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The Brightest Carbon Stars

C. A. Frost[1,2], R. C. Cannon[1,3], J. C. Lattanzio[1,2,4], P. R. Wood[5], M. Forestini[4]

[1] Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, U.K.
[2] Department of Mathematics, Monash University, Clayton, Victoria, 3168, Australia
[3] Department of Physiology and Pharmacology, School of Biological Sciences, University of Southampton, SO16 7PX, U.K.
[4] Laboratoire d'Astrophysique, Observatoire de Grenoble, Université Joseph Fourier, BP 53, F–38041 Grenoble Cedex 9, France
[5] Mount Stromlo and Siding Spring Observatories, The Australian National University, Private Bag, Weston Creek P.O., A.C.T. 2611, Australia

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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).

Send offprint requests to: J. Lattanzio, Department of Mathematics, Monash University, Clayton, Victoria, 3168, Australia

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" λ 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;

- dredge-up alters the evolution of the star by cooling the intershell region and changing the core-mass (e.g. VW93).
- once dredge-up begins it occurs after each pulse, and the number of pulses depends critically on mass-loss which is the primary phenomenon determining the duration of the AGB phase (Schönberner 1979);
- mass-loss determines the envelope mass, and hence the amount of dilution which the dredged material experiences. The less dilution the sooner the star will become a C star;
- hydrostatic equilibrium of the envelope forces a given temperature at the bottom of the envelope, so that a minimum envelope mass is required for HBB to occur.

Synthetic AGB evolution calculations of Iben (1981) identified the so-called "Carbon star mystery", namely that the then current models predicted too many bright C stars and not enough faint C stars. The importance of high mass-loss rates had been underestimated in these models, and this is part of the explanation for the deficit of bright C stars. Recent models of low-mass stars by Straniero et al. (1995) have reduced, but not eliminated, the discrepancy at low luminosity.

For AGB stars more massive than about 4 to 5 $M_\odot$, 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 ^{12}C added to the stellar envelope by dredge-up can then be processed into ^{13}C and ^{14}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_e^{HBB} or temperatures will not rise sufficiently at the base of the envelope. A minimum envelope mass M_e^{TDU} is also required for third dredge-up to occur, the exact value of which is currently unknown. If $M_e^{HBB} < M_e^{TDU}$ 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 $M_e^{HBB} = M_e^{TDU}$). From computations we have performed, which will be reported fully elsewhere (Frost et al. 1997), it appears that $M_e^{HBB} > M_e^{TDU}$, 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_C/N_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 $M_{bol} = -7$, the value of N_C/N_O lies between 0.2 and 0.5[1]. Further, they find a C-rich object with $M_{bol} = -6.8$, 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 5×10^{-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

[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.

fully elsewhere (Frost et al. 1997). Calculations were performed with the Mount Stromlo Stellar Evolution Code, with OPAL opacities (Iglesias & Rogers 1993) and mass-loss rates from VW93[2]. Calculations of dredge-up have been performed as recommended by Frost & Lattanzio (1996a) and include the entropy adjustment of Wood (1981). We use a post-processing nucleosynthesis code to follow the composition changes of 74 species up to sulphur within the stellar models. Each was evolved from before the ZAMS through many thermal pulses, until rapid convergence problems occurred.

Here we discuss only the 6 $M_\odot$ cases with compositions appropriate to the Magellanic Clouds. We computed 68 and 92 pulses for the $Z = 0.008$ and 0.004 cases, respectively. Let $^{13}C/^{12}C$ be the number ratio $n(^{13}C)/n(^{12}C)$ and $C/O = [n(^{12}C)+n(^{13}C)]/[n(^{16}O)+n(^{17}O)+ n(^{18}O)]$, consistent with the observational definition based on molecular studies.

After each dredge-up event the ^{12}C abundance is increased. During the following interpulse phase HBB transforms ^{12}C into ^{13}C and ^{14}N, driving the $^{13}C/^{12}C$ ratio toward its equilibrium value of about 0.3 and decreasing the C/O value. These effects are clearly seen in Fig. 1 which shows the results for the 6 $M_\odot$ case with $Z = 0.008$, appropriate to the Large Magellanic Cloud. The C/O ratio rapidly drops from the initial (pre-thermally pulsing) value of 0.31 as soon as the envelope bottom temperature produces HBB and reaches a minimum value of about 0.07. With each dredge-up event we see the increase in ^{12}C produced by strong dredge-up (we find $\lambda \sim 0.9$) but during the subsequent interpulse phase this ^{12}C is burned into ^{13}C and ^{14}N by HBB, so that the $^{13}C/^{12}C$ ratio remains at its equilibrium value. Note that as the evolution proceeds, the C/O ratio begins to rise again. Initially this is simply due to the large amount of ^{12}C added to the envelope. However during the later pulses the decreasing envelope mass means less dilution of the dredged-up material following each pulse as well as a decrease in the peak temperature at the bottom of the convective envelope. In fact, we find that HBB ceases four or five pulses from the end of the calculations. From that time, the C/O ratio climbs very rapidly. The model passes through C/O=1 and continues up to 1.5 at the time that calculations ceased. We find M_e^{HBB} exceeds M_e^{TDU} and we determine $M_e^{HBB} \simeq 1.98\,M_\odot$. Except for the last few pulses, after HBB has ceased, the $^{13}C/^{12}C$ ratio remains at its equilibrium value. Note that this model reaches a peak of $M_{bol} = -7$ but that this has declined to -6.6 when the star becomes a C star. Boothroyd, Sackmann & Ahern estimate that HBB should prevent the appearance of C stars brighter than $M_{bol} = -6.4$, which the current model shows is not always the case.

[2] 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 $5 \times 10^{-6}\,M_\odot$/yr then our model would disappear from optical surveys at an age of 6.841×10^7 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.

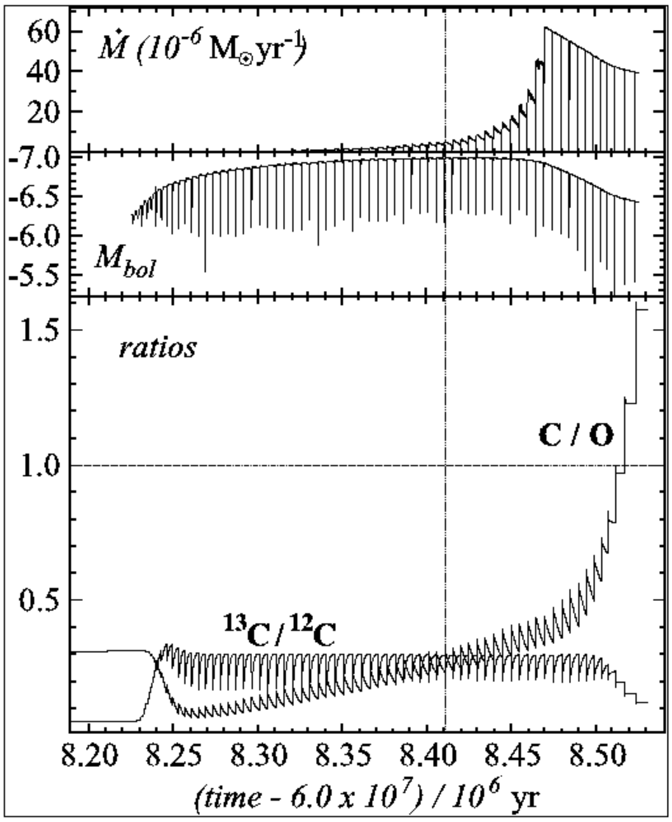

Fig. 1. AGB evolution of our 6 $M_\odot$ model with $Z = 0.008$. The top frame shows the mass-loss rate, the middle frame gives M_{bol}, and the lower frame presents the $^{13}C/^{12}C$ and C/O ratios. The time when the mass-loss rate exceeds our critical value of $5 \times 10^{-6}\,M_\odot$/yr is shown 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}C-rich, which would see it classified as a J star. When HBB ceases, the envelope mass is $M_e^{HBB} \simeq 2.02\,M_\odot$. The luminosity when the model became a C star was $M_{bol} = -7.2$, with post-flash dips decreasing this to

-6.3. Taking 5×10^{-6} $M_\odot$/yr as the critical mass-loss rate for an enshrouded star, we find that this model would no longer be visible for $t > 6.781\times10^7$ 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 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.

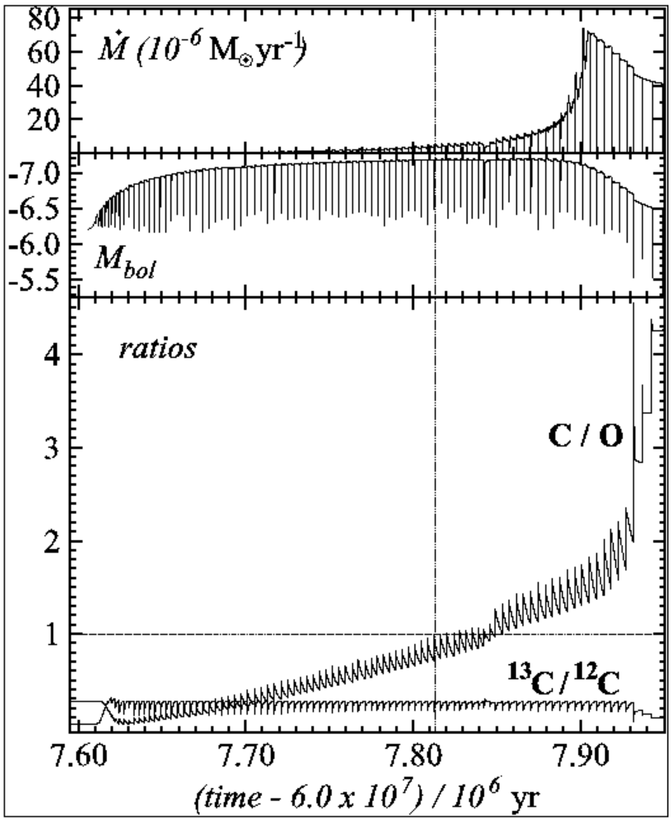

Fig. 2. Same as Fig. 1 but for $Z = 0.004$. Note that the two "glitches" in the abundances seen at $t = 6.785$ and 6.793×10^7 yr are the result of "degenerate pulses", which will form the basis of a separate paper.

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 $M_e^{HBB}\simeq 2.57$ $M_\odot$.

These very bright C stars, dredging-up material enriched in ^{12}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 conpositions 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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