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Carbon Rich Binary Remnants of Extremely Low-Metal AGB Stars

H. B. Lau[*]
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge. CB3 0HA UK
E-mail: `HBL21@ast.cam.ac.uk`

R. J. Stancliffe, C. A. Tout
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge. CB3 0HA UK

E-mail: `rs@ast.cam.ac.uk, cat@ast.cam.ac.uk`

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The Cambridge STARS code is used to model the evolution and nucleosynthesis of binary zero-metallicity low to intermediate mass stars. The surfaces of these stars are enriched in CNO elements after second dredge up. During binary interaction metals can be released from these stars and the secondary enriched in CNO. The observed abundances of HE 0107-5240 can be reproduced from enhanced wind accretion from a $7\,M_{\odot}$ after second dredge up. HE 1327-2326, richer in nitrogen and Sr, can similarly be formed by wind accretion in a later AGB phase after third dredge up.

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[*] Speaker.

1. Introduction

Mass loss from primodial stars is very important because any metals released from the stars enrich the interstellar medium, increasing the metallicity of the following generations of stars. However, mass loss from single stars is not well understood. Stellar winds from intermediate-mass zero-metallicity stars are very weak without any metals at the surface. During the AGB phase we do not know whether the mass loss is dependent on metallicity. On the other hand, mass loss from primary stars during binary interaction is more well-defined and understood. If the mass transfer is non-conservative, the surroundings are enriched in metals. If some of the material lost by the primary is deposited on the secondary the surface abundance of the secondary becomes CNO rich but otherwise metal-poor. This could be one way to form the observed carbon enhanced metal poor stars.

2. Evolution of single stars

We use the Cambridge STARS code, with nucleosynthesis of forty-six isotopes (Stancliffe et al 2005) to simulate the evolution of the primodial stars. Eldridge & Tout (2004) updated the opacity table. The evolution of zero-metallicity stars differs significantly from that at higher metallicity, because of the absence of carbon, nitrogen and oxygen. Hydrogen cannot be burned though the CNO cycle so it is burned via the proton-proton chain. This is less temperature dependent so zero-metallicity stars are considerably hotter. and their main-sequence lifetime is much shorter. Also, the burning is much extended around the core. The temperature at the core is hot enough that carbon is produced through the 3α reaction. When the central carbon mass fraction reaches about 10^{-12}, hydrogen burning switches to the CNO cycle. For stars more massive than $1.8M_{\odot}$, the core is hot enough for helium to burn non-degenerately when hydrogen is exhausted in centre, so these stars remain on the blue side of the H-R diagram throughout central helium burning and the red giant phase and first dredge up are absent. The surface abundances are unchanged during the He burning phase. The critical mass for a helium flash to occur is much lower than for solar metallicity because zero-metallicity stars are much hotter and hence have less dengerate cores.

When He is depleted at the centre, the star undergoes a large expansion and moves rapidly to the red side of the H-R diagram. H and He burning are active in two seperate shells. The energy generated by the He shell causes expansion and cooling of the outermost layers and then the convective envelope deepens. This is second dredge up, although it is actually the first episode of dredge up that occurs in zero-metallicity stars above $1.8M_{\odot}$.

Enough carbon is produced that the H is mainly burned through the CNO cycle in the H-burning shell, and nitrogen is produced within there. The internal profiles of hydrogen, carbon, nitrogen and oxygen is shown in Figure 1 for a $7M_{\odot}$. Therefore, when the convective envelope deepens, both carbon and nitrogen are dredged to the surface. Lower-mass stars dredge up less CNO elements because their convective envelopes penetrate less deeply. Another reason is that because the stars are cooler, the CNO abundance is lower in the H-burning shell. The surface C/N ratio (Table 1) is in CNO quilibrium for lower mass stars but increases rapidly for $6M_{\odot}$ and $7M_{\odot}$, implying that the second dredge-up reaches down to the helium burning shell for those stars.

Also, the ratio of $^{12}\mathrm{C}/^{13}\mathrm{C}$ increases requiring an additional source of $^{12}\mathrm{C}$ that is not from the CNO H-burning shell.

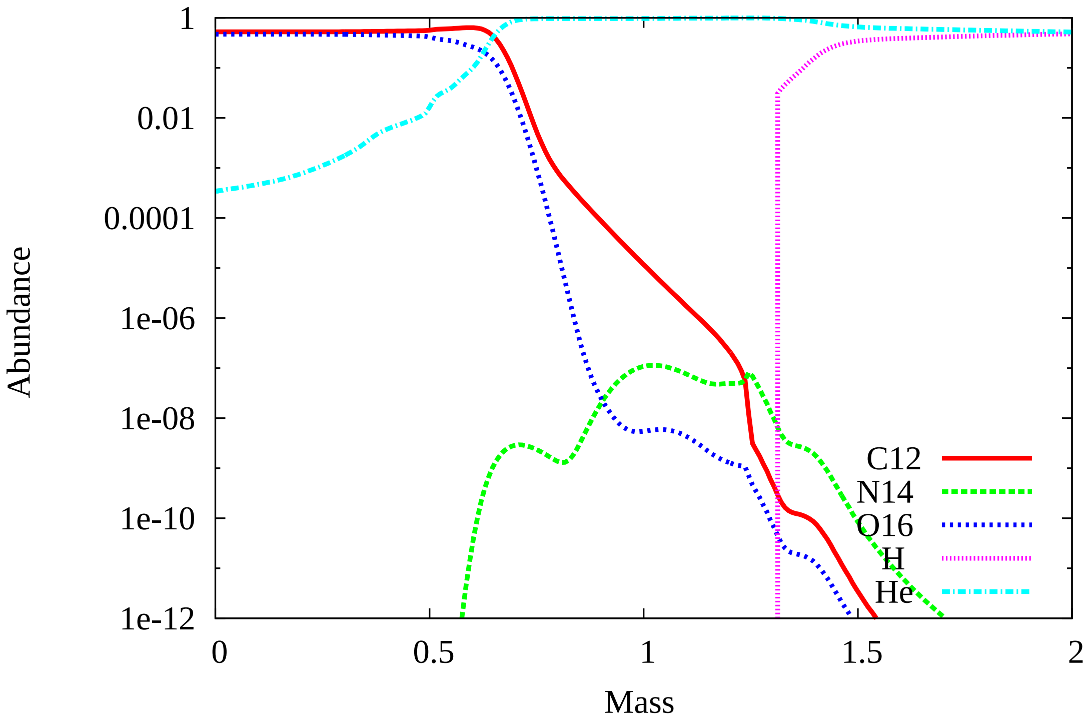

Figure 1: Mass fraction profile of $7M_\odot$ model at the end of central He burning

Mass	^{12}C	^{13}C	^{14}N	^{16}O
3.0	2.51×10^{-18}	7.18×10^{-19}	3.08×10^{-16}	7.80×10^{-18}
4.0	2.63×10^{-14}	7.46×10^{-15}	2.77×10^{-12}	6.05×10^{-14}
5.0	4.07×10^{-11}	1.16×10^{-11}	2.56×10^{-9}	3.56×10^{-11}
6.0	9.38×10^{-8}	1.20×10^{-9}	1.73×10^{-8}	1.27×10^{-10}
7.0	2.64×10^{-6}	2.64×10^{-9}	2.28×10^{-8}	3.85×10^{-9}

Table 1: surface abundances at the end of the early AGB before thermal pulses

3. Mass loss from AGB stars

Mass loss is probably negligible from intermediate-mass zero-metallicity stars because stellar winds are very weak without any metals at the surface. However, the mechanism of mass loss during AGB evolution is not well understood. It has been suggested that the increase of mass-loss rate during the AGB may be caused by the onset of radial pulsation. Whether the mass loss would then be dependent on metallicity is not known. From our models, the $3M_\odot$ releases negligible metals because the dredge up is not deep enough. The $7M_\odot$ models completely dominate the carbon yield, and to a less degree, the oxygen yield. This is because the convective envelope needs to reach very close to the helium burning shell to dredge up carbon and this is only possible if the star is more massive than $5\,M_\odot$. On the other hand, in order to dredge up nitrogen, the convective envelope only needs to reach the hydrogen burning region, which happens below $5\,M_\odot$. Without any known initial mass function for zero-metallicity stars, we cannot give an accurate prediction of the relative contribution of different mass ranges. Assuming a Salpater IMF we can see that the higher-mass end of AGB stars would completely dominate the metal contribution. Unless the ratio of $5\,M_\odot$ to $7\,M_\odot$ is a few times higher than Salpater's ratio we can even neglect the contribution of nitrogen from $5\,M_\odot$ stars.

4. Binary stars

Mass transfer in binaries however is likely to proceed in a similar way to higher metallicity stars. If the mass transfer is non-conservative, the surroundings are also enriched in metals. However, we don't know exactly how much mass is lost from the binary systems. Nevertheless, the radius of a zero-metallicity intermediate mass star only increases rapidly during the early AGB phases and at second dredge up so, when the primary fills its Roche lobe, the mass lost contains a significant amount of metals.

Binary models with initial mass ratio of two-third are used. For example, in the $7\,M_\odot$ models the envelope can be completely lost to leave C/O white dwarf of $1\,M_\odot$. Significant amounts of metals are released from the primary. It seems that changes in initial orbital period have only a small effect on the compositions released. The radii of the stars only increase rapidly after the start of second dredge up, so there is little change if Roche Lobe overflow first occurs after this. The remnant mass increases as the binary period increases but it has only a very small effect on the total metals released from primary because the envelope is convective.

The fraction of metals released from the primary stars is serveral orders of magnitude higher than the metals released during the single-star mass loss. Although not all the metals would be released to the medium, even if only small fraction of the mass transferred is lost from the system, the enrichment can be more significant than the single stars.

Normally, mass transfer would proceed very rapidly because of the primary's greater mass and deep convective envelope. During the ensuing common envelope evolution, these metals can be released to the ISM. Alternatively, even if the system is too wide for Roche lobe overflow, Tout and Eggleton (1988) suggested that mass loss may be tidally enhanced by the presence of a moderately close companion. Mass is lost by the primary at a high rate. A small fraction of the matter can be accreted by the secondary. The system widens owing to the loss of angular momentum and remains too wide for Roche-lobe overflow. This mechanism provides a possible formation scenerio for carbon enhanced matel poor stars.

Primary Mass $M_\odot$	Period (days)	Final Mass	^{12}C	^{14}N	^{16}O
7.0	1.0	1.00366	2.97×10^{-5}	4.11×10^{-7}	1.52×10^{-7}
7.0	4.0	1.03236	4.00×10^{-5}	5.23×10^{-7}	1.93×10^{-7}
6.0	1.0	0.95516	8.59×10^{-7}	2.67×10^{-7}	2.42×10^{-9}
6.0	3.0	0.97650	1.01×10^{-6}	2.68×10^{-7}	2.92×10^{-9}
5.0	1.0	0.91337	6.47×10^{-11}	5.20×10^{-9}	9.25×10^{-11}
5.00	3.00	0.93518	1.51×10^{-10}	1.08×10^{-8}	1.68×10^{-10}
5.00	10.00	0.9406	9.27×10^{-11}	6.64×10^{-9}	1.04×10^{-10}

Table2: Amount of metals released from primary in binary interaction

5. Carbon enhanced metal poor stars

There have been two discoveries of carbon enhanced HMP stars, HE 0107-5240 (Christlieb et al 2002, 2004) and HE 1317-2326 (Frebel et al 2005, Aoki et al 2006). The $[\mathrm{Fe}/\mathrm{H}]$ of both stars are around -5.4. The former doesn't have significant enrichment of Sr while the latter has unexpectedly high Sr abundances. Carbon is very much enhanced relative to the solar C/Fe, by a factor of several thousands. Nitrogen and oxygen are also strongly enhanced by a factor of more than 100. The abundace ratio of C/N of 40 to 150 for HE0107-5240 is similar to the surface abundances of the early AGB phases of $6-7\,M_\odot$ stars. The obversed $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio, which is greater than 50, also fits well with the models. One possible formation scenario for HE 0107-5240 is that it is the secondary star of a wide binary system of which the original primary star has already evolved into an unseen white dwarf. Mass was transferred to the secondary through wind accretion during the AGB phases of the primary. To have avoided RLOF and hence common envelope evolution, the minimum initial period of the binary system must have been at least 600 days. Such a period would increase to around 30 years at the present day. HE 0107-5240 would now be the secondary star of a wide binary system of which the original primary star has already evolved into an unseen white dwarf. The radial velocity of the secondary would be about $6.5\,\mathrm{km\,s^{-1}}$ now. All this explains the non-detection of radial velocity variation of HE 0107-5240 (Bessell et al 2004). We model a primodial $0.6\,M_\odot$ star accreting $0.2\,M_\odot$ from the wind of a $7\,M_\odot$ star. The abundances from the models are estimated for two extreme cases a) the accreted material mixes with the whole star and b) the accreted material remains in a surface layer. (see table 3). The observed errors quoted are the differences between 1D and 3D atmospheric analsyses while the value from the 3D is used as the principal value. The total amount of CNO elements transferred to the secondary is too small to fit the original date in Christlieb et al 2004. However, the 3D abundances of C, N, and O published by Collet et al 2006 are significantly lower, by -0.8 dex or more, than the 1D analysis. Therefore, it is possible that the observed high CNO abundances of HE 0107-5240 are owing to mass transfer from AGB stars by wind accretion. However, our models do not show any significant surface enhancement of Na which is oberved to up more than a factor of 6 up. On the other hand HE 1327-2326 has strong enrichment in the neutron-capture element Sr. This would fit in the binary scenario if the mass transfer occurs after the start of third dredge up, when the surface of the primary is enriched in neutron-captured element. Also, HE 1327-2326 is much more enriched in nitrogen, which can be produced in hot bottom burning in late AGB stars.

On the whole, the abundances seems to suggest that binary transfer occurs at a later stage than in HE-0107-5240 which is adequately fit with early AGB mass transfer.

Element	observed log $\varepsilon(X)$	With mixing	Without mixing
C	5.72 ± 1.09	6.63	5.96
N	2.91 ± 2.02	4.57	3.90
O	4.95 ± 0.71	3.80	3.13

Table 3: Observed Abundances compared with binary models

6. Conclusion

Binary models of intermediate stars are worth investigating. In particular, mass transfer to the secondary during AGB phases could result in chemically peculiar stars such as the carbon-enhanced-metal poor stars. The abundances of HE 0107-5240 can be modeled by wind accretion from a $7 M_\odot$ primary during early AGB phases. On the other hand, if the mass transfer is non-conservative metals are released from the AGB stars after second dredge up and enrich the insterstellar medium.

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