BINARY LIFE AFTER THE AGB - TOWARDS A UNIFIED PICTURE

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Received 2006 xx; revised 2006 xx

Abstract. A unified evolutionary scheme that includes post-AGB systems, barium stars, symbiotics, and related systems, explaining their similarities as well as differences. Can we construct it? We compare these various classes of objects in order to construct a consistent picture. Special attention is given to the comparison of the barium pollution and symbiotic phenomena. Finally, we outline a ‘transient torus’ evolutionary scenario that makes use of the various observational and theoretical hints and aims at explaining the observed characteristics of the relevant systems.

Key words: stars: AGB and post-AGB, stars: binaries

1. AFTER-AGB BINARIES

The term “after-AGB binaries” will be used in this paper to refer to binary systems in which at least one of the components has gone through the AGB phase, as distinguished from the term “post-AGB”, commonly used to denote the short transition phase between AGB and PN core (CSPN) stages of (single or binary) stellar evolution. In many of such after-AGB systems, the mass transfer from an AGB star has left its mark on the companion, enhancing its abundances with the products of the AGB nucleosynthesis, most remarkably C, F, and s-process elements (see Habing & Olofsson 2003 for a recent review). This pollution will manifest itself later in the companion’s evolution. An exemplary case of after-AGB systems are barium stars: G-K type giants remarkable for their overabundances of Ba (McClure et al. 1980). Related families include Abell-35 subclass of PNe (Bond et al. 1993), barium dwarfs (including the so called WIRRing stars, Jeffries & Stevens 1996), subgiant and giant CH stars, extrinsic S stars and d’-type yellow symbiotics. But not all of the after-AGBs need to be s-process rich. The post-AGB binaries are an interesting case, as they are all by definition after-AGBs: some of them do exhibit s-process enhancement while others do not (Van Winckel 2003, also this volume). Red s-type symbiotic stars (SyS) with massive white dwarf companions ($M_{WD} > 0.5M_\odot$), another member of the after-AGB group, also do not exhibit s-process enhancement (Jorissen 2003a). Not much in this respect can be said about most binary CSPNe, as the unevolved companion is usually too faint to be seen. Finally, some of the cataclysmic variables (CV) with massive white dwarfs should also belong to the after-AGB family.
2. LINKS BETWEEN SYS AND PECULIAR RED GIANTS

Peculiar red giants are a characteristic part of the after-AGB family and are in many respects closely related to symbiotic stars. The links between them have been reviewed previously (Jorissen 2003a, Jorissen et al. 2005); here we provide an updated discussion based on Fig. 1 which displays the various types of SyS and peculiar red giants in a metallicity – spectral-type plane.

The vertical axis corresponds to metallicity which impacts (i) the taxonomy of the classes (CH giants for instance – box 1 – are the halo-equivalent of the disk barium stars – box 6); (ii) the efficiency of heavy-element synthesis (Clayton 1988), and (iii) the location of evolutionary tracks in the HR diagram (hence the correspondence between spectral type and evolutionary status, like the onset of TP-AGB, will depend on metallicity). Fig. 1 therefore considers three different metallicity ranges: (i) $[\text{Fe/H}] < -1$, corresponding to the halo population; (ii) $-1 \leq [\text{Fe/H}] < 0$, or disk metallicity; (iii) $[\text{Fe/H}] \geq 0$, solar and super-solar metallicities. The horizontal axis in Fig. 1 displays spectral type, which roughly corresponds to an evolutionary sequence at a given metallicity, passing from the red giant branch (RGB) to the thermally-pulsing AGB (TP-AGB) phases (between these two phases is the core He-burning phase which is hardly distinguishable from the lower RGB; CH giants probably belong to that phase). Symbiotic activity is expected in the middle of this sequence, because (i) at the left end, stars (like CH)
are not luminous enough to experience a mass loss sufficient to power symbiotic activity; (ii) at the right end, the stars with the barium syndrome need not be binaries (above the TP-AGB luminosity threshold, heavy-elements are synthesized in the stellar interior and dredge-up to the surface, so that “intrinsic Ba” (or S) stars occupy the rightmost boxes – 4 and 8 – of Fig. 1), and hence need not exhibit any symbiotic activity. Those evolved giants which are members of binary systems (like Mira Ceti – box 9) will of course exhibit symbiotic activity. It is noteworthy that late M giants are inexistent in a halo population (hence the crossed box 5), because evolutionary tracks are bluer as compared to higher metallicities. Examples of such very evolved (relatively warm) stars in a halo population (box 4) include CS 30322-023 (Masseron et al. 2006) and V Ari (Vant Eck et al. 2003).

2.1. Halo

In the halo population, the most interesting issue is to understand the origin of the difference between yellow s-type SyS (box 2) and metal-deficient Ba stars (box 3): why do the latter not exhibit any symbiotic activity? The reason seems to reside in a difference in their orbital period distributions: yellow s-type SyS represent the short-period tail of the distribution (Fig. 2), where for a given mass-loss rate accretion will be more efficient, and hence will trigger symbiotic activity.

2.2. Intermediate metallicities

In the intermediate-metallicity regime, the situation is quite clear: as the star evolves to the right along the spectral sequence, its luminosity (hence mass loss) increases, and for binary stars along that sequence, the symbiotic character will become stronger. The real issue here is to understand the origin of the difference between boxes 7 and 10/11: why are red s- (and d-)type SyS never exhibiting the barium syndrome, despite very similar locations in the HR diagram and similar orbital-period distributions (Fig. 2)? In former discussions of this issue (e.g. Jorissen 2003a), it had been suggested that binary stars with the barium syndrome (box 7) and SyS without it (box 10) differ in their metallicities. It is known that at high metallicities heavy-element synthesis is less efficient (Clayton 1988). However, there is so far no evidence for red symbiotic stars being on average more metal-rich than barium or extrinsic S stars. Schild et al. (1992) and Schmidt & Mikołajewska (2003) have compared the carbon abundances of SyS and normal giants, and found abso-
lutely no difference, thus confirming at the same time the absence of any signature of internal nucleosynthesis and dredge-ups, or of pollution through mass transfer.

Other solutions to this puzzle may be suggested, such as (i) s- and d-type SyS are not intrinsic barium stars, because they are not TP-AGB stars; (ii) neither are they extrinsic barium stars, because their companion never went through the TP-AGB phase, either because it is a He WD or because it is a main sequence star. Regarding item (i), it is very likely indeed that red s-type SyS are not TP-AGB stars, since they rather involve early M giants. The situation is less clear for d-type SyS, as they involve Miras which are often claimed to be TP-AGB stars. Nevertheless, many Miras do not exhibit signatures of heavy-element nucleosynthesis (they are not carbon stars and lack lines from the unstable element Tc; Little et al. 1987).

Regarding item (ii), the possibility for hot companions to SyS to be He WDs is the most appealing since (a) the eccentricities observed for symbiotic systems are much smaller than those observed in pre-mass-transfer systems (M giants in the period range 200 – 1000 d have eccentricities up to 0.3; Jorissen et al. 2004), thus suggesting that mass transfer has taken place in these systems; (b) the mass distribution of the hot components peaks between 0.4 and 0.5 $M_\odot$ (Mikołajewska 2003 and this volume), as expected for He WDs. Of course, an alternative explanation – like a main sequence companion – needs to be found for those SyS companions with masses exceeding 0.5 $M_\odot$ (T CrB, FG Ser, FN Sgr, AR Pav, V1329 Cyg; Mikołajewska 2003). Although a main sequence companion is quite unlikely in recurrent or symbiotic novae like T CrB and V1329 Cyg, the situation regarding the nature of symbiotic-star companions for non-nova systems is far from being settled, as mentioned by Mikołajewska (2003) while answering a question by one of the authors at the La Palma symbiotic-star conference: the question of whether [the companion to CI Cyg, Z And, FN Sgr] is a disk-accreting main-sequence star or a quasi-steady hydrogen-burning white dwarf is open so long as we have no good theory to distinguish between these possibilities. Indeed, the nature of the companion to CI Cyg has changed over the years, from main-sequence accretor (Kenyon & Webbink 1984; Kenyon et al. 1991; Mikołajewska & Kenyon 1992) to hot and luminous stellar source powered by thermonuclear burning (Mikołajewska 2003)! The same move from main-sequence to white-dwarf accretor holds true for AR Pav (Kenyon & Webbink 1984; Quiroga et al. 2002).

2.3. Solar metallicities

The evolutionary status of the rare set of yellow d’ SyS (box 12), which were all shown to be of solar metallicity, has recently been clarified (Jorissen et al. 2005) with the realisation that in these systems, the companion is intrinsically hot (because it recently evolved off the AGB), rather than being powered by accretion or nuclear burning. Several arguments support this claim: (i) d’ SyS host G-type giants whose mass loss is not strong enough to heat the companion through accretion and/or nuclear burning; (ii) the cool dust observed in d’ SyS (Schmid & Nussbaumer 1993) is a relic from the mass lost by the AGB star; (iii) the optical nebulae observed in d’ SyS are most likely genuine planetary nebulae (PN) rather than the nebulae associated with the ionized wind of the cool component (Corradi et al. 1999). d’ SyS often appear in PN catalogues. AS 201 for instance actually hosts two nebulae (Schwarz 1991): a large fossil planetary nebula detected
by direct imaging, and a small nebula formed in the wind of the current cool component; (iv) rapid rotation is a common property of the cool components of d’SyS (see Table 1 of Jorissen et al. 2005). It has likely been caused by spin accretion from the former AGB wind like in WIRRing systems (Jeffries & Stevens 1996; Jorissen 2003b). The fact that the cool star has not yet been slowed down by magnetic braking is another indication that the mass transfer occurred fairly recently (Theuns et al. 1996). Corradi & Schwarz (1997) obtained 4000 y for the age of the nebula around AS 201, and 40000 y for V417 Cen.

The possible existence, in box 13, of binary systems of nearly solar metallicity with orbital properties typical of barium systems, but not exhibiting the barium syndrome, is still controversial, as discussed by Jorissen (2003b).

3. ORBITAL CHARACTERISTICS: RIDDLES AND HINTS

Intense AGB mass loss/transfer is not only important for chemical abundances; it does also influence the orbital properties of after-AGB systems. Four binary evolution processes are usually invoked when describing the after-AGB systems formation: (i) tidal interactions, (ii) wind accretion, including tidally enhanced winds (Companion-Reinforced Attrition Process or CRAP, Eggleton 1986), (iii) stable Roche-lobe overflow (RLOF), and (iv) common envelope (CE) evolution.

Alas, current evolutionary computations fail to reproduce the correct ranges of orbital periods, eccentricities and s-process enhancement levels (e.g. Pols et al. 2003; Frankowski 2004). The basic reason for this problem is quite simple, as nicely put by Iben & Tutukov (1996): as a result of CE interaction, initially close systems become closer and, because of wind mass loss, initially wide systems become wider. [...] most known symbiotic systems belong to a rare population on the borderline between initially close and wide binaries. The models do not produce eccentric systems with periods below \( \sim 2000 – 3000 \) d and all systems below \( \sim 1000 \) d enter a CE and undergo a dramatic orbital shrinkage.

The observed after-AGB systems with intermediate periods (100 –2000 d) have somehow avoided the catastrophic outcome of a CE, but the theoretical concepts proposed so far are not satisfactory in explaining this fact: (i) the inclusion of tidal forces affects only the detached evolution and does not improve the final results; (ii) CRAP does allow for slightly shorter final periods in detached evolution but still not below 2000 d and any stronger effect would prevent TP-AGB, thus impeding s-process; (iii) stable RLOF occurs only for a narrow range of initial parameters; (iv) lowered binding energy of the AGB envelope due to the inclusion of ionisation energy as proposed e.g. by Han et al. (1994) is problematic (Harpaz 1998); (v) CE formalism based on angular-momentum instead of on energy (Nelemans et al. 2000) is promising, however, for the moment it lacks physical explanation.

Also puzzling is high eccentricity (up to \( e = 0.4 \)) at periods down to 300 d observed among post-AGB binaries, and to a lesser extent Ba stars and extrinsic S stars. The most promising explanation here is eccentricity pumping by a circumbinary disk (Waelkens et al. 1996; Artymowicz et al. 1991). Another suggestion is periastron mass loss eccentricity pumping (Soker 2000) but this mechanism can operate only for wide (detached on the AGB) systems.

We suggest that these conundrums are part of a bigger puzzle together with the following observational and theoretical hints. First, some of the young after-AGB
objects exhibit combined RS CVn and Ba star properties: X-rays, H$_\alpha$ emission and fast rotation combined with Ba enhancement and long orbital periods. The list consists of Ba stars 56 Peg (Frankowski & Jorissen 2006), HD 165141 (Jorissen et al. 1996), d’ symbiotics (Jorissen et al. 2005, see also the discussion in Sect. 2.3), WIRRing stars, (Jeffries & Stevens 1996), and Abell-35 CSPNe (Thévenin & Jas- niewicz 1997). They form a strong evidence for fast rotation in young after-AGB systems, supposedly due to spin accretion from wind (Jeffries & Stevens 1996; Jorissen 2003b). Second, post-AGB systems, the youngest among the after-AGB family, are known to possess circumbinary disks (Van Winckel 2003). Dusty circumbinary disks, tori and bipolar outflows are common among bipolar and ring-like PNe, and have also been observed in some AGB stars, notably π 1 Gru (Sahai 1992) and V Hya (Knapp et al. 1999). The latter object is also remarkable for having fast rotation velocity (6-16 km s$^{-1}$) and a long secondary photometric period ($\sim 6200$ d, in addition to the radial pulsation period of 530 d), possibly due to a binary companion. Another notable factor is that dust formation and radiation-driven wind cause reshaping of Roche equipotentials and reduction of the effective gravity of the mass-losing star (Jorissen 2003b; Schuerman 1972; Frankowski & Tylenda 2001).

4. THE ‘TRANSIENT TORUS’ SCENARIO

Gathering the observational and theoretical constraints described above, we propose a ‘transient torus’ scenario for explaining the observed orbital periods and eccentricities of “after AGB” binaries. This scenario can be divided into four phases, schematically represented in Fig. 3:

1. Wind accretion. The system is well detached and the companion accretes mass and angular momentum from the giant’s wind. Spin accretion is especially efficient, proceeding through an accretion disk formed around the companion (Theuns et al. 1996; Mastrodemos & Morris 1998). Orbital evolution proceeds roughly as in spherically-symmetric wind case (Jeans mode), i.e., $a(M_1 + M_2) = \text{const}$ and the eccentricity stays almost constant.

2. (Near) RLOF with substantial $L_2/L_3$ outflow. Tidal forces and evolutionary expansion of the giant bring it closer to its Roche lobe. The outflow becomes concentrated in the direction to the companion, which happens even before the actual Roche-lobe filling (e.g. Frankowski & Tylenda 2001). The matter is ‘funnelled’ through the vicinity of $L_1$.

3. Formation of a circumbinary torus. Matter escaping through the vicinity of $L_2$ (or $L_3$, after mass ratio reversal) forms a spiral around the system. But after one orbital period every portion of ejecta becomes shadowed from the giant by the newly ejected matter and ceases being accelerated outwards by the radiation pressure on dust. Part of the older ejecta gravitationally falls back onto the binary and collides with the new stream. A thick circumbinary torus is formed.

4. Formation of a Keplerian circumbinary disk. The torus drags angular momentum from the binary and at the same time it is slowly pushed outwards by the radiation pressure on dust. The leftovers become a Keplerian disk. Only small part of the ejecta is pulled into Keplerian motion, so the angular momentum removal from the central binary is moderate and the orbital period can stay as long as a few hundred days.
Point 2. in this sequence deserves particular consideration. At this stage the companion resides within the wind acceleration zone which is governed by the dust condensation radius, $R_{\text{cond}}$. On TP-AGB $R_{\text{cond}}$ is 2–5 $R_*$ (Gail & Sedlmayr 1988).

Thus the matter flowing preferentially through $L_1$ in the direction of the companion is still moving slowly in the vicinity of the companion (which favors higher accretion rate) and is still feeling an outward acceleration due to radiation pressure on dust (so the modified Roche potential is in force and a dynamical mass transfer leading to a CE can be avoided). Mass loss from the binary can proceed on a dynamical time scale for some part of this phase without an ensuing CE. These effects do not play a role for non-dusty winds, thus not changing the classical CE at RGB and E-AGB, leading to pre-CV and CV systems, as required for explaining those close binary populations.

![Fig. 3. The 'transient torus' scenario. For description of the phases, see text.](image)

REFERENCES

Artymowicz P., Clarke C. J., Lubow S. H., Pringle J. E. 1991, ApJ, 370, 35
Bond H. E., Ciardullo R., Meakes M. G. 1993, in *Planetary nebulae*, IAU Symp. 155, eds. R. Weinberger & A. Acker, Kluwer Academic Publishers, Dordrecht, p. 397
Clayton D. D. 1988, MNRAS, 234, 1
Corradi R., Schwarz H. E. 1997, in *Physical Processes in Symbiotic Binaries and Related Systems*, ed. J. Mikolajewska, Copernicus Foundation for Polish Astronomy, Warsaw, p. 147
Corradi R. L. M., Brandi E., Ferrer O. E., Schwarz H. E. 1999, A&A, 343, 841
Eggleton P. P. 1986, in J. Trümper, W. H. G. Lewin, W. Brinkmann (eds.), *The evolution of galactic X-ray binaries*, Reidel, Dordrecht, p. 87
Frankowski A. 2004, PhD thesis, N. Copernicus Astronomical Center, Warsaw
Frankowski A., Jorissen A. 2006, Obs., 126, 25
Frankowski A., Tylenda R. 2001, A&A, 367, 513
Gail H.-P., Sedlmayr E. 1988, A&A, 206, 153
Habing H. J., Olofsson, H. 2003, *Asymptotic Giant Branch Stars*, Springer Verlag, New York
Han Z., Podsiałowski P., Eggleton P. P. 1994, MNRAS, 270, 121
Harpaz A. 1998, ApJ, 498, 293
Iben I. Jr., Tutukov A. V. 1996, ApJS, 105, 145
Jeffries R. D., Stevens I. R. 1996, MNRAS, 279, 180
Jorissen A. 2003a, in R. L. M. Corradi, J. Mikolajewska, T. J. Mahoney (eds.), Symbiotic stars probing stellar evolution, ASP Conf. Ser., 303, 25
Jorissen A. 2003b, in H. Habing, H. Olofsson (eds.), Asymptotic Giant Branch Stars, Springer Verlag, New York, p. 461
Jorissen A., Famaey B., Dedecker M., Pourbaix D., Mayor M., Udry S. 2004, Rev. Mex. Astron. Astrof. Conf. Ser. 21, 71–72
Jorissen A., Schmitt J. H. M. M., Carquillat J. M., Ginestet N., Bickert K. F. 1996, A&A, 306, 467
Jorissen A., Zács L., Udry S., Lindgren H., Musaev F. A. 2005, A&A, 441, 1135
Kenyon S. J., Oloversen N. A., Mikolajewska J., Mikolajewski M., Stencel R. E., Garcia M. R., Anderson C. M. 1991, AJ, 101, 637
Kenyon S. J., Wehlink R. F. 1984, ApJ, 279, 252
Knapp G. R., Dobrovolsky S. I., Ivezic Z., Young K., Crosas M., Mattei J. A., Rupen M. P. 1999, A&A, 351, 97
Little S. J., Little-Marenin I. R., Bauer W. H. 1987, AJ, 94, 981
Masseron T., Van Eck S., Famaey B., Goriely S., Plez L., Siess L., Beers T., Primas F., Jorissen A. 2006, A&A, 455, 1059
Mastrodemos N., Morris M. 1998, ApJ, 497, 303
McClure R. D., Fletcher J. M., Nemec J. M. 1980, ApJ, 238, 35
Mikolajewska J. 2003, in R. L. M. Corradi, J. Mikolajewska, T. J. Mahoney (eds.), Symbiotic stars probing stellar evolution, ASP Conf. Ser., 303, 9
Mikolajewska J., Kenyon S. J. 1992, MNRAS, 177
Nelemans G., Verbunt F., Yungelson L. R., Portegies Zwart S. F. 2000, A&A, 1011
Pols O. R., Karakas A. I., Lattanzio J. C., Tout C. A. 2003 in R. L. M. Corradi, J. Mikolajewska, T. J. Mahoney (eds.), Symbiotic stars probing stellar evolution, ASP Conf. Ser., 303, 290
Quiroga C., Mikolajewska J., Brandi E., Ferrer O., García L. 2002, A&A, 387, 139
Sahai R. 1992, A&A, 253, 33
Schild H., Boyle S. J., Schmid H. M. 1992, MNRAS, 258, 95
Schmid H. M., Nussbaumer H. 1993, A&A, 268, 159
Schmidt M., Mikolajewska J. 2003, in R. Corradi, J. Mikolajewska, T. J. Mahoney (eds.), Symbiotic stars probing stellar evolution, ASP Conf. Ser., 303, 163
Schuerman D. W. 1972, Ap&SS, 19, 351
Schwarz H. E. 1991, A&A, 243, 469
Soker N. 2000, A&A, 357, 557
Theuns T., Boffin H. M. J., Jorissen A. 1996, MNRAS, 280, 1264
Thévenin F., Jasniowicz G. 1997, A&A, 320, 913
Van Eck S., Goriely S., Jorissen A., Plez B. 2003, A&A, 404, 291
Van Winckel H. 2003, ARA&A, 41, 391
Waelkens C., Van Winckel H., Waters L. B. F. M., Bakker E. J. 1996, A&A, 314, 17