in numerical treatment of convection and mixing was shown by [5], which partly explains some of the different results which appear in the literature. The details depend on how one implements the mixing of convective zones within an iteration scheme, on the one hand, and whether one naively uses the Schwarzschild criterion for determining the convective boundary or whether one allows the model to find a buoyantly neutral edge. Exactly how one performs the mixing can have large effects too ([24]).

The recent work by [11] on overshooting is promising, but does suffer from the (necessary) inclusion of another unknown parameter. Their models show deep dredge-up, which saturates at a level independent of further changes of the numerical parameters ([10]) which is consistent with calculations by [18]. Much work remains to be done on this complex problem, which is basically a multi-dimensional time-dependent hydrodynamical one. It is really no wonder that our one dimensional hydrostatic models are in trouble!

5 Conclusions

Table 1 lists the main elements involved in nucleosynthesis in AGB stars and indicates where they are made or destroyed. This (rough) summary explains the interest in AGB stars: although a short phase they are common and of great importance to the chemical enrichment of the galaxy.

But there are still more things to learn about these stars. The recent possibility of “degenerate pulses” ([8]) has yet to be investigated fully. AGB stars exhibit much complex physics, and we should not be so complacent as to think that we have uncovered most of their workings yet!
Table 1. Main nucleosynthesis results on the AGB

| Element | Thermal Pulses | Hot Bottom Burning |
|---------|----------------|-------------------|
| $^{12}\text{C}$ | produced | destroyed |
| $^{13}\text{C}$ | little effect | produced |
| $^{14}\text{N}$ | little effect | produced |
| $^{15}\text{N}$ | little effect | destroyed |
| $^{16}\text{O}$ | little effect | destroyed |
| $^{17}\text{O}$ | little effect | produced |
| $^{18}\text{O}$ | little effect | destroyed |
| $^{19}\text{F}$ | produced | destroyed |
| $^{26}\text{Al}$ | slight production | large production |
| s-elements | produced | little effect |

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