The Effect of Binary Stars on Carbon Production

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ABSTRACT.
Carbon is synthesized by helium burning in many stars but it can only be returned to the interstellar medium under special circumstances namely by AGB stars, Wolf-Rayet stars and supernovae. AGB stars are probably responsible for as much carbon as Wolf-Rayet stars and supernovae combined. During their most productive phase they are largest and so very likely to interact with any nearby binary companion. The usual result of such interactions is to curtail the AGB phase and reduce nucleosynthesis but in exceptional circumstances it may be prolonged. We report on progress in our understanding of the effects of binary companions through detailed calculation and population synthesis.

1. Introduction

Carbon ranks with oxygen and nitrogen as one of the most abundant elements in the interstellar medium (ISM) after hydrogen and helium. It is essential to life as we know it and perhaps even for the formation of rocky planets via dust formation. However, helium fusion takes place deep inside a star and is usually encased within a shell of hydrogen burning, so that it is not easy to bring the products to the surface whence they can be returned to the ISM. Three processes can overcome this. First, massive stars ($> 8\,M_\odot$), that end there lives in supernovae throw off a C/O region between helium- and carbon-burning shells. Because of the ease with which a fourth He^4 nucleus is added to C^{12} much of this material has been processed to O^{16} and beyond. Second a very massive star ($> 25\,M_\odot$) can lose its entire hydrogen envelope in a stellar wind while helium is still burning in its core and leave a naked helium star. A pulsational instability in the atmospheres of naked helium stars makes them vulnerable to even higher mass-loss rates and the surface of such a star can eat down into regions that were formerly part of its convective helium-burning core. This region is rich in carbon that was formed early in the helium burning phase before much of it was converted to oxygen. Some calculations (Maeder and Meynet 1994) indicate that Wolf-Rayet stars are the major source of carbon enrichment of the ISM.

The other process, that can liberate carbon, is third dredge up on the asymptotic giant branch (AGB). As the unstable helium-burning shell thermally pulses, hydrogen-shell burning is temporarily extinguished and the deep convective envelope reaches into the carbon-rich inter-shell region. AGB stars also have relatively strong winds so this processed and dredged material is readily returned to the ISM. When almost all the

the envelope has blown off, the star cools to a white dwarf, trapping most of the star's carbon. Mass loss determines the AGB lifetime, its maximum core mass and the number of thermal pulses and dredge up events. Though models differ in the exact amount of carbon returned to the ISM (Frost & Lattanzio 1996), the existence of carbon stars, AGB stars with carbon to oxygen ratio greater than one, confirms that our understanding is qualitatively correct. In order to assess the effect of binary companions on the carbon yield of a population of stars, we must first quantify the carbon yield of single stars.

2. Carbon Production in Single Stars

For evolution up to a Wolf-Rayet stage or supernova we use synthetic nucleosynthesis based on that of Groenewegen & de Jong (1993) to obtain the surface carbon abundance at any stage in a star's life. We then integrate the product of this abundance and the mass loss rate over the lifetime of the star to obtain the mass of carbon returned to the ISM. The yield is this mass less the mass of carbon that would have been ejected by the same amount of lost mass with the zero-age carbon abundance. The surface abundance remains at its initial value until central hydrogen is exhausted and the star crosses the Hertzsprung gap to join the red giant branch. At this point of first dredge up the deep convective envelope reaches into regions where CNO equilibrium has converted much of the carbon to nitrogen. Dredging this material lowers the surface abundance. Any wind from the star at this stage contains less carbon than the original ISM.

At the beginning of the AGB a second dredge up event takes place for stars more massive than about $4.5\,M_\odot$. As the helium shell burns out to catch up with the hydrogen burning shell the latter is extinguished and the deep convective envelope reaches down into the inter-shell region, further reducing the surface carbon fraction. Hydrogen reignites in a shell very close to the helium-burning shell and, as this double shell-burning region moves out, its ashes are added to a degenerate C/O core. When this core reaches a critical mass ($0.562\,M_\odot$ in our model) third dredge up following thermal pulses begins and carbon enriched material is dredged to the surface for the first time. Repeated pulses raise the surface carbon abundance, eventually producing a carbon star. However, in stars initially over about $4\,M_\odot$, the temperature at the base of the convective envelope later reaches temperatures at which hydrogen burning can take place. This hot bottom burning converts a substantial fraction of the dredged carbon to nitrogen along with some of that already in the envelope so that the surface abundance begins to fall again in these more massive stars. In these exploratory models we have used a Reimers' (1975) mass-loss rate throughout the post-main-sequence evolution. Alternatives that concentrate mass loss towards the tip of the AGB would return more carbon.

Figure 1 shows the integrated yield of carbon returned to the ISM as a function of initial stellar mass. Massive stars return the most carbon but they are fewer so we weight the ejected mass of carbon by the initial mass function $\xi(\log M)$ of Kroupa, Tout and Gilmore (1993) to give the relative contributions. We look at the yields over the first 10^9 yr since the stars formed because this is the typical time for ejected material to be recycled into new stars. Stars less massive than $2\,M_\odot$ do not evolve at all in this time. Between $2\,M_\odot$ and $2.2\,M_\odot$ they have not begun third dredge up and so eject only material deficient in carbon following first dredge up. ¿From here up to $5\,M_\odot$ third

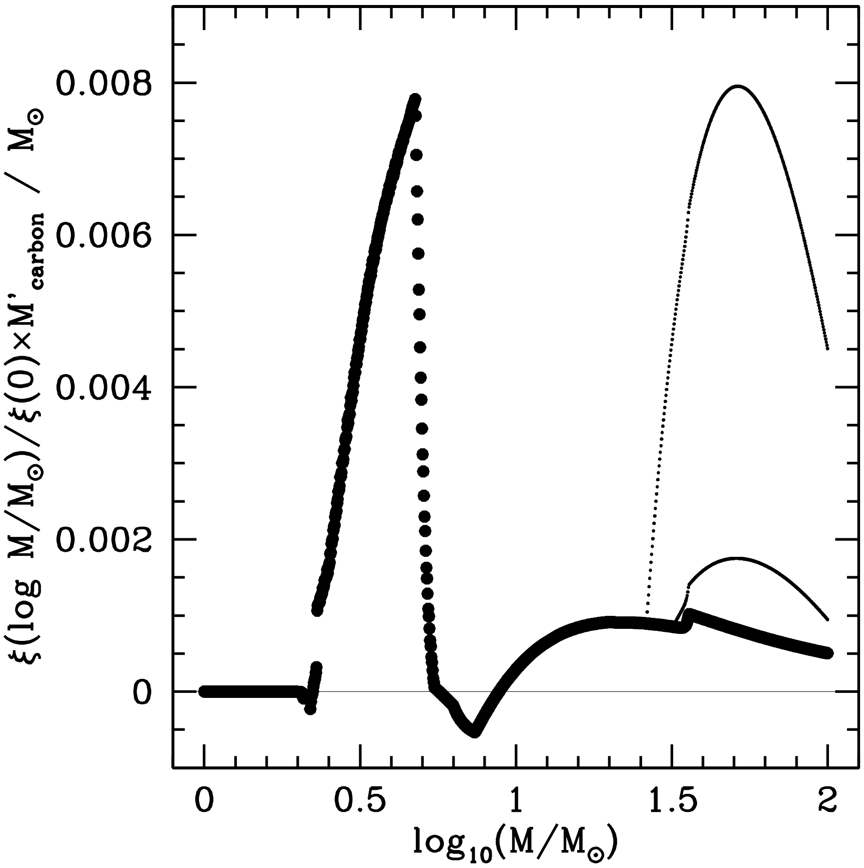

Fig. 1. Carbon yields M'_{carbon}, over 10^9 yr for stars with metallicity $Z = 0.02$ in the range $1 - 100\,M_\odot$, weighted by the initial mass function. The area under the points over a given mass range measures the contribution of that range of masses to carbon production. Large overlapping filled circles are without a Wolf-Rayet contribution while small circles include either the maximum expected yield (large peak) or our preferred, more conservative yield.

dredge up and mass loss on the AGB lead to a large peak in the carbon yield. The rise is due to the increasing amount of dredge up while the decline is due to hot bottom burning which eventually leads to the negative valley between 5 and $8\,M_\odot$.

Above $8\,M_\odot$ supernovae begin to contribute. We take their carbon yields from Maeder (1992). Above $25\,M_\odot$ there is an additional contribution from a Wolf-Rayet phase. We illustrate three cases in the figure. The continuation of the solid circles represents only the supernovae yield while the large peak of small dots is obtained using the maximum yield predicted by Maeder and Meynet (1994). In this case the integrated yield for Wolf-Rayet stars dominates over both the supernovae and the AGB stars. However the very high mass-loss rates mean that the cores of massive stars are unable to grow to a large enough mass to leave behind a black hole remnant, as opposed to a neutron star, when they end their lives in a supernova. The discovery of a number of quite massive black holes in binary soft X-ray transients (Casares, Charles & Naylor 1992) can only be explained if stars above about $25\,M_\odot$ can form black holes. Although it might be envisaged that black holes in binary systems might result from accretion on to a neutron star, our population synthesis models show that such a scenario cannot be a viable explanation for the number of systems observed. In order to obtain sufficient black hole systems we must reduce the long-term average mass-loss rate from naked helium stars by at least a factor of ten below the instantaneous rates observed for Wolf-Rayet stars (Hamann, Koesterke & Wessolowski 1995). The lesser peak of small dots in figure 1 results from such a model. In this case the combined supernova and Wolf-Rayet carbon yield of massive ($M > 10\,M_\odot$) stars is comparable to that of intermediate mass ($2 < M/M_\odot < 5$) from the thermally pulsing AGB. We do however emphasize that the yields of both AGB stars and Wolf Rayet stars are very model and mass-loss dependent and the quantities should only be taken as illustrative until our understanding has improved.

3. Binary Interaction

Of the carbon producers, AGB stars, by their very nature, attain the largest radii. It is these that will be most affected by interaction with a companion. In general a binary companion will curtail its evolution by interaction that increases mass loss. The only well quantified effect is Roche-lobe overflow. The initially more massive component of a binary system evolves and grows until it fills its last stable potential surface, most often as a red giant or AGB star, whereupon it begins to transfer mass to its companion. As it loses mass the envelope of a giant expands. If it is still the more massive component of the binary, and mass transfer is conservative, the orbit and Roche lobe shrink. Consequently the process of mass transfer leads, on a dynamical timescale, to the giant overfilling its Roche lobe yet more. The overflow rate rapidly rises and the companion, typically a lower-mass main-sequence star, cannot accrete the material. Its own Roche lobe is quickly filled and a common envelope engulfs the whole system. The two cores, the relatively dense companion and the core of the giant are then assumed to spiral together by some, as yet undetermined, frictional mechanism (figure 2). Some fraction of the orbital energy released is available to drive off the envelope. If all of it is ejected while the cores are still well separated we are left with a closer binary system comprising the unscathed companion and a white dwarf which may evolve to a cataclysmic variable. Alternatively, if some of the envelope still remains when the companion reaches the denser depths of the common envelope, they can merge leaving a single, rapidly rotating, giant. FK Comae may be such a merged system. Magnetic braking quickly spins down these merged giants and it is possible that the R stars, none of which appear to be binary (McClure, private communication), may be merged AGB stars. When the entire envelope is lost there can be no further AGB evolution or carbon enrichment. If part of the envelope remains AGB evolution is still curtailed, unless the companion, in merging with the envelope, adds even more mass than was lost. In this case AGB evolution is

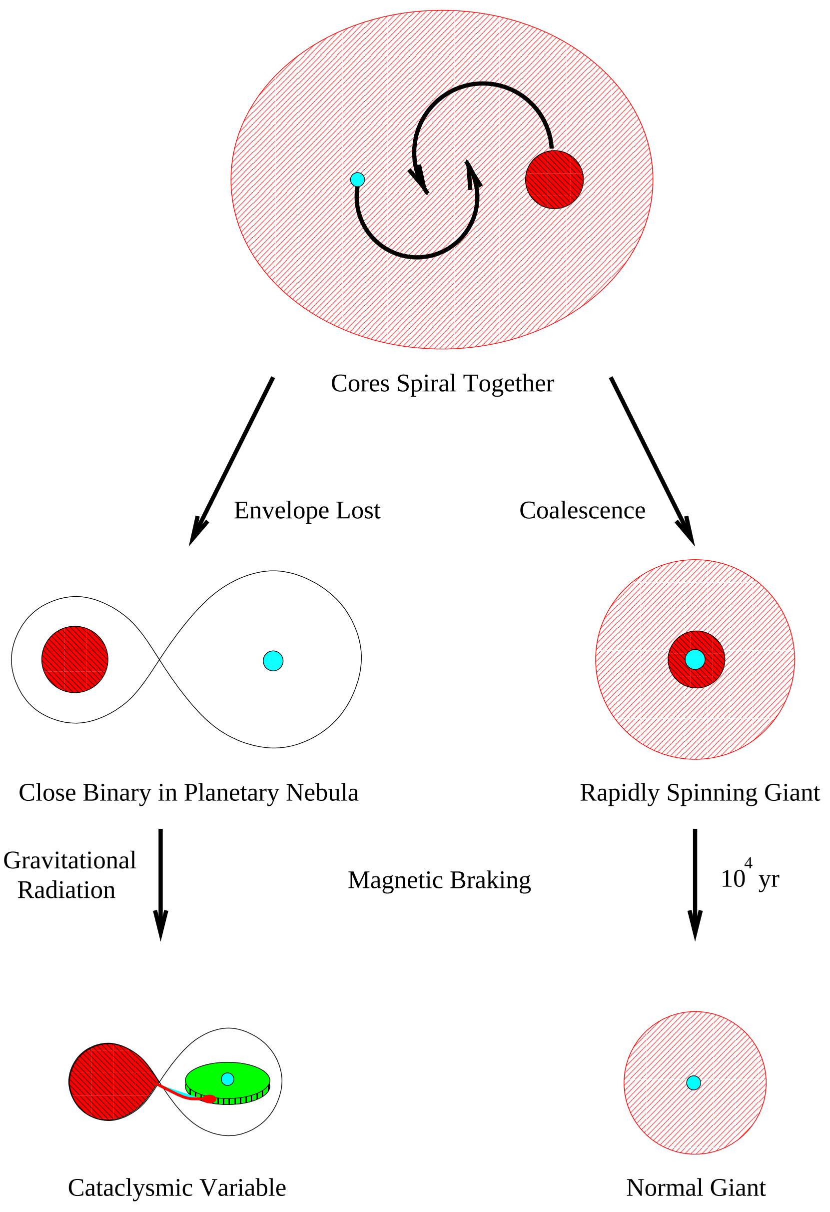

Fig. 2. Common-envelope evolution. After dynamical mass transfer from a giant, a common envelope enshrouds the relatively dense companion and the core of the original giant. These two spiral together as their orbital energy is transferred to the envelope until either the entire envelope is lost or they coalesce. In the former case a close white-dwarf and main-sequence binary is left, initially as the core of a planetary nebula. Magnetic braking or gravitational radiation may shrink the orbit and create a cataclysmic variable. Coalescence results in a rapidly rotating giant which will very quickly spin down by magnetic braking.

prolonged and the merged star returns more carbon to the ISM than a single AGB star of the same initial mass.

Similar events follow mass transfer that begins on the first giant branch, though the denser envelope makes coalescence more likely. Any Roche-lobe overflow that begins before the giant branch proceeds in a stable manner and may eliminate AGB evolution altogether. However the companion that accretes the transferred mass can itself go through an AGB phase at a later stage. Another effect of a binary companion was proposed by Tout and Eggleton (1988) to account for inverted mass ratios in some RS CVn binaries and for the formation of wider Algol-like systems. They proposed that the companion, probably by forcing the giant to spin faster, can enhance its stellar wind by orders of magnitude. This appears to be necessary, though weaker than originally proposed, to account for the distribution of Barium stars (Karakas, Tout & Lattanzio 1999). Though some of the material is accreted by the companion, the AGB lifetime is generally shortened and less carbon is ejected. This can affect much wider systems than Roche-lobe overflow. With account taken of all these processes we can expect half of the 60% or more of stars that are binary systems to interact during their lives.

To illustrate the effects we consider two particular cases (figure 3). To each of the stars in figure 1 we give a companion of mass $M_2 = 1\,M_\odot$ at a separation of either $a = 750\,R_\odot$ or $40\,R_\odot$. In the former case all the stars fill their Roche lobes on either the first giant branch or the AGB and experience common-envelope evolution. Below $3\,M_\odot$ the entire envelope is lost on the giant branch after first dredge up. The substantial positive yield of the single star becomes a negative one. For more massive primaries the cores merge while a fraction of the envelope still remains allowing partial carbon enrichment. The area under the AGB peak is reduced by a factor of six, substantially decreasing the average carbon yield for such a hypothetical population. At $a = 40\,R_\odot$ all the stars fill their Roche lobes before or early on the red giant branch while their envelopes are still relatively dense. Apart from primaries in the small range from 3.5 to $4\,M_\odot$ these stars go on to experience common-envelope evolution but the companions merge with the envelope before very much mass has been ejected. The AGB lifetime is increased and carbon enrichment enhanced so that the peak is doubled in area. The exceptions between 3.5 and $4\,M_\odot$ come about because above $3.5\,M_\odot$ the stars first fill their Roche lobes while crossing the Hertzsprung gap where mass transfer begins stably on a thermal timescale. Above $4\,M_\odot$ these stars go on to common-envelope evolution as the star becomes a fully fledged giant. Below $4\,M_\odot$ sufficient mass has been transferred by this point that the mass ratio has fallen below the critical value (about $M_1/M_2 = 0.7$) for the Roche lobe to expand faster than the giant envelope. Common-envelope evolution is avoided. However the, now quite massive, companion itself evolves up the AGB and fills its own Roche lobe. Common-envelope evolution ensues but the orbit is now so much wider, and the envelope less dense, that it is all ejected before carbon enrichment can begin. Above $8\,M_\odot$ most of the carbon comes from the final supernovae and, at these separations, the binary companion has little effect.

We have not investigated the interaction of Wolf-Rayet stars with a companion in any detail. However these stars can expand substantially, to as much as $1{,}000\,R_\odot$, before losing the last vestiges of their hydrogen envelopes. A common-envelope at this point might well affect the evolution but we note that the naked helium core with a radius

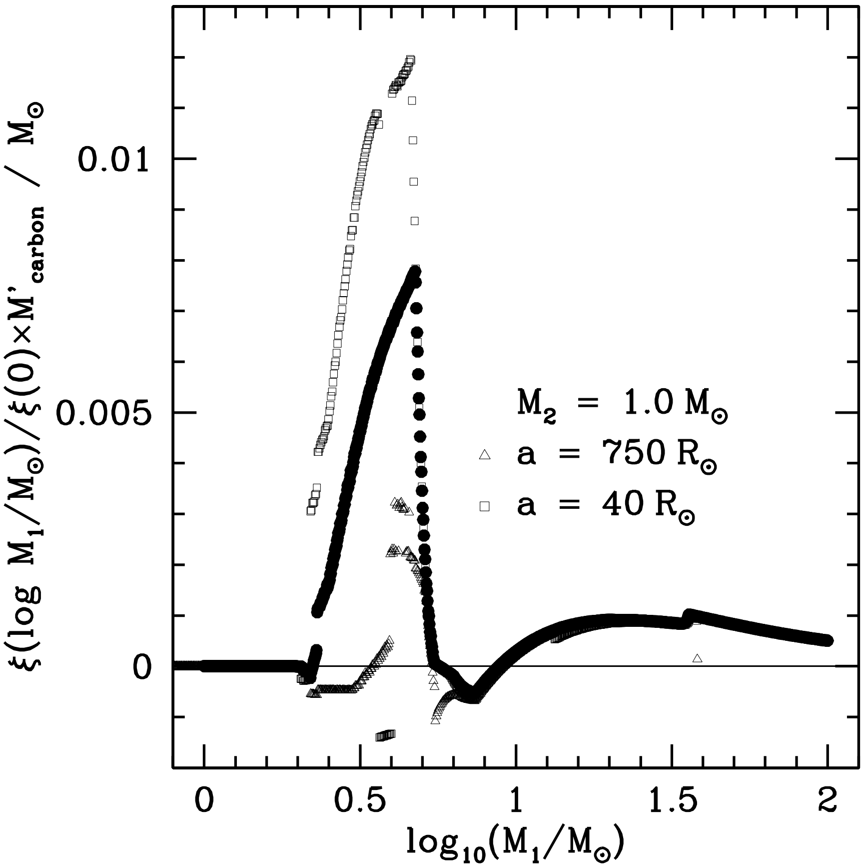

Fig. 3. Filled circles are those of figure 1, without the Wolf-Rayet contributions. Open symbols are the weighted yields from binary systems in which the primary mass M_1 varies as before. The companion has mass $M_2 = 1\,M_\odot$ and the separations are $a = 750\,R_\odot$ (triangles) and $40\,R_\odot$ (squares).

of less than $1\,R_\odot$, small compared with its mass of about $15\,M_\odot$, has a good chance to survive intact. On the other hand wind accretion on to the companion will be significant and in many cases will lead to further interesting evolution of what might be a low mass-star, otherwise unable to evolve in the lifetime of the Galaxy.

In practice binary systems have a wide range of masses and separations and the overall picture is rather convoluted. To model it we synthesize populations of several million systems in which the masses are each chosen randomly from the IMF and the separations from a distribution ranging from 5 to $5\times10^6\,R_\odot$ that peaks around $5{,}000\,R_\odot$. The procedure used to model binary evolution is described by Tout et al. (1997) and Karakas et al. (1999). As expected we find that the interactions that reduce the carbon yield win out over those that increase it. If we do not include Tout & Eggleton's binary enhanced mass loss the overall yield drops by about 7% while if we do include it the yield drops by 15%. Oxygen, coming mostly from supernovae, is little affected while the yield of s-process elements, such as barium, coming only from AGB stars can drop by as much as 30%.

4. Conclusion

AGB stars are a major source of carbon in the ISM, probably contributing as much as supernovae and Wolf-Rayet stars together, though the contribution from the latter remains very uncertain. A binary companion to a star can affect its evolution by tides and mass transfer. Although various outcomes, interesting in their own right, are possible, the most important scenario, as far as the overall carbon enrichment of the ISM is concerned, is the interruption or prevention of thermal pulses on the AGB by common-envelope evolution and ejection, following dynamical mass transfer on to a less massive companion. This systematic effect, although small compared with other uncertainties, brings about a significant reduction of the carbon yield of a population of binary stars when compared with a population of single stars of similar mass.

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References

Casares, J. Charles, P. A. Naylor, T.: 1992, *Nature* **355**, 614

Frost, C. A., Lattanzio, J. C.: 1996, *Astrophys. J.* **473**, 383

Groenewegen, M. A. T., de Jong, T.: 1993, *Astron. Astrophys.* **267**, 410

Hamann, W.-R., Koesterke, L., Wessolowski, U.: 1995, *Astron. Astrophys.* **299**, 151

Karakas, A. I., Tout, C. A., Lattanzio, J. C.: 1999, *Mon. Not. R. Astr. Soc.*, submitted

Kroupa, P., Tout, C. A., Gilmore, G.: 1993, *Mon. Not. R. Astr. Soc.* **262**, 545

Maeder, A.: 1992, *Astron. Astrophys.* **264**, 105

Maeder, A., Meynet, G.: 1994, *Astron. Astrophys.* **287**, 803

Reimers, D.: 1975, in *Problems in Stellar Atmospheres and Envelopes*, eds. B. Baschek, W. H. Kegel, G. Traving, Springer, Berlin, p. 229.

Tout, C. A., Aarseth, S. J., Pols, O. R., Eggleton, P. P: 1997, *Mon. Not. R. Astr. Soc.* **291**, 732

Tout, C. A., Eggleton, P. P.: 1988, *Mon. Not. R. Astr. Soc.* **231**, 823