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Effects of binarity on asymptotic giant branch evolution

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Abstract. Binarity can have a significant effect on the evolution and nucleosynthesis in a substantial fraction of all AGB stars. In this contribution I discuss the evidence for binary interaction among AGB stars and their progeny, and I provide an overview of the various binary interaction processes that play a role in AGB binaries and discuss their uncertainties.

Key words. AGB stars – binaries – stellar evolution

1. AGB stars in binaries

The majority of stars occur in binary or higher-order multiple systems (Abt 1983), and this must also be true of AGB stars although it is harder to prove directly than for dwarfs or normal giants. A significant fraction of these binaries are expected to interact during the AGB phase in one way or another. This interaction can strongly affect the properties, the further evolution and the nucleosynthesis of the AGB star and that of its companion. Sometimes the interaction can be directly observed, as in the case of symbiotic binaries with relatively wide orbits (D-type symbiotics), consisting of a Mira-type variable with a wind-accreting companion, probably a white dwarf (Mikołajewska 2003). More commonly the remnants of past interaction in AGB binaries are found, in various guises: binary post-AGB stars, often surrounded by a dusty circumbinary disk (van Winckel 2004), and a zoo of chemically peculiar stars which appear to occur only in binary systems (see § 2). Our current understanding of AGB stars in binaries and their descendants has been nicely reviewed by Jorissen (2003).

Interaction during the AGB phase occurs in binaries that are fairly wide. If the orbit is too close, the stars do not have room enough to expand to AGB dimensions, and their evolution will be cut short before they reach the thermally pulsing AGB phase. This puts a lower limit on the orbital period[1] of about 2 years, for solar metallicity (for Population II, this limit is lower because the TP-AGB is reached at smaller radius). Strong interaction by Roche-lobe overflow, which can significantly change the internal evolution (§ 3.3), is possible in binaries with periods up to about 10 years. However, even in orbits that are so wide that the stars never approach their Roche lobes, interaction can still occur via the strong stellar wind of the AGB star. Observations of the widest symbiotic binaries with an AGB component imply orbital periods of at least 50 years (Mikołajewska 2003). Mira (*o* Ceti) itself is in a binary system showing indications of wind accretion by the companion (Kastner

[1] Note that this is the initial orbital period; the remnants of interacting AGB binaries can be (much) closer.

& Soker 2004). Its current separation is about 75 AU and the implied orbital period at least 100 years. Hence, interaction in AGB binaries occurs for orbital periods between about 2 and at least 100 yrs. According to the study of binarity among solar-type stars in the solar neigbourhood by Duquennoy & Mayor (1991), this period range is close to the peak of the orbital period distribution at 180 yrs, and comprises $\sim$ 25 % of all solar-type binaries. Therefore, binarity could have important effects in a substantial fraction of all AGB stars.

2. Chemically peculiar stars: the progeny of AGB binaries

Many types of binary system exist, in which a relatively unevolved star shows abundance anomalies that are typical of TP-AGB stars. This phenomenon is best studied in the barium stars, G-K giants with a prominent overabundance of barium in their spectra and also showing enhancements of carbon and other *s*-process elements. These star cannot have produced these elements themselves, and indeed the radioactive element Tc is lacking in their spectra: a sign that the s-process is currently inactive. The origin of these chemical peculiarities was not understood until McClure et al. (1980) discovered that Ba stars are all part of binary systems. The companion stars are inferred (and in some cases observed) to be white dwarfs: the remnant of an AGB star that has polluted its companion with its nucleosynthesis products. Other chemically peculiar stars show very similar properties to the Ba stars, and were also discovered to be binaries: the CH stars (McClure & Woodsworth 1990), non-Mira S stars that lack Tc (Jorissen & Mayor 1992), subgiant CH stars (McClure 1997), and dwarf Ba stars (North et al. 2000).

These various classes of chemically peculiar binaries also show similar orbital properties: orbital periods that range between about 0.3 and 30 years, and moderate eccentricities up to about 0.5. These orbital elements are also very similar to those of binary post-AGB stars (van Winckel 2003, 2004), strongly suggesting an evolutionary link between all these classes. Since the orbital period range extends beyond the maximum period for which Roche-lobe overflow is expected in AGB binaries, wind accretion must be responsible for the pollution, at least in the widest systems (Boffin & Jorissen 1988). However, in the closer systems with periods of a few years or less, stronger forms of interaction must have played a role. These interaction processes are further examined in the next section.

3. Binary interaction processes

Stars in binary systems can interact in various ways. In this section I will briefly review the interaction processes that are especially relevant in binary systems containing an AGB star, and the uncertainties involved.

3.1. Wind accretion

A process that does not affect the AGB star directly, but has an effect on the companion and its chemical composition, is accretion from the stellar wind of the AGB star. Because AGB winds are dense and slow, the companion can capture a substantial amount of matter from the wind, even in quite wide orbits. The accretion process is usually described by the Bondi-Hoyle (B-H) mechanism (Bondi & Hoyle 1944), in which a fraction of the outflow within a so-called accretion radius is gravitationally deflected and shocked behind the star moving through the wind, and subsequently accreted. The amount of matter that can be accreted in this way is a strongly decreasing function of the ratio of wind velocity v_w to orbital velocity v_{orb}, and can be quite large in the case of the slow AGB wind. However, the B-H treatment is strictly valid only when the ratio v_w/v_{orb} is much greater than unity, and this is generally not the case in AGB binaries. Hydrodynamical simulations of wind accretion in AGB binaries, e.g. by Theuns et al. (1996); Mastrodemos & Morris (1998) and Nagae et al. (2004), show that the accretion flow becomes very complicated when $v_w \lesssim v_{orb}$, and the efficiency of accretion is less (by a factor 5 . . . 10) than predicted by the B-H formalism. When $v_w \ll v_{orb}$ the accretion flow resembles that of Roche-lobe overflow in the Nagae et al. (2004)

simulations. Recent population synthesis studies of the formation of barium stars (Karakas et al. 2000; Pols et al. 2003; Bonačić & Pols 2004) indicate that efficient wind accretion results in a large population of barium stars with periods larger than 30 years, which are not observed. Clearly, the process of wind accretion in AGB binaries requires more detailed investigations.

3.2. Tidal interaction

When the size of the AGB star is a considerable fraction of the binary separation, tidal interaction becomes effective. The differential gravitational field of the companion raises tidal bulges on the surface, which are misaligned with the line connecting the centers of gravity of the two stars when the stellar spin is not synchronized with the orbit, or when the orbit is eccentric. Frictional dissipation then tends towards synchronous rotation and a circular orbit, which is the situation of minimum energy at a given total angular momentum (which is conserved). The timescale at which the tides synchronize rotation and circularize the orbit depends on the most effective dissipation mechanism, which in the case of AGB stars is turbulent viscosity in their convective envelopes. These timescales are strong functions of the ratio of the stellar radius to the separation, R/a: the synchronization timescale scales as $(R/a)^{-8}$ and the circularization timescale as $(R/a)^{-6}$ (Zahn 1977; Hut 1981; Rasio et al. 1996). In practice this means that, for AGB stars in binaries, tidal circularization becomes very effective when a is less than about three times the maximum radius reached on the AGB, translating to orbital periods less than $3 \ldots 10$ years (depending on stellar mass and metallicity). The orbits of such binaries are expected to be circularized by the end of the AGB phase.

Another important effect of tidal interaction is the spin-up of the AGB star. By the time a star reaches the AGB its envelope has acquired a very large moment of inertia and, since the star has at most conserved its rotational angular momentum (and has probably lost some due to prior stellar winds), it will be rotating much more slowly than the orbital frequency. When tides become effective, angular momentum is therefore transferred from the orbit to the stellar spin. As a result the orbit will therefore shrink somewhat, and the AGB envelope will be spun up significantly. This spin-up could have interesting consequences for nucleosynthesis in the AGB star, in particular for extra-mixing processes that may depend on the (differential) rotation rate in the intershell region, such as the formation of the ^{13}C-pocket (Herwig et al. 2003) that provides neutrons for the s-process. The effects of a relatively fast-spinning envelope on AGB nucleosynthesis are still unexplored.

The tides raised on the AGB star can also potentially increase its mass-loss rate, similar to the 'companion-reinforced attrition process' (CRAP) proposed by Tout & Eggleton (1988) for RS CVn binaries. In their model, the tides increase the magnetic activity of the spun-up star, and although AGB winds are not believed to be magnetically driven, the decrease of effective surface gravity induced by the tides and the resulting more rapid rotation could have a similar effect.

Another unexplored effect is the possibility of resonances between the tides and the Mira-type pulsations of an AGB star, which could be important because the pulsation period is of the same order as the orbital period. Such resonances have been shown to have important effects on tidal circularization in close main-sequence binaries (Witte & Savonije 2002), but have not been investigated in the context of binaries containing evolved giants.

3.3. Roche-lobe overflow

When the separation is small enough for the AGB star to fill its critical tidal potential surface, mass will be transferred to the companion through the inner Lagrange point. The process is known as Roche-lobe overflow (RLOF) and is a very efficient means of mass loss and, potentially, mass transfer that can strongly alter the subsequent evolution. The dynamical stability of RLOF depends on the evolutionary state of the mass donor and on the mass ratio, $q = M_{\rm donor}/M_{\rm comp}$. When q is less than a critical value, RLOF is stable and mass is transferred on the evolution timescale of the donor. For giants with deep convective envelopes, the critical mass ratio is less than unity (depending somewhat on the ratio of core to envelope mass). Since an AGB star usually transfers mass to a less massive main-sequence companion, RLOF is generally unstable. This means the mass transfer rate increases exponentially until the companion is swamped by the envelope material of the donor, and a common envelope is formed around the binary (see § 3.4). Therefore, RLOF is expected to lead to very little mass transfer before a common envelope is formed. The only way for RLOF to be an efficient means of mass transfer is when the AGB star has already lost so much mass prior to filling its Roche lobe (by stellar wind, possibly enhanced by tides) that the binary mass ratio has been reversed. Since mass loss appears to be concentrated at the end of the AGB phase (Vassiliadis & Wood 1993), the window for stable RLOF is very small.

The above discussion is based on the implicit assumption that AGB stars, like less evolved stars, have well-defined sharp outer boundaries so that it is possible to make a clear distinction between filling or not filling the Roche lobe. However, an AGB star has a large atmospheric density scale height (up to a few per cent of the radius) owing to its low surface gravity. This could change the picture considerably. Pioneering calculations by Pastetter & Ritter (1989) that take the finite scale height into account show that substantial mass transfer rates ($\sim 10^{-6} M_{\odot}$/yr) can be driven as a result of atmospheric RLOF, when the stellar radius (as defined by the effective temperature) is still far from the Roche-lobe radius. In practice the atmospheric density scale height can be even larger than assumed by Pastetter & Ritter (1989) because of stellar pulsation (Bowen 1988). These effects could postpone the onset of a dynamical instability of RLOF and significantly increase the amount of mass that can be transferred by RLOF. Future calculations of RLOF involving AGB stars should take this into account.

3.4. Common envelope evolution

Dynamically unstable RLOF is expected to produce a differentially rotating common envelope (CE) surrounding the engulfed companion and the core of the AGB star. What follows is a complicated hydrodynamical process that is far from being well-understood (see Iben & Livio 1993 for a review). Frictional dissipation of the orbital energy will bring the stars closer together, and this spiral-in process is held responsible for the formation of very close binaries containing a compact object, such as cataclysmic variables. Whether the CE can eventually be ejected or whether the binary merges during the spiral-in process, depends on the ratio between the reservoir of orbital energy and the binding energy of the envelope, and on the efficiency of converting one into the other. The more evolved the giant star when RLOF sets in, the more likely CE ejection becomes, since the envelope binding energy is smaller while the initial orbital energy is larger. In binaries containing AGB stars, with very loosely bound envelopes, ejection of the CE without a very drastic shrinking of the orbit seems possible. Binaries in the orbital period range $10^{2\ldots3}$ d containing a post-AGB star or a barium star have likely undergone such a mild CE phase. However, theoretically the final orbital periods are hard to predict, depending also on the role of additional energy sources (e.g. Bonačić & Pols 2004) and on the role of the angular momentum balance (Nelemans & Tout 2004) in the CE ejection process.

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