Binary AGB Nucleosynthesis

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Summary. The evolution of stars in binary systems is radically different to single-star evolution if and when the stars expand such that their radii are comparable with their separation. This is particularly relevant to Asymptotic Giant Branch (AGB) stars as their radii are many hundreds of times that of the sun. Their demise may be observed as a planetary nebula. Stellar envelope ejection due to the presence of a companion star truncates evolution up the thermally pulsing AGB and reduces the effect of the third dredge up. As such, binary PNe should not be as enhanced in carbon, nitrogen or *s*-process elements as their single star equivalents.

Key words: Binary Stars, Nucleosynthesis, Mass Transfer, Roche Lobe Overflow, Common Envelope Evolution, Carbon Stars, Barium Stars

1 Introduction

The thermally-pulsing AGB (TPAGB) is the final nuclear-burning phase of evolution of stars with mass less than about $8\,\mathrm{M}_\odot$ (see Karakas, this volume, for a review). After each thermal pulse a third dredge up episode may bring the products of helium burning, especially carbon and *s*-process elements, to the stellar surface. In stars of mass greater than about $4\,\mathrm{M}_\odot$ carbon is converted to nitrogen by hot-bottom burning. At the end of the AGB a strong wind develops which removes the stellar envelope, exposes the hot central core and possibly forms a planetary nebula (PN).

In a binary system AGB evolution can be prematurely ended by interaction with the companion star. This is particularly common during the AGB because during this phase the stellar radius is largest. If the binary components are close enough, mass transfer by wind or Roche-lobe overflow (RLOF) removes the AGB envelope and exposes the core. As in single stars, this may lead to PN formation. However, because the AGB star undergoes fewer, possibly zero, third dredge up episodes before its envelope is lost, its surface abundance, and hence that of the PN, is not as enhanced in carbon, nitrogen or *s*-process elements as would be a single-star of the same mass. This has consequences for chemical yields and the abundance distribution in the PN. If, as has been suggested, asymmetric PNe are formed in binary systems, a correlation of asymmetry with PN chemical abundances should exist.

While most AGB envelope material will be lost from the system, some may be accreted onto the secondary star. This mass transfer is thought to be responsible for the formation of the Barium (Ba) stars at solar metallicity, the CH stars at lower metallicity and carbon-enhanced metal poor stars (CEMPs) in the Galactic halo. In rare cases, the companion star may spiral into the core of the AGB star during the common envelope phase leading to formation of a single star. More likely, spiral-in leads to a compact binary at the center of a PN.

2 Mass Transfer Scenarios

Mass loss and/or transfer is most relevant during evolutionary phases when the stellar radius is large, i.e. the (first) giant branch and AGB. Traditionally, mass loss is split into two regimes: stellar wind and Roche-lobe overflow. While the following discussion follows this dichotomy, it should be kept in mind that this is a simplification and that efforts are ongoing to unify the scheme into something more physical (Frankowski, this volume, Mohamed and Podsiadlowski, this volume, also Bonacic, Glebbeek and Pols, submitted to A&A). Figure 1 outlines the typical binary mass-transfer evolutionary scenario, for further details see the review of Jorissen [9].

In most binary stellar models, including ours, mass transfer by a stellar wind is treated according to the Bondi and Hoyle [1] prescription. In binaries that are sufficiently wide that RLOF is avoided, wind accretion onto the secondary may be significant. It is thought to be responsible for CH and Ba star formation, and maybe also CEMP stars. Figure 2a shows the effect of wind accretion on a secondary star: as the separation (and hence binary period) increases, wind accretion becomes inefficient. However, if the separation is too small, RLOF occurs and truncates the evolution.

During RLOF mass is transferred through the inner Lagrange point. The envelope of an AGB star is convective so it expands as mass is removed and this further increases the mass-transfer rate. It is most likely that the secondary star cannot accrete at such a high rate so the system passes into a common envelope phase (Taam, this volume). This will likely remove all the envelope of the AGB star and truncate the evolution, leaving a white dwarf and the companion star in a close(r) orbit. Figure 2b shows that as the separation decreases RLOF sets in earlier. This prevents further third dredge up events, leads to less carbon in the primary (compared to a single star of the same mass) and hence less carbon transferred to the secondary. The same applies to other elements produced during the AGB such as *s*-process elements and nitrogen.

3 Binary Effect on the Primary Star: Chemical Yields and PNe

The effect of binarity on the chemical yields of TPAGB stars compared to equivalent-mass single-star yields is a reduction of the yield of elements made on the AGB, especially helium, carbon, nitrogen and the *s*-process elements. To illustrate this,

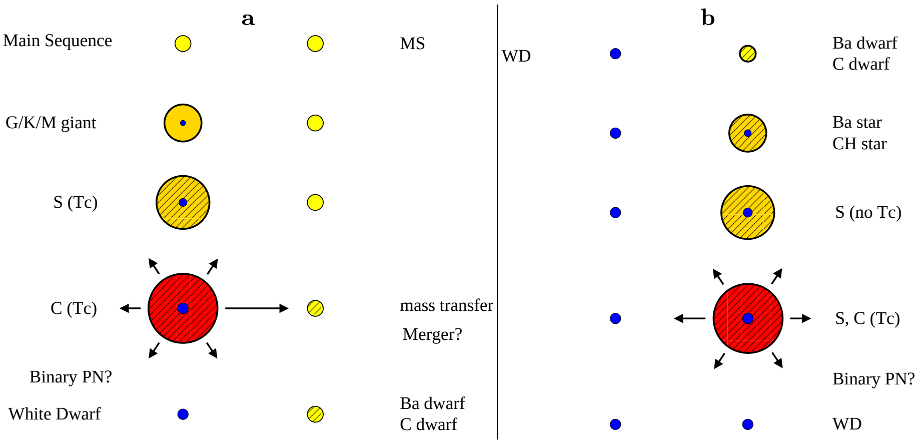

Fig. 1. Binary evolution and mass transfer, adapted from [9]. The star on the left is the (initially) more massive primary. Panel a shows the evolution of the primary from the main sequence, through the AGB to the white dwarf phase. During the AGB phase mass transfer to the companion may pollute it with carbon and/or s-process elements (denoted by hashed lines), forming a CH or Ba star (depending on the metallicity). Panel b shows the evolution of the secondary, which is qualitatively similar except that the secondary will be observed as a CH/Ba dwarf or giant during its main sequence and giant branch respectively.

figure 3 shows the terminal AGB abundances of $Z = 0.02$ single and binary stars as a function of initial separation. The terminal AGB abundance is of direct relevance to planetary nebula formation because it is observed in the PN.

In initially long-period binaries, the stars behave as single stars and there is little effect due to binarity. In short-period binaries mass transfer before the AGB leads to either a merger, and hence yields and abundances similar to a single star of higher mass, or complete suppression of the AGB phase. Intermediate-period binaries have their AGB phase truncated to a greater or lesser extent depending on the period. In a population of stars, AGB suppression is the dominant effect.

In summary, if the presence of a companion star terminates AGB evolution and leads to a PN, it is expected that the abundances of the PN are "less evolved" compared to a single star of the same initial mass, i.e. *not so enriched* in carbon, nitrogen and s-process abundances. According to [6] the effect on chemical yields *from AGB stars only* is a reduction of perhaps up 50% in the yields of ^{12}C, ^{14}N and s-process elements, but of course there are many uncertainties in binary evolution folded into this number and it should *definitely not be taken quantitatively.*

4 Binary Effect on the Secondary Star: Carbon and Ba stars

As described above, the secondary may accrete material from either the wind of the primary of by RLOF. In both cases the accreted material has a larger molecular

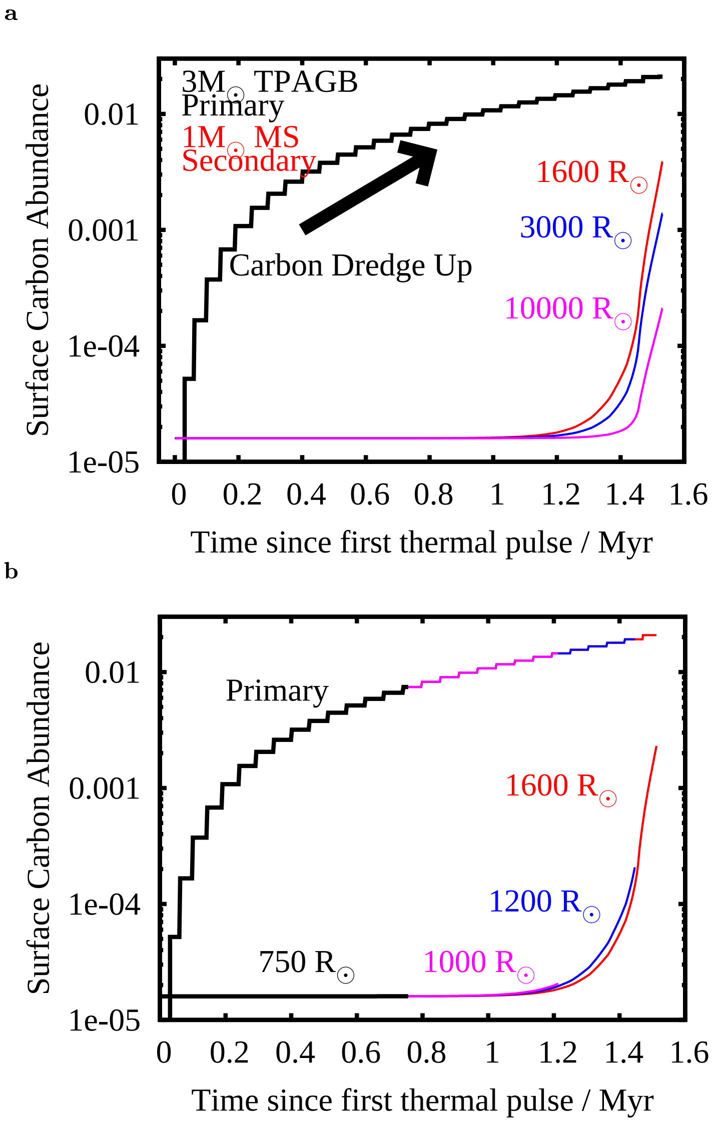

Fig. 2. Surface carbon abundance vs time since the first thermal pulse (in the primary star) for a circular binary with initial parameters $M_1 = 3\,\mathrm{M}_\odot$ (donor), $M_2 = 1\,\mathrm{M}_\odot$ (accretor), variable separation (as shown) and $Z = 10^{-4}$. The abundance of the primary is shown by the thick lines and clearly shows each third dredge up event. The secondary is shown by the thin lines, different colours represent various initial separations, as labeled. In panel (**a**) the separation is large enough ($1600 \leq a/\mathrm{R}_\odot \leq 10^4$) that mass transfer is by wind accretion only. The secondaries go on to evolve through a carbon-enhanced metal poor (CEMP) phase. In panel (**b**) the separation is smaller and TPAGB evolution is truncated by Roche-lobe overflow and common envelope ejection. The effect is to reduce the amount of carbon accreted by the secondary, to the point where a binary with a separation of $750\,\mathrm{R}_\odot$ accretes very little carbon. The binaries were simulated with the code of [7].

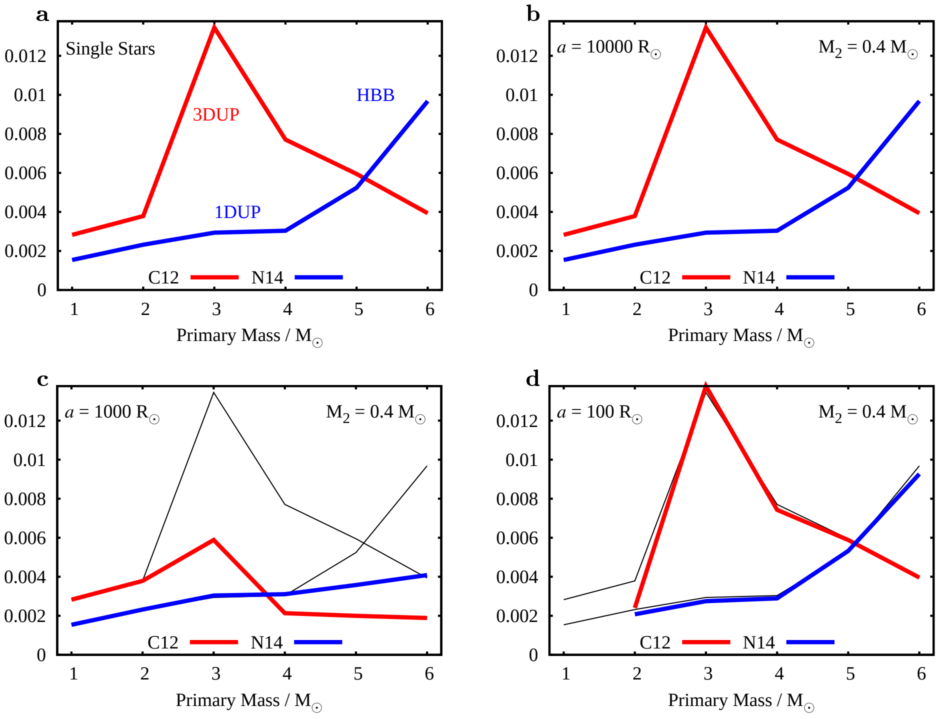

Fig. 3. Terminal abundances of ^{12}C and ^{14}N as a function of single-star mass (panel **a**) or binary primary mass (panels **b**, **c** and **d**) for $Z = 0.02$ with $M_2 = 0.4\,\mathrm{M}_\odot$. Panel **a** shows the typical single-star yield pattern of ^{12}C from third dredge-up around $3\,\mathrm{M}_\odot$ and ^{14}N from HBB above about $4\,\mathrm{M}_\odot$. Panel **b** shows the same for wide binaries, with initial separation $a = 10^4\,\mathrm{R}_\odot$: there is little difference. However, if the separation is reduced to $10^3\,\mathrm{R}_\odot$ as in panel **c**, which is comparable to the radius of AGB stars, third dredge up and the yields of both ^{12}C and ^{14}N are reduced by RLOF truncating the AGB phase. To illustrate that caution is required when dealing with complex binary evolution, panel **d** shows the evolution of stars which start with $a = 100\,\mathrm{R}_\odot$:
If $M_1 \geq 2\,\mathrm{M}_\odot$ these merge during the pre-AGB evolution and then evolve in a very similar way to single stars and will be observed as single stars;
If $M_1 < 2\,\mathrm{M}_\odot$ a common envelope phase during the first giant branch prevents evolution to the AGB (no terminal abundance is shown in this case).

weight than that of the envelope of the secondary, so mixes and dilutes into it by the thermohaline instability [11].

In low-metallicity stars enough carbon may be accreted that the secondary becomes a carbon star (i.e. has $N_\mathrm{C} > N_\mathrm{O}$ in the stellar envelope). Such stars are known as *extrinsic* carbon stars and may be observed as CH stars at low metallicity ([Fe/H] ~ -1) and CEMP stars at very low metallicity ([Fe/H] $\lesssim -2$). Figure 4 shows that low-luminosity extrinsic carbon stars formed by mass transfer account for the tail of SMC carbon-star luminosity function which is missing in single-star simulations [5].

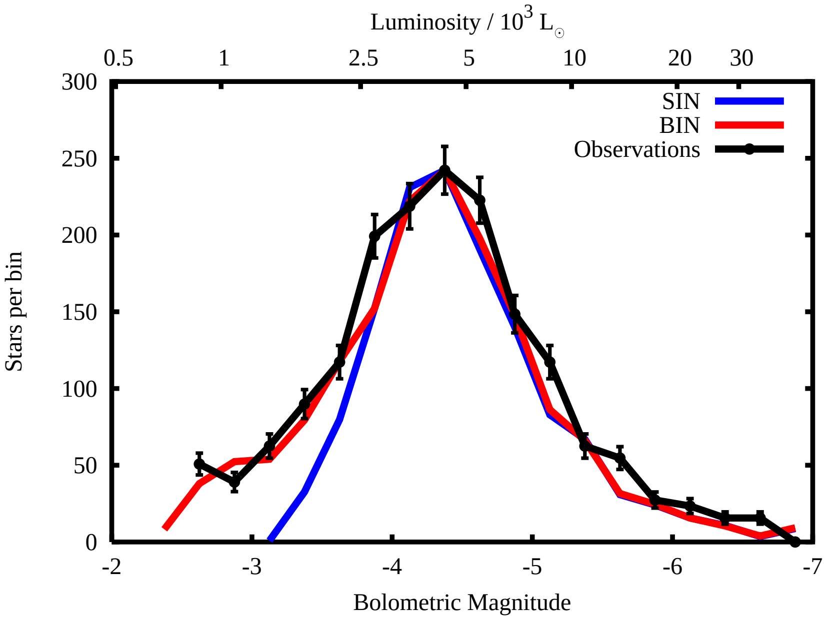

Fig. 4. The luminosity functions of single (blue) and binary (red) carbon stars in the SMC (after [5]) compared to the observed distribution of [2]. The single-star distribution fails to reproduce the low-luminosity stars around $M_{\rm bol} \lesssim -3$, but these are naturally reproduced in binaries: they are pre-TPAGB *extrinsic* carbon stars.

The barium stars are giants which have accreted material rich in barium (an *s*-process element) from a TPAGB star at some point in their past (see figure 1 and [8]). Current binary-star evolution models suggest that all Ba stars with orbital periods less than 10 years should be circularized because of tides [10], but the observations show significant eccentricity down to the shortest observed periods. Simulations of binaries with a more sophisticated treatment of the transition from wind to RLOF mass-transfer regimes seem to improve the match between observations and models (Frankowski, this volume, Mohamed and Podsiadlowski, this volume, also Bonacic, Glebbeek and Pols, submitted to A&A), but there is some way to go before we can claim that the problem is solved.

5 Conclusions

Most stars are in binary stars so it is clearly important to include them in studies of planetary nebulae. Abundances measured in PNe correspond to the surface abundances of an AGB star when it sheds its envelope. In binaries envelope ejection may occur at an earlier time than in an equivalent-mass single star because of RLOF and associated common envelope ejection. This reduces the number of third dredge up episodes and/or time for hot-bottom burning during the TPAGB and hence yields of ^{12}C, ^{14}N and s-process elements drop relative to single stars. It is expected that binary planetary nebulae should show relatively normal abundances, similar to unevolved pre-TPAGB single stars.

We recommend that interested readers try to evolve some binaries for themselves using our online binary stellar evolution and chemical yield tool at `http://www.phys.uu.nl/~izzard/cgi-bin/binary2.cgi` which is based on the codes of [3, 4, 7].

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