The Brightest Carbon Stars

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Abstract. It is currently accepted that Hot-Bottom-Burning (HBB) in intermediate-mass asymptotic giant branch (AGB) stars prevents the formation of C stars. Nevertheless, we present in this paper the results of some detailed evolutionary calculations which show that even with HBB we obtain C stars at the highest luminosities reached on the AGB. This is due to mass-loss reducing the envelope mass so that HBB ceases but dredge-up continues. The high mass-loss rate produces an optically thick wind before the star reaches C/O > 1. This is consistent with the recent results of van Loon et al. (1997a,b) who find obscured C stars in the Magellanic Clouds at luminosities up to $M_{bol} = -6.8$.

Key words: stars: AGB – stars: Carbon stars – stars: Nucleosynthesis

1. AGB Evolution: Mass-Loss and Dredge-Up

AGB stars present a significant challenge to theorists because they combine many physical processes which are not well understood, such as mass-loss and third dredge-up. Both are firmly established theoretically and observationally, but reliable calculations are still impossible at present (Vassiliadis & Wood 1993, hereafter VW93; Frost & Lattanzio 1996a). Nevertheless, we do have a qualitative understanding of these fascinating stars and the main physical processes which govern their evolution (for recent reviews see Frost & Lattanzio 1996b, Lattanzio et al. 1996) as well as their extensive nucleosynthesis (for example, see Sackmann & Boothroyd 1992, Gallino et al. 1996, Forestini & Charbonnel 1997).

In the absence of Hot-Bottom Burning (HBB), that is for AGB stars initially less massive than about 4 to 5 $M_\odot$ (depending on metallicity $Z$), the question of whether a star actually becomes a C star or not depends primarily on two things:

– the extent and time-variation of mass-loss on the AGB;
– the efficiency (i.e. the depth) of dredge-up.

Mass-loss is usually included by fits chosen to simulate observed rates. For reliable models we require a self-consistent scheme for determining the mass-loss rate and its variation along the AGB and beyond. There are observational indications that toward the end of their evolution, some AGB stars experience a short phase of extremely rapid mass-loss, often called a “super-wind” (Justtanont et al. 1996, Delfosse et al. 1997). These stars are often surrounded by a dense circumstellar envelope and are no longer visible in optical studies. Some show at present rather low mass-loss rates (Jura et al. 1988), suggesting a complex time dependence.

The efficiency of dredge-up is usually described by the “dredge-up parameter” $\lambda$ which is defined as the ratio of the mass dredged to the stellar surface following a flash to the mass processed by the hydrogen burning shell between two successive shell flashes. There is no agreement concerning the value and dependence of this parameter on time, stellar mass and composition. It suffers from many physical and numerical uncertainties (Frost & Lattanzio 1996a), and evolution calculations show that it varies greatly with luminosity, mass and metal abundance (Wood 1996). In synthetic evolution calculations (e.g. Groenewegen & de Jong 1993, Marigo, Bressan & Chiosi 1996) it is usually assumed to be a constant.

Dredge-up and mass-loss are crucial because:

– the deeper the dredge-up the more $^{12}$C is added per pulse;
the discrepancy at low luminosity.

of bright C stars. Recent models of low-mass stars by models, and this is part of the explanation for the deficit of bright C stars and not enough faint C stars. The importance of that the then current models predicted too many bright C stars, identified the so-called "Carbon star mystery", namely 2 The Brightest Carbon Stars

The occurrence of HBB has been found to be the major factor affecting C star formation (Sackmann & Boothroyd 1992). In this phenomenon the bottom of the convective envelope penetrates the top of the hydrogen burning shell so that some nuclear processing occurs at the bottom of the envelope (during the interpulse phase). This region is mixed throughout the photosphere and any abundance changes produced by HBB can be directly observed at the surface. This appears to provide a simple explanation for the high-luminosity Li-rich AGB stars found by Smith & Lambert (1989, 1990), as shown by Sackmann & Boothroyd (1992). However it can also lead to CN cycling with the result that the $^{13}\text{C}$ added to the stellar envelope by dredge-up can then be processed into $^{13}\text{C}$ and $^{14}\text{N}$. If this CN cycle is operating almost at equilibrium conditions, the star can avoid becoming a C star altogether. This was suggested some time ago by Wood, Bessell & Fox (1983), and was verified by Boothroyd, Sackmann & Ahern (1993). Although this is largely true, synthetic evolution models of Forestini & Charbonnel (1997) have recently suggested that a population of very bright C stars can still be produced even for stars experiencing strong HBB if the mass-loss rate is not too high (so that there are enough dredge-up episodes). It is the aim of this Letter to confirm that very bright C stars can indeed result from a combination of effects which have revealed themselves when detailed evolutionary models have been computed nearly all the way to the end of the AGB evolution.

HBB requires a minimum envelope mass $M_{\text{e}}^{HBB}$ or temperatures will not rise sufficiently at the base of the envelope. A minimum envelope mass $M_{\text{e}}^{TDU}$ is also required for third dredge-up to occur, the exact value of which is currently unknown. If $M_{\text{e}}^{HBB}$ < $M_{\text{e}}^{TDU}$ then the dredge-up will cease before HBB. If the opposite is true, then dredge-up will continue after HBB has ceased. Note that Groenewegen & de Jong (1993) assumed that both processes stopped at the same time (i.e. that $M_{\text{e}}^{HBB} = M_{\text{e}}^{TDU}$). From computations we have performed, which will be reported fully elsewhere (Frost et al. 1997), it appears that $M_{\text{e}}^{HBB}$ > $M_{\text{e}}^{TDU}$, so that HBB ceases but dredge-up continues. This is, of course, relevant for the formation of high luminosity C stars.

2. The brightest C stars observed

Recent observations by van Loon et al. (1997a,b) have been directed toward finding stars with circumstellar envelopes in the Magellanic Clouds, in an attempt to correct for the incompleteness of optical surveys at the highest luminosities. They found 19 new objects and tried to determine which were O-rich and which are C-rich. Although this proved impossible for some objects, they reached two important conclusions:

- the ratio $N_{\text{C}}/N_{\text{O}}$ of the number of C-rich to O-rich objects decreases with increasing luminosity. As the most massive AGB stars are also among the brightest ones, this is compatible with HBB effects;
- this ratio does not decrease to zero even at the highest luminosities. This is inconsistent with a simple-minded understanding of HBB, but is consistent with our models, as we show below.

van Loon et al. (1997b) estimate that even at $M_{\text{bol}} = -7$, the value of $N_{\text{C}}/N_{\text{O}}$ lies between 0.2 and 0.5. Further, they find a C-rich object with $M_{\text{bol}} = -6.8$, which makes it one of the most luminous AGB stars in the Magellanic Clouds. Note that this is a C star, but note also that the brightest optically visible AGB stars in the Magellanic Clouds are in fact O-rich (VW93). Thus the conversion to a C star appears to be related to the mass-loss which produces the enshrouding. It is important for us to know the critical mass-loss rate above which a star is no longer optically visible. As there are very few visible stars with mass-loss above $10^{-6}$ M$_{\odot}$/yr, and none above $10^{-5}$ M$_{\odot}$/yr (Guélin, private communication) we shall use $5 \times 10^{-6}$ M$_{\odot}$/yr as the critical value.

3. The brightest C stars explained?

In this section we show some preliminary results from a study of AGB evolution of 4, 5 and 6 M$_{\odot}$ models for Magellanic Cloud compositions ($Z = 0.004$ and 0.008) as well as solar ($Z = 0.02$). The models will be discussed

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1 They suggest that the occurrence of both C-rich and O-rich stars at the same luminosity is possibly due to a mixture of compositions. We believe it is more likely due to a mixture of evolutionary stages.
We have not included here the modification to the formula for \( M > 2.5 \, M_\odot \) that delays the onset of the super-wind.

If a star is assumed to be no longer optically visible when its mass-loss rate exceeds \( 5 \times 10^{-6} \, M_\odot / \text{yr} \) then our model would disappear from optical surveys at an age of \( 6.841 \times 10^7 \) yr, as shown in Figure 1, when it is still clearly O-rich. This model only appears as a C-star after it has become heavily enshrouded. This is consistent with the observations of van Loon et al. (1997a,b), and is due to the fact that the mass-loss rate determines three crucial things: the termination of HBB, the dilution of dredged-up material in the envelope, and the time at which the star becomes no longer optically visible. The order of these events is crucial.

![AGB evolution of our 6 M_\odot model with Z = 0.008.](image)

The top frame shows the mass-loss rate, the middle frame gives \( M_{\text{bol}} \), and the lower frame presents the \( ^{13}\text{C}/^{12}\text{C} \) and C/O ratios. The time when the mass-loss rate exceeds our critical value of \( 5 \times 10^{-6} \, M_\odot / \text{yr} \) is shown as a vertical line. We also show, by a horizontal line, the critical value C/O=1.

Figure 2 shows the Z = 0.004 case. Here again we see the continual rise in the C/O ratio. For this composition (appropriate to the Small Magellanic Cloud) the C/O ratio exceeds unity long before HBB ceases. This model is both a C star and \( ^{13}\text{C} \)-rich, which would see it classified as a J star. When HBB ceases, the envelope mass is \( M_{HBB} \approx 2.02 \, M_\odot \). The luminosity when the model became a C star was \( M_{\text{bol}} = -7.2 \), with post-flash dips decreasing this to
−6.3. Taking $5 \times 10^{-6} \, M_\odot / \text{yr}$ as the critical mass-loss rate for an enshrouded star, we find that this model would no longer be visible for $t > 6.781 \times 10^7$ yr, when C/O $\simeq 0.8$. The probability of observing a C star is proportional to the fraction of the interpulse period which the stars spends with C/O $> 1$. Hence this model is not a C star while visible, but becomes a C star soon after it drops from visibility.

The two models presented show clearly that HBB prevents optically visible C stars from forming, but that mass-loss can then hide the star, extinguish HBB, and permit it to become a (heavily obscured) C star. This is entirely consistent with the observations of AGB stars in the Magellanic Clouds.

![Graph](image.png)

Fig. 2. Same as Fig. 1 but for $Z = 0.004$. Note that the two “glitches” in the abundances seen at $t = 6.785$ and $6.793 \times 10^7$ yr are the result of “degenerate pulses”, which will form the basis of a separate paper.

4. Discussion and prospects

These full evolutionary models for AGB stars reveal a very complex interplay between mass-loss, dredge-up and HBB. The carbon isotopic ratio is very sensitive to these processes. Consequently, it is not currently possible to confidently predict its evolution at the surface of AGB stars of various initial masses and metallicities.

The intermediate-mass C stars shown in this work become C stars earlier in their evolution as the metallicity is decreased. Similarly, the time (and luminosity range) over which they show high $^{13}$C/$^{12}$C also increases with decreasing $Z$. We finally note that, for the two cases shown here, HBB is terminated before dredge-up ends. This was also found to be the case for the solar metallicity case (not reported here), with $M_e^{\text{HBB}} \simeq 2.57 \, M_\odot$.

These very bright C stars, dredging-up material enriched in $^{13}$C while undergoing strong HBB, substantially increase their $^{14}$N envelope abundance. Compared to the beginning of the AGB phase, the $^{14}$N enhancement factor in the wind of these C stars is about 4, 13 and 40 for the $Z = 0.02, 0.008$ and 0.004 cases respectively, which would make these intermediate-mass stars significant producers of primary $^{14}$N.

The present evolution models of AGB stars also reveal that the dredge-up depth together with both the rate and time-variation of the mass-loss are crucial quantities deciding the final envelope composition of an AGB star (and its planetary nebula). In particular, they determine whether such stars become C stars or not, and whether they are optically visible or not. The transformation of the convective envelope (and wind) from O-rich to C-rich is made even more complicated by HBB for the higher mass stars. Both mass loss and dredge-up depth are very uncertain, and the calculations reported here are extremely computationally intensive. Only synthetic evolution, based on the results of these detailed models, can investigate more fully the possible ranges of C/O and $^{13}$C/$^{12}$C that can be found on the AGB. This work is in progress.

Note that calculations with diffusive mixing (Herwig et al. 1997) produce different amounts of dredge-up and different intershell compositions to canonical calculations. The implications of this are yet to be determined.

5. Conclusion

Regardless of the details of the evolutionary calculations, we only expect to see luminous, massive C stars when there has been a significant reduction in the envelope mass, so that the HBB has stopped turning the $^{12}$C into $^{14}$N and the dredged-up $^{12}$C is not highly diluted in a large envelope. Since the envelope mass only reduces significantly when the super-wind is operating, we expect all the massive, luminous C stars to be dust-enshrouded.

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