Transient Torus – A Unified After-AGB Binary Scenario?

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Summary. Links between Planetary Nebulae and binarity are often invoked when explaining complicated shapes of PNe. These shapes may be a result of the companion's influence, but the binary itself is in turn affected by the nebular ejection. Many classes of binary objects are supposedly related to binary systems interacting at the end of the AGB phase (i.e., at the future nebular material ejection). These include close binary CSPNe, post-AGB binaries, Ba/CH/S stars, a fraction of symbiotics and of the cataclysmic variables. Because of their common origin, a general term 'after-AGB binaries' seems appropriate, despite of other differences. But the present orbital characteristics of many of these systems resist explanation by current theoretical models. Using recent observational results about the omnipresence of circumbinary tori and disks or often high rotation rates in young 'after-AGB' systems, and stressing the role of radiation driven dusty winds, this paper presents a new evolutionary scheme combining L1 mass transfer, L2/L3 systemic mass loss, transient circumbinary torus/disk formation, binary-disk interactions and accompanying orbital evolution. This 'transient torus' scenario, including key observational features of the various 'after-AGB' binaries, appears to be promising in explaining some of the puzzling properties of their e–$\log P$ diagrams, thus offering a unified picture for the formation of these systems.

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

1 After-AGB Binaries

There are several families of more or less peculiar binary systems that share one key characteristic – at least one of the two binary components in these systems has gone through the AGB phase in the past. The term "after-AGB binaries" will be used to refer to such binaries in this paper, 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 [11] for a recent review). This pollution will manifest itself later in the companion's evolution. Of course, heavy AGB mass loss and mass transfer, as well as tidal effects, important due to the giant dimensions of an AGB star, lead also to orbital evolution of these systems. Results of these relatively short-lasting interactions can then be observed during much longer after-AGB lives of such systems.

An exemplary case of after-AGB systems are barium stars: G-K type giants remarkable for their overabundances of Ba [26]. Related families include Abell-35 subclass of PNe [4], barium dwarfs (including the so called WIRRing stars [15]), 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 [35]. Red s-type symbiotic stars with massive white dwarf companions ($M_{\rm WD} > 0.5 M_\odot$), another member of the after-AGB group, also do not exhibit s-process enhancement [16]. Not much in this respect can be said about most binary CSPNe, as the unevolved companion is usually too faint to be seen. Some of the cataclysmic variables (CV) with massive white dwarfs should also belong to the after-AGB family.

2 The Observational Puzzle

The orbital parameters of after-AGB systems supplied by the observers are a long-standing challenge for the binary evolution theory. Four binary evolution processes are usually invoked when modeling formation of the after-AGB systems: tidal interactions, wind accretion (including tidally enhanced winds: Companion-Reinforced Attrition Process or CRAP [5]), stable Roche-lobe overflow (RLOF), and common envelope (CE) evolution. Alas, thus constructed evolutionary computations fail to reproduce the correct ranges of orbital periods, eccentricities and s-process enhancement levels (see e.g. [29, 6]). A typical model result from [6] is shown in Fig. 1. The basic reason for this problem is quite simple, and has nicely been put by [14]: *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.* As a result, the models do not produce eccentric systems with periods below ~2000–3000 d and all systems below ~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 ionization energy as proposed e.g. by [12] is problematic [13]; (v) CE formalism based on angular-momentum instead of on energy [27] is promising, however, for the moment it lacks physical explanation.

Equally puzzling are high eccentricities at relatively short periods observed especially among post-AGB binaries (up to $e = 0.4$ at $P_{\rm orb} \sim 300$ d and up to $e = 0.6$

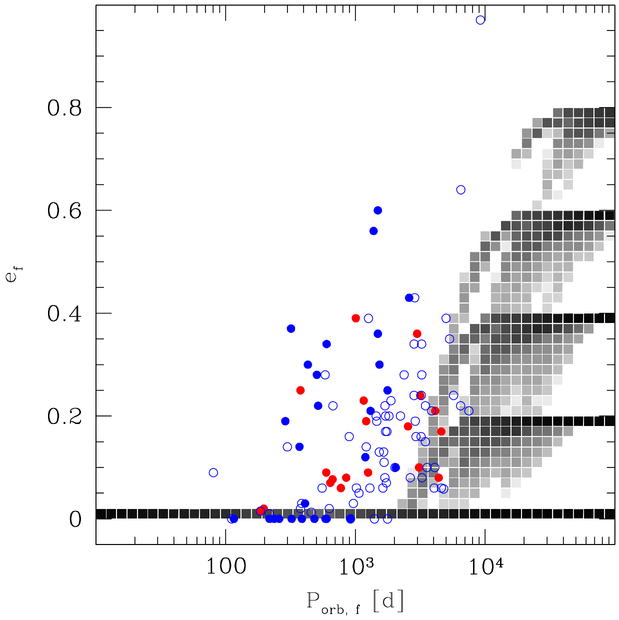

Fig. 1. Observational e–$\log P$ diagram for after-AGB binaries overplotted on a typical modeling result [6]. Red: post-AGB [36] (supplemented with Van Winckel, private comm.), empty blue circles: Ba stars [19], filled blue circles: extrinsic S stars [19]. Shades of grey represent density of model after-AGB systems in a given area.

at $P_{\rm orb} \sim 1500\,$d). Ba stars and extrinsic S stars also exhibit this feature, but to a lesser extent. The most appealing explanation here is eccentricity pumping by a circumbinary disk [38, 2]. Another suggestion is periastron mass loss eccentricity pumping [32] but this mechanism can operate only for wide (detached on the AGB) systems.

We have suggested [8] 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_α emission and fast rotation combined with Ba enhancement and long orbital periods. The list consists of Ba stars 56 Peg [7], HD 165141 [18], d' symbiotics [20], WIRRing stars [15], and Abell-35 CSPNe [34]. They form a strong evidence for fast rotation in young after-AGB systems, supposedly due to spin accretion from wind [15, 17]. Second, post-AGB systems, the youngest among the after-AGB family, are known to possess circumbinary disks [35]. 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 [30] and V Hya [22]. 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), possibly due to a binary companion. Third, non-catastrophic RLOF has to be reconsidered, not only with the usual stability conditions, but also in the light of possibility of matter outflows through the outer Lagrangian points L_2/L_3 (e.g. [28]). 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 [17, 31, 9].

3 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 the after-AGB binaries. This scenario can be divided into four phases, schematically represented in Fig. 3:

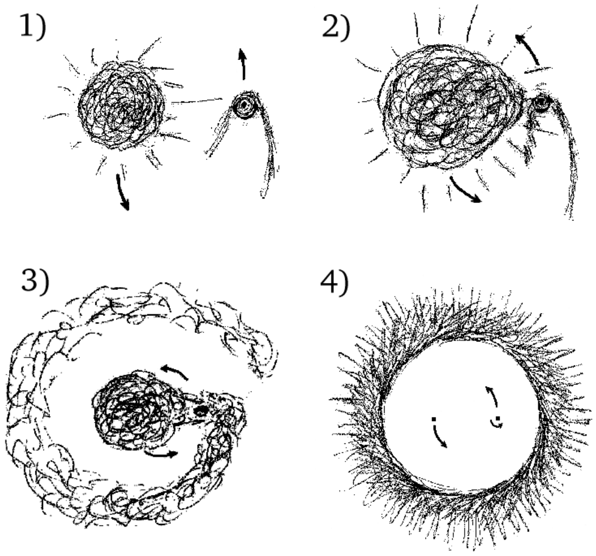

Fig. 2. The 'transient torus' scenario. For description of the four phases, see text.

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 [33, 25]. 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. [9]). The matter is 'funnelled' through the vicinity of L_1. This effect can be important even for very large separations, as suggested by recent images of *o* Ceti [21].

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 may gravitationally fall back onto the binary and collide with the new stream. A thick circumbinary torus is formed.

4. Formation of a Keplerian circumbinary disk. The torus drags angular momentum and energy 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. The orbital period can stay as long as a few hundred days, while the binary eccentricity is pumped-up significantly.

Point 2. in this sequence deserves more consideration. At this stage the companion resides within the wind acceleration zone which is governed by the dust condensation radius, $R_{\rm cond}$. On TP-AGB $R_{\rm cond}$ is 2–5 R_* [10]. 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.

4 Effects on the e–$\log P$ Diagram

The circumbinary disk-binary interaction places a natural limit on the maximum eccentricity. This can already be noticed in an oversimplistic description which reduces tidal interaction with the disk to dragging the stars at apastron. In this picture the angular momentum transfer to the disk ceases when angular velocity of a star at apastron becomes smaller than the disk velocity. It turns out that detailed studies of disk-binary interactions and resonances [23, 1], place a similar limit around $e = 0.7$, with the rate of e pumping strongly reduced already at $e \sim 0.5$. This agrees with the recently found highest eccentricities observed among post-AGB stars of about e=0.6 [36, 37].

To further investigate the possibilities of the transient torus scenario as presented above, a preliminary check has been conducted using the typical theoretical results available at hand. A 'normal' (that is, inconsistent with observational the e–$\log P$) results from an AGB binary evolution code [6] have been post-processed to include eccentricity pumping by a circumbinary disk. The procedure was as follows. Systems entering dynamically stable RLOF were assumed to produce an L_2/L_3 outflow and circularise tidally, so that immediately after the massive outflow the system had a separation of a, zero eccentricity, and a tight Keplerian disk with an inner radius of $1.7a$ (a minimal stable radius for a circumbinary disk [3]) and with a mass up to $0.01\,M_\odot$. From this point the disk was pushed away by the tidal interaction with the binary. The interaction was assumed to vanish when the disk had escaped to $50a$. This last value was chosen somewhat arbitrarily to roughly reflect the observations of post-AGB disks; the results are not very sensitive to this parameter.

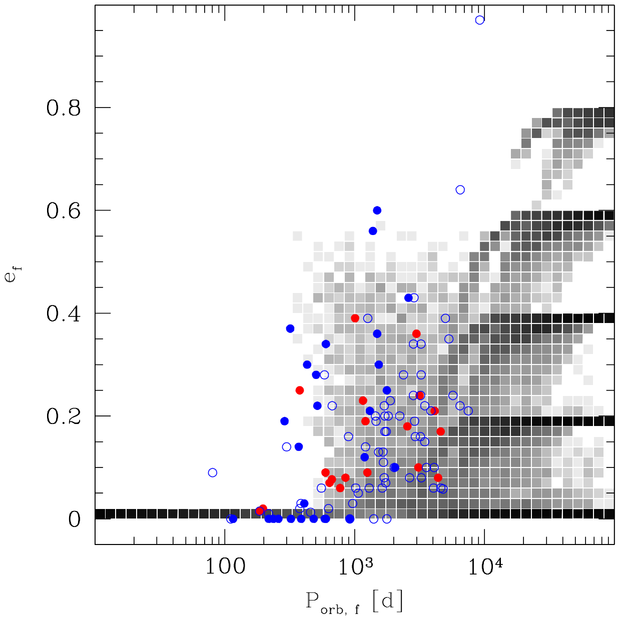

Fig. 3. Observational e–$\log P$ diagram for after-AGB binaries overplotted on a model including transient torus evolution. Symbols as in Fig. 1.

The resulting theoretical e–$\log P$ diagram for after-AGB binaries is shown in Fig. 3, again overplotted with the observations: post-AGB, Ba and extrinsic S stars data. The same base model has been used for the transient torus case as presented above in Fig. 1. When comparing these two figures, the region covered by the transient torus systems becomes immediately evident as a trapezoidal area contained within $P > 300$ d and $e < 0.6$. Most of the previously troublesome observational points lie within this area. The agreement with observations in much better now! Note that the model parameters have been chosen with the observational data in mind, but have not been too much fine-tuned. The agreement can still be improved by adjusting some of the values. For example varying the product of the final disk distance and its maximum mass by a factor of two moves the upper eccentricity limit by roughly 20%.

In the presented transient torus scenario the s-process enriched and non-enriched after-AGB systems are mixed in the e–$\log P$ in a natural way, depending on the event's timing in the evolution of the primary and on the mass of the companion (higher binary mass allows to expel the disk with less eccentricity pumping). The somewhat smaller eccentricities of Ba and S giants at a given period, compared to the post-AGBs, can be attributed to a systematic difference in the average companion masses, as indeed hinted by the observational data [19, 24]. A combination of primary's evolutionary stage at the torus event and tidal effects at companion's RGB ascent (to become observable as a Ba giant) can be invoked as additional factors to explain this difference.

In summary, application of the transient torus scenario described here gives quite promising first results in explaining the e–$\log P$ diagram of after-AGB binaries. The eccentricity pumping mechanism can indeed lead to the observed orbital characteristics. Seemingly, the 'theoretical gap' at intermediate periods and eccentricities of these binaries finally starts to fill in.

References

1. P. Artymowicz: PASP **104**, 769 (1992)
2. P. Artymowicz, C. J. Clarke, S. H. Lubow, J. E. Pringle: ApJ **370**, 35 (1991)
3. P. Artymowicz,, S. H. Lubow: ApJ **421**, 651 (1994)
4. H. E. Bond, R. Ciardullo, M. G. Meakes: The Abell 35-Type Planetary Nuclei. In: *Planetary nebulae*, IAU Symp. 155, ed by R. Weinberger, A. Acker (Kluwer Academic Publishers, Dordrecht 1993) p 397
5. P. P. Eggleton: From wide to close binaries? In: *The evolution of galactic X-ray binaries*, ed by J. Trümper, W. H. G. Lewin, W. Brinkmann (Reidel, Dordrecht 1986) pp 87–105
6. A. Frankowski: Late stages of stellar evolution in binary systems. PhD Thesis, N. Copernicus Astronomical Center, Warsaw (2004)
7. A. Frankowski, A. Jorissen: Obs **126**, 25 (2006)
8. A. Frankowski, A. Jorissen: BaltA **16**, 104 (2007)
9. A. Frankowski, R. Tylenda R.: A&A **367**, 513 (2001)
10. H.-P. Gail, E. Sedlmayr: A&A **206**, 153 (1988)
11. H. J. Habing, H. Olofsson: *Asymptotic Giant Branch Stars* (Springer, New York 2003)
12. Z. Han, P. Podsiadlowski, P. P. Eggleton: MNRAS **270**, 121 (1994)
13. A. Harpaz: ApJ **498**, 293 (1998)
14. I. Iben Jr, A. V. Tutukov: ApJS **105**, 145 (1996)
15. R. D. Jeffries I. R. Stevens: MNRAS **279**, 180 (1996)
16. A. Jorissen: The Link between Symbiotic Stars and Chemically Peculiar Red Giants. In: *Symbiotic stars probing stellar evolution*, ASP Conf. Ser., vol 303, ed by R. L. M. Corradi, J. Mikołajewska, T. J. Mahoney (ASP, San Francisco 2003) pp 25–40
17. A. Jorissen: AGB stars in Binaries and their Progeny. In: *Asymptotic Giant Branch Stars*, ed by H. Habing, H. Olofsson (Springer, New York 2003) pp 461–518
18. A. Jorissen, J. H. M. M. Schmitt, J. M. Carquillat, N. Ginestet, K. F. Bickert: A&A **306**, 467 (1996)
19. A. Jorissen, S. Van Eck, M. Mayor, S. Udry: A&A **332**, 877 (1998)
20. A. Jorissen, L. Začs, S. Udry, H. Lindgren, F. A. Musaev: A&A **441**, 1135 (2005)
21. M. Karovska, E. Schlegel, W. Hack, J. C. Raymond, B. E. Wood: ApJ **623**, 137 (2005)
22. G. R. Knapp, S. I. Dobrovolsky,Z. Ivezić, K. Young, M. Crosas, J. A. Mattei, M. P Rupen: A&A **351**, 97 (1999)

23. S. H. Lubow, P. Artymowicz: Eccentricity Evolution of a Binary Embedded in a Disk. In: *Binaries as Tracers of Stellar Formation*, ed by A. Duquennoy, M. Mayor (Cambridge University Press, Cambridge New York 1992) pp 145–154
24. T. Maas: A study of post-AGB stars with a dusty disc. PhD Thesis, Katholieke Universiteit Leuven, Leuven (2003)
25. N. Mastrodemos, M. Morris: ApJ **497**, 303 (1998)
26. R. D. McClure, J. M. Fletcher, J. M. Nemec: ApJ **238**, 35 (1980)
27. G. Nelemans, F. Verbunt, L. R. Yungelson, S. F. Portegies Zwart: A&A **360**, 1011 (2000)
28. Ph. Podsiadlowski, P. C. Joss, J. J. L. Hsu: ApJ **391**, 246 (1992)
29. O. R. Pols, A. I. Karakas, J. C. Lattanzio, C. A. Tout: Can Standard Evolution Models Explain the Properties of Barium Stars? In: *Symbiotic stars probing stellar evolution*, ASP Conf. Ser., vol 303, ed by R. L. M. Corradi, J. Mikołajewska, T. J. Mahoney (ASP, San Francisco 2003) pp 290–293
30. R. Sahai: A&A **253**, 33 (1992)
31. D. W. Schuerman: Ap&SS **19**, 351 (1972)
32. N. Soker: A&A **357**, 557 (2000)
33. T. Theuns, H. M. J. Boffin, A. Jorissen: MNRAS **280**, 1264 (1996)
34. F. Thévenin, G. Jasniewicz: A&A **320**, 913 (1997)
35. H. Van Winckel: ARA&A, **41**, 391 (2003)
36. H. Van Winckel: BaltA, **16**, 112 (2007)
37. H. Van Winckel: this volume (2007)
38. C. Waelkens, H. Van Winckel, L. B. F. M. Waters, E. J. Bakker: A&A, **314**, 17 (1996)