New results on planetary nebula shaping and stellar binarity

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Abstract. The question of what physical mechanisms shape planetary nebulae into their observed morphologies remains open. However, intensified efforts since the last meeting in this series, Asymmetrical Planetary Nebulae IV, in July 2007 have yielded some excellent results. In this review we concentrate on those developments that have taken place in the last three years, with emphasis on results obtained since the review by De Marco (2009).

1. The Problem of Shaping a non-Spherical PN

Approximately 80% of all planetary nebulae (PN) exhibit morphologies that diverge greatly from a spherical shape (Parker et al. 2006). Despite advancements in the last 10 years, a convincing answer to what the shaping agent might be is still lacking (for a review see De Marco et al. 2009). Stellar or even sub-stellar companions have the capacity to interact with upper asymptotic giant branch (AGB) stars and shape the ejected envelope either by strong interactions such as common envelopes (Paczynski 1976; Soker 1989) or wider binary interactions such as wind accretion and gravitational focussing (e.g., Mastrodemos & Morris 1998, 1999; Edgar et al. 2008).

However, the fraction of stellar companions to the progenitors of AGB stars that may interact with them is of the order of 30% (Duquennoy & Mayor 1991), so how can the fraction of non spherical PN be as high as 80%? This discrepancy could be explained if not all the 1-8 M\(_\odot\) stars result in a PN. Moe & De Marco (2006) and Moe & De Marco (2010) argued, based on population synthesis, that only \(\sim 20\%\) of intermediate mass stars make a PN, with the remainder transiting between the AGB and white dwarf (WD) phases with invisible, or under-luminous nebulae.

Soker & Subag (2005) predicted that deep searches could find the brightest among these under-luminous PN and that they would be spherical (and of course that spherical PN have no binaries in their centres). This prediction has been partly borne out by the MASH survey (Parker et al. 2006; Miszalski et al. 2008), the deepest PN survey to date that doubled the fraction of spherical PN from \(\sim 10\%\) to \(\sim 20\%\) and by the Deep Sky Hunters survey, that found a similar fraction in the very faint population (Jacoby et al. 2010). These are, in the binary hypothesis, the bright end of the under-luminous, spherical PN formed by single stars and non-interacting binaries.

A main priority established by the community during the Asymmetrical PN IV meeting has therefore been to find more binaries in order to relate their parameters to the PN morphology and to determine the PN binary fraction and period distribution. A great deal of success has been enjoyed in the former search (see §2), while progress has been slow in the latter (§).
2. The growing (and shrinking) binary list

In Table 1 we present new PN that have a highly probable or confirmed binary central stars (for the list of previously known ones see [De Marco et al. 2009]). Below, we discuss some of them, as well as some that did not make the list, but are likely binaries.

- [Hajduk et al. 2010] announced the first binary, Wolf-Rayet type (\([WC7]\)) central star. Its PN (PN G221.8-04.2, aka PHR J0652-0951 and PM 1-23) is similar to A 63, showing an edge-on waist of what may have been a bipolar structure. For assumed primary and secondary masses of 0.6 and 0.3 \(M_\odot\), respectively, the orbital separation would be \(\sim 3\) or \(5\ R_\odot\), depending on whether the variability is from irradiation (\(P=0.63\) days) or ellipsoidal effects (\(P=1.2\) days). The primary Roche lobe radius would be at 1.3 or 2.2 \(R_\odot\). Although the primary radius would be \(\sim 0.3\ R_\odot\) (this is the radius of NGC 40, a slightly hotter \([WC8]\) star (Leuenhagen et al. 1996)), a \([WC]\) stellar atmosphere actually extends past the nominal radius value (see, e.g., De Marco & Crowther 1998), so the primary should be filling its Roche lobe. Of the 33 \([WC]\) and “week emission line stars” studied by Hajduk et al. (2010), only this PN revealed a periodically-variable central star, from which the authors concluded that the short-period binary fraction among the hydrogen-deficient central stars may be lower than for the hydrogen-normal ones. This may be in line with a predominant merger origin of these stars (De Marco 2008) or indicate that the observational biases that affect the \([WC]\) class are different.

- NGC 6804 and NGC 7139 have a strong IR excess (Bilikova et al. 2009) that may be indicative of a companion. We have not included them in Table 1 because a fit to the data imply “secondary” temperatures of only 1500 K, too cool for a late M companion and possibly too bright for a sub-stellar companion. This temperature, however, is at the condensation limit for dust and possibly unbelievable. Better data are needed to constrain the fits.

- Frew & Parker (2010) introduced a new class of PN that have a high density, unresolved nebulosity coincidental with the central star. They called this class EGB6-like objects because this PN was the first to have such nebulosity identified. Interestingly, this PN central star was later resolved by the Hubble Space Telescope (HST) to have a companion and the nebulosity was found to be around the companion, not the central star (Bond 2009). Other objects were recently detected to have such high density unresolved nebulae, usually from the fact that the \([OIII]\) line at 4363 Å is stronger than the Hy line at 4340 Å, indicative of high densities. These include NGC 6804 (De Marco et al., in preparation), Bran 229 (Frew et al. 2010a), M 2-29 (Gesicki et al. 2010), PHR J1641-5302 (Parker et al. 2003, Frew & Parker 2010), A 57 and PHR J1553-5738 (Miszalski et al., these proceedings), to name a few. Approximately a dozen EGB6-like objects are known today. Both Bond (2009) and Gesicki et al. (2010) argue that such high density material may be distributed in a disk like structure, or else it would disperse. In the case of EGB6, this disk would be around the companion and would have formed by accretion of AGB primary envelope gas. It is likely that such structures have arisen by binary interactions.

- NGC 2346 (a binary, Mendez & Niemela 1981), M 2-29 (a suspected binary, Hajduk et al. 2008, Gesicki et al. 2010) and CPD-568032 (a \([WC10]\) with a detected dusty disk; De Marco et al. 2002) have lightcurves showing deep irregular declines, possibly associated with dust emission or a patchy dusty disk.
Wesson et al. (2008) discovered a PN around the V 458 Vul (nova Vul 2007), the second such association after GK Per (Bode et al. 1987). Rodríguez-Gil et al. (2010) determined the period of the binary to be 0.068 days, the shortest period known for a binary central star, and found the binary to be composed of a WD primary and a post-AGB secondary. Another line of evidence associates novae with PN: the high abundance of neon in the hydrogen-deficient ejecta of A30 and A58 (Wesson et al. 2003, 2008) interpreted by Lau et al. (2010) as the products of a nova explosion that took place shortly after the final helium shell flash (Herwig 2001).

Santander-Garcia et al. (these proceedings) determined that the secondary star in the binary central star of PN Hen 2-428 is evolved. In agreement with Hillwig (these proceedings), they also determined that about a third of the known central star binary sample (De Marco et al. 2008; Miszalski et al. 2009a) has degenerate companions, likely too large compared to the predictions of Moe and De Marco (2010) of ~5%.

Hajduk et al. (these proceedings) announced the detection of a 0.2-mag sinusoidal variation with a period of 20.1 days for the central stars of PN G249.8-02.7 (PHR J0755-3346), the longest period irradiated central star binary. The variability amplitude appears too large for such a long period, unless the secondary’s radius is quite large and/or the central star very hot. We have not listed this PN in Table 1 because the star may not be associated to the nebula (Miszalski, private communication). The binary in the middle of PN K 1-16 (Table 1) also has a long (21.3 days) photometric period, which may or may not be caused by the binary motion.

Østensen et al. (2010) detected periodic light variability in the central star of the PN DSH J1919.5+4445 (Patchick 5; Jacoby et al. 2010) a faint, high excitation, elliptical PN with a hint of bipolarity. The asymmetric lightcurve has a period of 1.1 days and an amplitude of only 0.05 magnitude, the smallest known. The central star is a hot subdwarf. Such small amplitude could only be explained with an almost pole-on viewing angle and/or a small secondary radius.

A35 was demoted from PN status by Frew (2008, see also Frew & Parker 2010). It is more likely to be a Strömgren sphere around a binary star comprising a G subgiant and a hot component that has left the AGB relatively recently. Finally, four PN from the list of De Marco et al. (2009) should not be considered binaries until more data is obtained: PHR J1744-3355, PHR J1801-2718, PHR J1804-2645 and PHR J1804-2913 (Miszalski et al. these proceedings).

3. The PN Binary Fraction and Period Distribution

So far we know that 12-21% of all PN have post-common envelope central stars, with periods < 3 days (Miszalski et al. 2009a). This number is not the definitive central star binary fraction for several reasons: (i) The photometric variability technique to detect these binaries is biased to short periods (likely shorter than about 2 weeks; De Marco et al. 2008). We still do not know how many binary central stars have periods longer than ~2 weeks. (ii) The survey of Miszalski et al. (2009a) was affected by a brightness bias and was carried out only in the Galactic Bulge. (iii) Some of the binaries detected by them have been later questioned (Miszalski et al., these proceedings). (iv) Finally, the period distribution of the binaries found by Miszalski et al. (2009a) implies that there is a dearth of binaries in the 3 day to 2 week period range. It is however possible that post-CE binaries with periods in the 3-day to 2 week gap are more plentiful than found by Miszalski et al. (2009a), but their irradiation properties may be
Table 1. New or updated binary central stars (update on De Marco et al. 2009).

| PN name     | Type | Period (days) | Morph. | Reference                      |
|-------------|------|---------------|--------|--------------------------------|
| V 458 Vul   | S1   | 0.068         | B:W:   | Rodríguez-Gil et al. 2010      |
| Te 11       | El:  | 0.12          | E      | Miszalski et al. these proceedings |
| NGC 6778    | I:   | 0.15          | BPJ    | Miszalski et al. these proceedings |
| He 2-428    | El:  | 0.18          | RW     | Santander-Garcia et al., these proceedings |
| K 6-34      | I:   | 0.20          | B:RJ:  | revised by Miszalski et al. (2009b) |
| Lo 16       | EcI  | 0.49          | PJ     | Frew 2008 and Frew et al., in prep. |
| ETHOS 1     | I:   | 0.53          | BJ     | Miszalski et al. 2010, submitted |
| PM 1-23     | I:   | 0.63          | W      | Hajduk et al. 2010             |
| Necklace$^3$| I:   | 1.16          | RJB    | Corradi et al. 2010           |
| MPA J1508-6455 | I: | 12.50 | B | Miszalski et al. these proceedings |
| A 14        | Cool,S1: | ? | BR | De Marco et al., in preparation |
| Bran 229    | Cool | ?          | R:P    | Frew & Parker (2010), Frew et al., in prep. |
| A 70        | Cool,UV | ? | R | Miszalski et al., in preparation |
| K 1-6       | Cool,UV | ? | E | Frew et al. (2010b) |

$^1$Legend: S1: single-lined spectroscopic binaries; El: ellipsoidal variability; I: irradiated; Ec: eclipsing; Cool: only a cool stars is known in the system; UV: a hot component is identified in the UV. “:” means that the designation is uncertain.

$^2$Legend: E: elliptical or indistinct; B: clear, bipolar lobes; R: clear ring(s); W: very likely that PN is the edge-on waist of a faded bipolar; J: presence of one or a pair of jets or jet-like structures. P: point symmetry. “:” means that the designation is uncertain.

$^3$IPHASXJ194359.5+170901.
different due, for instance, to the lack of synchronisation of the orbital and spin period of the secondary for these slightly longer period binaries. This would leave the entire secondary irradiated, reducing the contrast between day and night sides. Although this sounds plausible, the period distribution of central stars is similar to that found via radial velocity technique for the WDs by Schreiber et al. (2009), see also Hillwig, these proceedings). That technique would not suffer this bias.

Radial velocity surveys of central stars of PN are affected by dramatic wind variability that induces spectral line changes that masks even strong periodic binary signals (De Marco et al., 2004, 2007). So the best method to determine the binary fraction with the least number of biases is to test for near-IR excess of a volume-limited sample. With this method we cannot detect periods, although we can get an approximate idea of the companion mass. This method detects unresolved binaries: for a PN at 1 kpc, the orbital separation can be as wide as 500 AU. As a result we will include central star binaries whose separation may be too wide for an interaction having taken place. After detecting the binary fraction in this way, it may not be trivial to account for the fraction of these binaries that has suffered an interaction.

In Fig. 1 (kindly provided by M. Moe) we show the detectability of companions in the I and J bands. From this figure it is clear that to detect faint companions one has to use intrinsically faint central stars. Precision photometry is also needed such that the PN has to be faint in order to afford good background subtraction. The J band is more sensitive, but logistically problematic (IR and optical photometry of the same targets is needed), such that observing in the I band is a more practical approach. Finally, the H band can provide some confirmation as well as an idea of the spectral type of the companion. While the H band can be contaminated by hot dust the J band is unlikely to be.

We have initiated a search using the NOAO 2.1 m telescope in 2007. So far we have found I-band excesses indicative of companions brighter than M5V, in 19-42% of the central stars of PN observed (5-11 out of 26) at the 3-1σ level (Passy et al., in preparation). Frew & Parker (2007) used the 2MASS and DENIS databases showing that 53% of 34 objects in a volume-limited sample have a J-band excess down to ~M6V, at the 2σ level. Combining these results and de-biasing them to include companions down to the M9V limit using the companion mass distribution for the WD population (Farhi et al., 2005), we conclude that (52±10)% of all central stars have a stellar companion closer than ~500 AU. This is tantalisingly higher than predicted by the current PN formation scenario (35%; Duquennoy & Mayor, 1991). However, with a small sample size we cannot call this a solid result, because small number statistics reject the classical scenario with only 1-2σ confidence.

The period distribution of central stars of PN will be very hard to determine. For the short period central star binaries known to date a histogram of the known periods can be found in Miszalski et al. (these proceedings) and Hillwig (these proceedings). Like the post-CE binary period of WDs (Schreiber et al., 2009), the post-CE period for central star of PN peaks at shorter periods than is predicted by any theory of common envelope evolution (e.g., Davis et al., 2010).

4. Shaping PN with Planets and Brown Dwarfs

Brown dwarfs and super-Jupiter companions at separations in the range ~2-30 AU may also shape PN (e.g., Soker, 1996). The actual limits are extremely uncertain. Com-
companions closer than the lower limit will interact on the red giant branch and either be unavailable to interact later on during the AGB evolution or even prevent the AGB ascent altogether. Companions farther than the upper limit have no influence on the AGB star.

We already know that the reservoir of brown dwarfs may be small (also called the brown dwarf desert; Grether & Lineweaver 2006) although it is slightly larger for larger separations (∼10% Metchev et al. 2008). However, we do not know how frequently planetary companions at the appropriate orbital separations exist around intermediate mass stars. Bowler et al. (2010) determined that (26 +9)% of stars having a main sequence mass of 1.5 < M/M⊙ < 2.0 host massive planets at large separations (but still less than 3 AU). The new finding is not only of a larger fraction of planet-hosting stars, but also puts the planets at larger orbital separations, where they can more easily be available to shape winds from AGB stars.

De Marco et al. (2009) pointed out that aside from our ignorance of planetary companion frequency, we also did not know what effect, if any, such low mass companions would have on an AGB star. Geier et al. (2009) discovered an 8-23-MJ in a 2.4-day period orbit around the post-red giant branch subdwarf B star HD149382. This companion must have been in a common envelope with its primary and been able to eject the envelope.

Based on the morphological considerations of Soker (1997) and Soker & Subag (2005) and the population study of Moe & De Marco (2006), as well as from the most recent planetary statistics De Marco & Soker (2010) argued that the fraction of PN that have been shaped by planets is of the order of 20%. If we consider that only 20% of all intermediate mass stars make PN, then one would also conclude that the fraction of
intermediate mass stars that interact with a planet-mass companion on the AGB is of the order of 4%.

5. What can be achieved by Asymmetrical Planetary Nebula VI

At the current rate of discovery, by the next Asymmetrical PN conference in 2013 we should be able to have:

- Precision (1-2%) photometry of 50-75 central stars of PN in the $B$, $V$ and $I$-band as well as accurate $J$-band photometry for one third to one half of them. This will refine considerably the current, extremely imprecise estimate of the overall PN binary fraction.

- A doubling of the sample of central stars binaries form ~50 to ~100. Most of them will be short period binaries as they are easier to detect and will therefore provide only a biased view of the PN binary population. However such a large sample will allow us to draw statistical conclusions regarding the association between binarity and bipolar morphology (see initial results by Miszalski et al. (2009b)).

- At least 20 objects with determined masses and inclinations via radial velocity analysis and stellar atmosphere modelling. There are currently only 6 central stars of PN for which such parameters are known. A larger sample can help characterise the efficiency of the common envelope ejection (De Marco et al. 2010, Zorotovic et al. 2010).

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