Duplicity: its part in the AGB’s downfall

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Abstract. Half or more of stars more massive than our Sun are orbited by a companion star in a binary system. Many binaries have short enough orbits that the evolution of both stars is greatly altered by an exchange of mass and angular momentum between the stars. Such mass transfer is highly likely on the asymptotic giant branch (AGB) because this is when a star is both very large and has strong wind mass loss. Direct mass transfer truncates the AGB, and its associated nucleosynthesis, prematurely compared to in a single star. In wide binaries we can probe nucleosynthesis in the long-dead AGB primary star by today observing its initially lower-mass companion. The star we see now may be polluted by ejecta from the primary either through a wind or Roche-lobe overflow. We highlight recent quantitative work on nucleosynthesis in (ex-)AGB mass-transfer systems, such as carbon and barium stars, the link between binary stars and planetary nebulae, and suggest AGB stars as a possible source of the enigmatic element, lithium.

1. Duplicitous AGB stars

The asymptotic giant branch (AGB) phase of stellar evolution is short relative to the nuclear-burning lifetime of a star. AGB stars are scarce but, because they are so bright, they are relatively easy to see. The chance of an AGB star being found in a binary system is also rare, especially given that AGB stars are bright, variable objects, so any companion is just hard to spot. There are some spectacular local examples, e.g. symbiotic systems such as Mira, but detecting a secondary star becomes increasingly difficult at longer distance. Nevertheless, AGB and ex-AGB stars with companions are vitally important to our understanding of many basic astrophysical processes, see, e.g., the review by Lagadec & Chesneau (this volume). Binary interactions involving AGB stars are crucial to planetary nebulae, post-AGB stars, white dwarfs, supernovae (especially type Ia), gamma-ray bursts, thermonuclear novae and stellar mergers, e.g. as gravitational wave sources.

AGB binaries may be rare, but the chemical and dynamical impact of an AGB star on its companion is commonly observed (Jorissen 1999). AGB stars are great chemical factories, making elements from the lightest, such as lithium, carbon and nitrogen, up to the heaviest such as barium, bismuth and lead. Material rich in these chemicals can be transferred to a companion star during the short AGB phase. This material pollutes the companion which retains the chemical signature for the rest of its life. In a lot of cases, this is for many billions of years.
Not all stars that are born in binaries are expected to show this peculiar chemistry from AGB accretion. Close binaries cannot evolve up the AGB because they undergo mass transfer before or during shell hydrogen burning on the first giant branch. Very wide binaries have stars that are so far separated that they do not interact except through their mutual gravitational attraction. The intermediate cases are those which interest us: the binary must be wide enough to allow evolution up the AGB, but close enough that there is mass transfer (probably) by wind accretion.

Consider a circular binary with a $2 \, M_\odot$ primary and a $0.5 \, M_\odot$ secondary star. The primary mass is deliberately chosen to maximize carbon production at a metallicity $Z = 0.02$ (Karakas 2010). The timing and mode of mass transfer depends on the initial separation of the stars. In very close systems with initial separation less than about $75 \, R_\odot$, mass transfer through Roche-lobe overflow starts on the first giant branch (using the models of Izzard et al. 2004, 2006, 2009 as can be found online at www.astro.uni-bonn.de/~izzard/cgi-bin/binary4.cgi). These binaries may merge, or eject their common envelope (Izzard et al. 2012; Ivanova et al. 2013), but either way will probably not lead to the formation of an AGB binary system.

At longer separations, up to about $230 \, R_\odot$, mass transfer begins when the primary is on the AGB but before thermal pulses start. These systems are not expected to be chemically enriched in, e.g., carbon or $s$-process elements, although they may show some nuclear burning signature, e.g. of CN cycling. Again, it is not clear whether such systems emerge from the common envelope as a binary or merge. In wider systems than these the primary AGB star manages to begin thermal pulses, but the system may then suffer mass transfer by Roche-lobe overflow, likely common-envelope ejection (the envelope is barely bound) and hence AGB termination. Only wide systems with separations longer than about $1900 \, R_\odot$ avoid Roche-lobe overflow.

Wide systems can still transfer mass by stellar wind accretion. Whether this is by classical Bondi-Hoyle-Littleton wind accretion (Bondi & Hoyle 1944), or an enhanced form of mass transfer (e.g. “wind-Roche-lobe-overflow”, Mohamed & Podsriadlowski 2007), is a matter of much current debate. The efficiencies of mass and and angular momentum transfer depend critically on which mass transfer mode dominates. This then determines the chemistry in the companion star as well as the final orbital separation (or period) and eccentricity of the binary. These are properties that can be observed in binaries such as barium, CH and carbon-enhanced metal-poor (CEMP) stars. These systems’ AGB primaries have long since shed their envelopes and become white dwarfs, so what we see now is the (originally) secondary, i.e. lower mass, star of the binary. Such systems provide potentially excellent observational constraints on our binary-star models.

2. Carbon stars: CH, CEMP, J and R

AGB stars are expected to be carbon rich, i.e. have $C/O > 1$ by particle number at the surface, if they have initial masses in the range $1.5 \, M_\odot$ to about $4 \, M_\odot$. Stars in evolutionary phases prior to the AGB should, according to canonical single-star evolution theory, not be carbon rich. The only way to make a carbon-rich dwarf or (pre-thermal pulsing AGB) giant star is then through binary mass transfer. This mass transfer is usually assumed to be by wind accretion rather than Roche-lobe overflow because the latter process is thought to lead to rapid ejection of a common envelope with little accretion on the secondary star. Assuming this to be the case, systems with $M_1 = 2 \, M_\odot$, $M_2 = 2 \, M_\odot$, and initial separation of about $230 \, R_\odot$,
$M_2 = 0.5 \, M_\odot$, as described above, transfer up to about $0.05 \, M_\odot$ by the Bondi-Hoyle mechanism at an initial separation of $2000 \, R_\odot$. The exact amount transferred is subject to considerable uncertainty and one may question whether the Bondi-Hoyle formalism – which requires a wind that is fast relative to the orbital speed – is at all valid in AGB stars (Edgar 2004). Nevertheless, models of this type successfully account for the frequency of barium and CH stars seen in our Galaxy (typically 1% of G and K giants), and also the paucity of CH stars at (super-)solar metallicity (Izzard & Tout 2004; Boyer et al., this volume).

Wind accretion models generally fail to reproduce the frequency of CEMP stars seen in the Galactic halo at metallicities less than $[\text{Fe}/\text{H}] = -2$. While observations suggest that CEMP stars are 20% or more of all halo stars (Yong et al. 2013), models predict similar fractions to CH stars, i.e. a few per cent (Izzard et al. 2009). Resolution of the CEMP problem is possible by modification of the initial mass function (Lucatello et al. 2005) however this poses other problems given the lack of nitrogen-enhanced stars (Pols et al. 2012). Enhancement of carbon in giant molecular clouds from which the stars formed is a possibility, but it has recently been re-confirmed by observations that the majority of CEMP stars, which are of the $s$-process rich CEMP-$s$ variety, are binary systems in agreement with the binary mass-transfer model (Starkenburg et al. 2014).

An alternative possibility is to increase the efficiency of wind accretion which in turn expands the binary-star parameter space available to CEMP formation. Recent works by the Nijmegen group of Pols, Abate et al. have attempted to do this both statistically and quantitatively (Abate et al. 2013). Their binary population models are based on those of Izzard et al. (2009) with updates to include wind-Roche-lobe overflow based on the detailed hydrodynamical models of Mohamed & Podsiadlowski (2007). The increased efficiency of wind accretion compared to earlier works (e.g. Hurley et al. 2002) almost doubles the predicted CEMP frequency, helping to reduce the discrepancy with observations.

The abundance patterns in individual CEMP stars can now be used to pin down the initial parameters of their progenitor binary star systems (Abate et al. Astronomy and Astrophysics, submitted). The abundance patterns in observed CEMP stars are compared to the binary-star models using a $\chi^2$ technique. This gives best-fitting initial parameters such as stellar masses and orbital periods. The preliminary results of this study also show that processes in the secondary star, such as thermohaline mixing, may not be as efficient as in previous models (e.g. Stancliffe et al. 2007; Izzard et al. 2009; Stancliffe 2009). This tells us that we do not well understand what happens to material when it is accreted in a binary system and that our population synthesis models are lacking some basic physics (e.g. diffusion, gravitational settling, radiative levitation?).

Close binaries may explain some of the carbon stars found with metallicity around solar. The R-type stars have identical surface properties to normal core-helium-burning stars, except that they are carbon rich, not $s$-process enhanced and are all single (Dominy 1984; McClure 1997). This is clearly an indication that they were all once binaries that have merged! Population synthesis studies, such as Izzard et al. (2007), show that it is possible to make a sufficient number of merged stars with the appropriate properties, i.e. luminosity, temperature, etc., if carbon, made in the core either during the merger or at a subsequent helium flash, is mixed to the surface to form the carbon star. The question then is whether this really happens.

Piersanti et al. (2010) model stars in the most likely R-star formation channel from Izzard et al. (2007), i.e. low-mass red giants merging with helium white dwarfs.
show that a carbon star does not form after the merger. Unfortunately for them, the most likely formation channel is that with the lowest-mass merged stars. Zhang & Jeffery (2013) instead model the highest-mass merger that is predicted by Izzard et al. (2007) and find that a carbon star is made when the ashes of repeated helium flashes are mixed into the convective stellar envelope. Most interestingly, their single star, after the merger, is inflated to roughly the size of an AGB star. In this inflated phase it appears as a J-type carbon star (with C/O > 1 and $^{12}\text{C}/^{13}\text{C} < 10$ by number). Material expelled during the merging process probably formed an oxygen-rich disk around the now single star, just as observed around J stars Abia & Isern (2000). The J star then radiates its excess thermal energy, shrinks and settles down to core-helium burning as a carbon-rich, R-type star. This unified model for R and J stars demonstrates the power of combining binary stellar evolution, population synthesis and nucleosynthesis, although of course there are many unanswered questions and uncertainties that remain.

3. Stellar ejecta: planetary nebulae and the lithium budget

Binary systems containing an AGB star at periods short enough to enter Roche-lobe overflow are likely to have their evolution truncated by common-envelope ejection. It has long been proposed that this induces the formation of a planetary nebula and some believe that all planetary nebulae are formed by common-envelope ejection (Moe & De Marco 2006). If a thermally-pulsing AGB star has its evolution terminated, its surface chemistry will show less of a typical AGB signature, so – at low mass – this should mean less carbon, less s-process elements, but perhaps still some enhancement depending on how many thermal pulses, with associated third dredge up, occurred.

To test this scenario, we have performed population synthesis calculations (Keller et al. in preparation) in which we tag systems as planetary nebulae when they form either by the classical (single-star) wind-loss mechanism, or by common-envelope ejection. We find that most planetary nebulae form through the wind loss channel and only about 20% from common-envelope ejection or merger. The majority of planetary nebulae are AGB stars, although a few per cent may be first giant branch stars (see also Hall et al. 2013).

Fig. 1 shows the elemental ratios C/O vs N/O (by number of particles) as predicted by our models compared to observed planetary nebulae. Most planetary nebulae are expected to have a carbon abundance which is essentially a function of their AGB progenitor’s initial mass, with peak carbon production around 2 $M_{\odot}$. Binary companions complicate the picture not only by truncating the AGB, but also because these stars may merge. In our model this leads to many nitrogen-rich planetary nebulae because the extra mass from the merger triggers hot-bottom burning in stars with mass in excess of 4 $M_{\odot}$. Caution should be exercised, however, because we assume that the efficiency of hot-bottom burning is a function of total stellar mass in the merged objects. This remains to be confirmed by detailed stellar evolutionary models: the CO core mass may be a more important parameter.

While usually the chemical yield from an AGB star is decreased by binary-star interaction, there is one element of which the yield may be increased: lithium. The source of lithium in our Galaxy is unknown (Prantzos 2012). AGB stars make lithium if they are massive enough to process their envelopes by hot-bottom burning. At solar metallicity this would be stars in the approximate initial-mass range of 4 to 8 $M_{\odot}$ (Weiss & Ferguson 2009; Karakas 2010), where the upper limit is set by the minimum
Figure 1. Elemental number ratios in planetary nebula progenitors. The panels show four different progenitor channels: 1) single-star wind, 2) binary-star wind (similar to single stars), 3) post-stellar merger wind and 4) common-envelope ejections. Single stars follow the expected track from detailed AGB models (e.g. Karakas 2010) while binaries are smeared out over much more of the parameter space. The symbols are observed planetary nebulae from Leisy & Dennefeld (1996); Stanghellini et al. (2005) and Leisy & Dennefeld (2006) which are round (⊙), elliptical (★), round or elliptical with a bipolar core (△), bipolar (□) and quadrupolar (♦).
Initially, this scenario becomes more complicated in binary-star systems. If mass transfer is initiated at just the right moment, the envelope – which is already poorly bound – should be rapidly ejected in a common-envelope event. The lithium is then ejected with the envelope, not destroyed, and contributes to the overall Galactic chemical evolution of lithium. For this scenario to be efficient, the initial orbital period must be finely tuned such that Roche-lobe overflow initiates exactly when the stellar lithium abundance is close to maximum. Fig. 2 shows this the mass of lithium ejected from typical binary stars as calculated with the binary_c code (Izzard et al. 2004, 2006, 2009) combined with stellar yields of (Karakas 2010; Fishlock et al. 2014). Integrating the mass ejected as lithium over all initial masses and periods, and compared to single stars, binaries make about 25% more lithium. While this does not solve the missing lithium problem, it helps and shows that these binary AGB stars – while rare – are important when considering the chemical evolution of galaxies.
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