The WD perspective on the PN binary hypothesis

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Abstract. There is no solid theoretical precept through which we can understand the amazing shapes of planetary nebulae (PN). The only plausible theoretical explanation of most PN shapes is that a companion interacts with the mass-losing progenitor of the central star of PN. Plausibility, however, is not sufficient to prove reality and efforts are ongoing to test the PN binary hypothesis observationally. Here, a short review is presented of the problem, but this time set within the context of binarity in the white dwarf (WD) population. We find that observationally the PN and WD binary populations agree. Most noticeably, both populations point to a deep flaw with current theories of the common envelope binary interaction. However, unexplained issues remain, several of which point to a sizable population of as yet undetected intermediate period binaries. Unfortunately, today the WD binaries do not constrain sufficiently the PN binary hypothesis.

1. Introduction

Text books tell us that a planetary nebula (PN) is produced by a mass-losing asymptotic giant branch (AGB) star and later ionized by the AGB star core, on its way to becoming a white dwarf (WD). The great majority of PNe are not spherical. They display axi- and point-symmetries, sometime with the addition of jet-like structures. These shapes have been attributed to the action of stellar rotation and/or magnetic fields (García-Segura et al. 1999, 2005), which result in an equatorially-concentrated AGB mass-loss. When the post-AGB star heats up, it blows a fast but tenuous wind, which is constrained at the equator, resulting in an elliptical or bipolar PN. In a minority of cases, the action of a companion is thought to be required in order to produce jets, point symmetries, or to explain off-center central stars (see Balick and Frank 2002 for a review).

For the last two decades the community debated whether stellar rotation and global magnetic fields can be sustained in a single AGB star (Soker and Livio 1989, Soker 1997, De Marco 2006, Zijlstra 2007). Recently, the debate has been rekindled (Soker 2006, Nordhaus et al. 2007) by the argument that in a large majority of cases, single AGB stars are unlikely be able to sustain large scale magnetic fields for long enough to affect shaping, because the field drains the star of angular momentum on short time scales and quenches itself. As the models have shown, magnetic fields can be an effective ingredient in shaping many PNe, but in those models the magnetic field strength was assumed constant and was not coupled to the negative feedback action of the stellar envelope. Without the action of an angular momentum source, the field would vanish.
Such angular momentum source could effectively be provided by a companion. If this is what actually happens, then PNe would be, by and large, a binary-interaction phenomenon.

1.1. Constraints on the binary hypothesis from an observational point of view

Ideally, we would detect the central star binary fraction and put an end to the debate. We know that 10-15% of all central stars are short period binaries with $P < \sim 3$ days (Bond 2000). All these stars have gone through a common envelope (CE), whereby the companion is engulfed by the primary when it expands on the red giant branch (RGB) or, in the case of central binaries of PN, the AGB. The core of the giant and the companion therefore find themselves inside the envelope of the giant and gravitational drag forces reduce their orbital separation. Deposition of energy and angular momentum into the envelope eventually results in its ejection and the emergence of a close binary (Paczynski 1976). We also know that about 10% of all central stars are in wide (visual) binaries (Ciardullo et al. 1999), which are unlikely to have interacted.

Radial velocity surveys have been carried out (e.g., De Marco et al. 2004, Afšar and Bond 2005) to detect binaries with $P > \sim 3$ days, but central stars have high luminosities and strong winds, resulting in strong spectral line variability which mask even the strongest binary signal (De Marco et al. 2008a). Near IR excess techniques have, when applied to central stars of PN, their own problems, such as the fact that central stars are bright even in the near IR and their distances tend to be large, such that (the common) M-type main sequence companions are hard to detect. This said, Frew and Parker (2008) has analyzed a sample of 2MASS and DENIS-observed objects and deduced that a third to one half of them have an IR excess indicative of binarity. The caveat here is that companions fainter than M4-8V stars (depending on the luminosity of the primary) cannot be detected.

1.2. Constraints on the binary hypothesis from a population synthesis point of view.

Moe and De Marco (2006) determined from a population synthesis study that the number of PN in the Galaxy should be 6 times larger than is observed, at the 3$\sigma$ level, if single stars and binaries within a certain mass range make PNe. Their prediction was based on the standard rules of stellar and galactic evolution. They therefore concluded that only some of these objects, maybe those which have gone through a binary interaction, can make a PN. Moe & De Marco (in preparation) have determined not only the fraction of all “classically-produced” PN that go through a binary interaction, but produce a binary period distribution for the central stars of PN and WDs that we will use later.

In this paper, we cast the information about central stars of PN in binaries in the context of the WD binary population and use the combined information to constrain the PN binary hypothesis.

2. Binarity on and after the AGB: consolidating period distributions

In Fig. 1 we show a cartoon Hertzsprung-Russell (HR) diagram portraying the evolution of binaries from the AGB, to the WD phase. Those binaries that enter a CE will quickly move to the hot side of the HR diagram, become close binary central stars of PN and eventually become close WD binaries, while those binaries that avoid a CE will become intermediate period binary post-AGB stars, intermediate period central star binaries and eventually intermediate period WD binaries. Below we review what we know of the periods of post-AGB binary populations and compare their distributions.

2.1. The WD binary periods distribution

All evolved populations should reflect the binary fraction and period distribution of their parent population with some exceptions. The main exceptions are that, binaries with periods shorter
Figure 1. Cartoon HR diagram portraying life as a binary. The lighter star evolves from the lower AGB, to the thermally-pulsing (TP) AGB to the post-AGB phase and then to the WD phase. The darker star is an unevolved low mass main sequence star. Depending on the binary separation on the AGB the resulting binary will be close (post-CE) or intermediate/wide. The post-AGB phase can be skipped if a CE takes place.

than a certain threshold will have their period shortened further by a CE interaction. In addition, some periods will be altered by other interactions, for instance tidal captures. There will be then a small fraction of binaries that merge and, finally, there are those binaries that are too wide to interact and have their separations widened further when one or both of the components suffer mass-loss.

Farihi et al. (2006) determined the projected separation distribution of a sample of WDs known to have near IR excess indicative of a cool companion. We have plotted the 42 objects from Table 5 of Farihi et al. (2006) that are marked WD+RD (red dwarf) in Fig. 2 where we have de-projected all separations by dividing them by 0.67, the average of sin i, and obtained periods by using a WD mass of 0.6 $M_\odot$ and a RD mass of 0.34 $M_\odot$ (corresponding to an M4V star). The group at lower periods are all upper limits. The gap between the two groups is the result of the CE interaction shortening orbital separations. The cluster of lower limit periods constitutes 30% of the total, possibly pointing to the fact that only 10-15% of all WD binaries are post-CE systems (assuming a total WD binary fraction of 30-40%; Holberg, these proceedings).

Schreiber et al. (2008) determined directly that 35% of all WD+RD binaries are post-CE systems. This is approximately the same figure one would deduce from the work of Farihi et al. (2006) and translates to about 10-15% of all WDs, assuming the same WD binary fraction of 30-40%. Schreiber et al. (2008) determined the periods of 7 post-CE WD+RD binaries, which we plot on a separate histogram (Fig. 3) alongside the work of Farihi et al. (2006). What is extremely surprising in their finding is that all post-CE binaries detected so far have periods smaller than a day, where one can confidently state that if binaries with periods longer than that limit and shorter than a few weeks had been present they would have been easily detected. This is in contradiction with all predictions of period distributions for post-CE populations (e.g.,
Yungelson et al. 1993, Han et al. 1995), no matter what values of the CE efficiency parameter is chosen. As we shall see below, this is also in line with the post-CE central stars of PN, as suggested already by De Marco et al. (2008b).

**Figure 2.** The WD+RD period distributions obtained by the HST imaging project of Farihi et al. (2006). The lower period group are upper limits, presumably corresponding to the distribution revealed by Schreiber et al. (2008) in Fig.3. The distributions is scaled to a total of 30, representing the $\sim$30% binary fraction of WD.

**Figure 3.** The WD+RD period distributions obtained by the radial velocity program of Schreiber et al. (2008). The distributions are scaled to a total of 10, representing the $\sim$10% post-CE binary fraction for WD.

2.2. The predicted vs. observed WD period distribution
In Figs. 4 and 5, we have combined the WD period distribution from Farihi et al. (2006) but have substituted the short period group in that distribution with the post-CE WD period distribution of Schreiber et al. (2008). This is in accordance with what we concluded in § 2.1. In the same Figure we also present a preliminary prediction by Moe & De Marco (in preparation) which evolved a population of G-F stars (using the period distribution of Duquennoy and Mayor 1991) to the WD stage. This distribution is scaled to 55%, which accounts for a 60% binary fraction determined by Duquennoy and Mayor (1991) minus a small percentage of stars which have merged. The predicted distribution should only be taken as indicative, except for the following four characteristics: (i) the WD binary fraction, at 30-40% seems lower than what might be expected if they derive from main sequence stars with spectral type G-F (which should approximately represent the mean WD progenitors as can be judged by the mean WD mass as determined by Liebert et al. 2005 and the initial-final mass relation of Weidemann 2000). (ii) The predicted post-CE period distribution extends to longer periods compared to the observations. While these predictions are still preliminary they are similar to those of previous population synthesis work (Yungelson et al. 1993, Han et al. 1995). (iii) The prediction has some intermediate period binaries. While the exact period of these objects is very uncertain, it is likely that such objects exist, since several companions should be tidally captured by the AGB giant, but will avoid CE because the giant rotation and orbit of the companion become synchronized before capture takes place. (iv) Finally, the position of the upper edge of the CE gap is predicted well.

2.3. The binary central star of PN period distribution
As we have already described, binary central stars are hard to detect. 10-15% are known to have periods smaller than $\sim$3 days. This has long been presumed to be a lower limit, due to the fact that the irradiation technique used to detect these objects is less effective for larger orbital
separations. However, De Marco et al. (2008b) showed that if systems with $3 \text{ days} \lesssim P \lesssim 15 \text{ days}$ were plentiful, the technique should have detected them. This led De Marco et al. (2008b) to suggest that either there is another bias that prevents the detection of systems with periods in the $\sim 3$-15 day range, or that these systems do not exist.

The wide central star binary period distribution was derived by using data from Ciardullo et al. (1999), de-projecting projected separations and using the same mass constraints to derive periods as used for the WD wide binaries in §2.1. The binary fraction for this population is 9%.

The comparison of short period systems between the WDs and the central stars can be carried out by looking at Figs. 4 and 5 where we have used the predicted distribution to facilitate the comparison. The obvious lessons to be drawn from the comparison are: (i) post-CE central star binaries might extend to slightly longer periods ($\sim 3$ days) than post-CE WD binaries ($\sim 1$ day), although this needs to be checked with a larger sample. (ii) Both central stars and WD close binary distributions fall short of the maximum period predicted for post-CE systems. We emphasize here once again that such prediction relies critically on the value chosen for the CE efficiency, but that no matter what this choice is, all predictions suggest that CEs can produce a substantial number of binaries with periods $\gtrsim 1$-3 days, contrary to these observations. (iii) for the wider binaries, the WD distribution is closer to the upper edge of the CE gap, while the central stars cluster at much larger periods. In fact, there are no wide central star binaries with separations near the HST resolution limit (0.05 arcsec or 50 AU at a typical PN distance of 1 kpc), while predictions suggest a rising number of binaries for decreasing periods down to the gap limit. (iv) We are not surprised at the dearth of WD and central star wide binaries with the very longest periods, since this is due to biases of the respective detection techniques.

We leave the discussion of the intermediate period binaries seen in the prediction to §2.4.

2.4. The post-AGB binary period distribution.
We finally discuss the intermediate period binaries. First of all, we point out that detecting central star, or WD, binaries with periods from several months to several years is extremely difficult. For all intents and purposes we can therefore assume that the large period gap between short and long periods WD and central star binaries could well be partly populated.

As we explained in §2.2, Moe and De Marco (in preparation) predict that there could be a population of binaries in that period gap where the secondary was tidally captured but avoided
the CE. This statement is in line with the existence of a population of binaries where the primary is a post-AGB star and the secondary is, most likely, a main sequence star. Post-AGBs are stars that are still too cool to ionize the circumstellar material that was ejected during the AGB and so they cannot yet have a PN. It is however likely that these stars will in due course ionize the PN and become intermediate period central star of PN and eventually WD+RD intermediate period binaries. In Fig. 1 these are labeled as post-AGB binaries. We should also point out that close post-AGB binaries are not possible since post-AGB stars have radii that are multiple times the solar radius \( (5-50 \ R_{\odot}) \) so that a stable companion must be at a few stellar radii, implying periods of the order of 100 days and above.

It appears that \( \sim 30\% \) of the entire post-AGB population has such intermediate period companions \((P=100-1500 \ \text{days}; \text{van Winckel} \ 2003) \). If so we could expect to find a sizable population of central star and WD binaries in this period range. This would in turn raise the overall binary fraction to be more in line with what we expect from the main sequence binary fraction (to something of the order of 40-45\%=10-15\%+30\%). (We note, however, that while this is plausible for the central star population, binary searches for WDs are more complete and it is likely that a population of intermediate period WD binaries would have been already discovered.) We plot these binaries along with the central stars and the prediction in Fig. 6, where we scaled the post-AGB binaries to a value of 30. As can be seen from the figure, their period range is not that predicted. However, predictions of these periods are extremely sensitive to assumptions and should be considered approximate.

![Central Star binaries & post-AGB binaries + prediction](image)

**Figure 6.** The central star of PN binary period distribution (black/burgundy), plotted along with the post-AGB binary period distribution (dark grey/dark orange) and compared with a preliminary prediction by Moe and De Marco (in preparation; light grey/blue).

### 3. Conclusion

The comparison of WD and central star period distributions has allowed us to draw a number of conclusions.

- There is a fundamental agreement between the period distributions of the shortest periods WD and central star binaries. This points to a deficit in our understanding of the CE interaction in that even using the whole range of plausible CE efficiency parameters, post-CE binaries are predicted with periods longer than we observe.
• There is an overall dearth of binaries in the WD population compared to the main sequence population which is plausibly its progenitor, but which could be reconciled with expectations if there were a population of intermediate period binaries that is as yet undetected.
• We must be aware that disks and tori present around a binary (e.g., all binary post-AGB objects have such disks) can alter their periods.
• The lack/dearth of wide central star binaries with separations in the 20-500 AU range is puzzling in that one would expect there to be more binaries at the short period end of the wide binary period/separation distribution; this is indeed the case for the WDs. Although more objects need to be detected to determine whether this is an effect of low number statistics, we wonder whether these wide binary central stars could be triple systems (one is known to be; A 63; Ciardullo et al. 1999, De Marco et al. 2008b). We know that \(~10\%\) of all main sequence stars of type G-F are indeed triples (Duquennoy and Mayor 1991). If so, it is possible that the wider of the three stars needs to be farther away to allow a stable system.
• Finally, even if an additional 30% of intermediate period central star binaries is detected, the central star binary fraction with an orbital separation that allows a past interaction, would only be about 40-45%, too small to justify the entire PN phenomenon with binarity. This unfortunately does not yet disprove the PN binary hypothesis, although it might be already suggesting that a binary-only evolutionary channel for PN might not be correct. Difficult to observe interactions with very faint companions such as brown dwarfs and planets cannot however be excluded and may make up a sizable part of the PN population. For a full review see De Marco (2009).

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References
Afşar M and Bond H E 2005 Memorie della Societa Astronomica Italiana 76 608
Balick B and Frank A 2002 ARAA 40 439–486
Bond H E 2000 ASP Conf. Ser. 199: Asymmetrical Planetary Nebulae II: From Origins to Microstructures p 115
Ciardullo R Bond H E Sipior M S Fulton L K Zhang C Y and Schaefer K G 1999 AJ 118 488–508
De Marco O 2006 Planetary Nebulae in our Galaxy and Beyond (IAU Symposium vol 234) ed Barlow M J and Méndez R H pp 111–118
De Marco O 2009 PASP, in press
De Marco O Bond H E Harmer D and Fleming A J 2004 ApJL 602 L93–L96
De Marco O Wortel S Bond H E and Harmer D 2008a Asymmetric Planetary Nebulae IV, in press pp ArXiv e–prints 0709.1508
De Marco O Hillwig T C and Smith A J 2008b AJ 136 323–336
Duquennoy A and Mayor M 1991 A&A 248 485–524
Farihi J Hosain D W and Wachter S 2006 ApJ 646 480–492 (Preprint arXiv:astro-ph/0603747)
Frew D J and Parker Q A 2008 Asymmetrical Planetary Nebulae IV, in press
García-Segura G Langer N Różycka M and Franco J 1999 ApJ 517 767–781
García-Segura G López J A and Franco J 2005 ApJ 618 919–925 (Preprint arXiv:astro-ph/0409595)
Han Z Podsadlowski P and Eggleton P P 1995 MNRAS 272 800–820
Liebert J Bergeron P and Holberg J B 2005 ApJ 156 47–68
Moe M and De Marco O 2006 ApJ 650 916–932 (Preprint arXiv:astro-ph/0606354)
Nordhaus J Blackman E G and Frank A 2007 MNRAS 376 599–608 (Preprint arXiv:astro-ph/0609726)
Paczynski B 1976 IAU Symp. 73: Structure and Evolution of Close Binary Systems ed Eggleton P,Mitton S and Whelan J pp 75
Schreiber M R Gänsicke B T Southworth J Schwöpe A D and Koester D 2008 AAP 484 441–450 (Preprint arXiv:0709.4545)
Soker N 1997 ApJS 112 487
Soker N 2006 PASP 118 260–269 (Preprint arXiv:astro-ph/0501647)
Soker N and Livio M 1989 ApJ 339 268–278
van Winckel H 2003 AARA 41 391–427
Weidemann V 2000 A&A 363 647–656
Yungelson L R Tutukov A V and Livio M 1993 ApJ 418 794
Zijlstra A A 2007 Baltic Astronomy 16 79–86 (Preprint arXiv:astro-ph/0610558)