

Post-common-envelope Wolf-Rayet central stars of planetary nebulae

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Nearly 50 post-common-envelope (post-CE) close binary central stars of planetary nebulae (CSPNe) are now known. Most contain either main sequence or white dwarf (WD) companions that orbit the WD primary in around 0.1–1.0 days. Only PN G222.8–04.2 and NGC 5189 have post-CE CSPNe with a Wolf-Rayet star primary (denoted [WR]), the low-mass analogues of massive Wolf-Rayet stars. It is not well understood how H-deficient [WR] CSPNe form, even though they are relatively common, appearing in over 100 PNe. The discovery and characterisation of post-CE [WR] CSPNe is essential to determine whether proposed binary formation scenarios are feasible to explain this enigmatic class of stars. The existence of post-CE [WR] binaries alone suggests binary mergers are not necessarily a pathway to form [WR] stars. Here we give an overview of the initial results of a radial velocity monitoring programme of [WR] CSPNe to search for new binaries. We discuss the motivation for the survey and the associated strong selection effects. The mass functions determined for PN G222.8–04.2 and NGC 5189, together with literature photometric variability data of other [WR] CSPNe, suggest that of the post-CE [WR] CSPNe yet to be found, most will have WD or subdwarf O/B-type companions in wider orbits than typical post-CE CSPNe (several days or months c.f. less than a day).

1 Close binary central stars of Planetary Nebulae

Planetary nebulae (PNe) are the ionised gaseous envelopes ejected by low to intermediate mass stars (1–8 M_{\odot}) at the end of the asymptotic giant branch (AGB) phase. The origin of the myriad shapes observed in PNe is a difficult problem that has persisted for several decades (Balick & Frank 2002). The most promising solution is now understood to be stellar or even sub-stellar companions (De Marco 2009). Observational evidence for binarity in PNe was relatively modest with pioneering photometric monitoring surveys producing around a dozen examples (Bond 2000). Most of these have orbital periods of 0.1–1.0 d and have therefore passed through the common-envelope (CE) phase (Ivanova et al. 2013). As the ejected CE is still visible as the PN with an age of $\sim 10^4$ years, post-CE central stars of planetary nebulae (CSPNe) are the youngest probes we have of the very short (unobserved) and poorly understood CE interaction.

To realise the potential of post-CE CSPNe as a population to address problems concerning CE evolution, as well as the shaping mechanism of PNe, a statistically significant sample must be gathered. Miszalski et al. (2008, 2009a) leveraged the large areal coverage, high time cadence and high sensitivity of I-band photometry from the microlensing survey OGLE-III (Udalski et al. 2008) to discover several more post-CE CSPNe. A major result from this work is that around 1 in 5 PNe have a post-CE CSPN, consistent with earlier estimates (Bond 2000). High-quality imaging of the enlarged sam-

ple has revealed post-CE PNe often show collimated outflows or jets, low-ionisation filaments and rings, as well as bipolar morphologies (Miszalski et al. 2009b). These morphological features have since been successfully used to target PNe with similar morphologies to discover several more post-CE binaries (Miszalski et al. 2011b; Jones 2015), bringing the total to nearly 50 binaries (Jones 2015).

The population of post-CE CSPNe mostly consists of white dwarf (WD) primaries with main sequence (MS) secondaries, however several double degenerate (DD) systems are also known (e.g. Tovmassian et al. 2010; Boffin et al. 2012; Santander-García et al. 2015). Photometric variability of WDMS CSPNe is often dominated by a large sinusoidal irradiation effect, produced by the heating of the hemisphere of the secondary facing the primary. Also present in post-CE CSPNe lightcurves are eclipses and ellipsoidal variability, the latter mostly occurring in DD systems. The optical photometric monitoring technique used in most surveys for post-CE CSPNe has introduced significant selection effects into the known population. Firstly, there is a strong bias against finding WDMS binaries with orbital periods > 1 d since the irradiation effect amplitude decreases rapidly with increasing orbital separation (De Marco et al. 2008). Secondly, DD systems are under-represented since they (a) do not usually produce an irradiation effect, and (b) require a close orbital separation to produce ellipsoidal variability or eclipses. Radial velocity (RV) monitoring is therefore the only reliable technique to establish if a post-CE CSPN is present (e.g. Boffin et al. 2012).

2 Binary status of Wolf-Rayet central stars

Over a hundred PNe have H-deficient Wolf-Rayet central stars (denoted [WR]), the low-mass ($M \sim 0.6 M_{\odot}$) spectroscopic mimics of massive WR stars (see the review of Todt & Hamann (2015), these proceedings). The origin of [WR] stars remains elusive, especially given the recent discovery of two bona-fide [WN] stars whose extremely He-rich atmospheres may be better explained by a merger scenario, rather than the traditional scenarios used to explain [WC] star formation (Miszalski et al. 2012; Todt et al. 2013). Some binary formation scenarios have been proposed (e.g. De Marco & Soker 2002), but there are currently too few known binaries to further develop these scenarios. The only known [WR] binaries are PN G222.8–04.2 ([WC7], Hajduk et al. 2010) and NGC 5189 ([WO1], Manick et al. 2015) with respective orbital periods of 1.26 and 4.05 d.

Why are there so few post-CE [WR] CSPNe known? The answer lies in the previous reliance on photometric monitoring to find post-CE CSPNe. At least 37 early-type [WC] stars and related H-deficient stars have been monitored photometrically by Ciardullo & Bond (1996) and González Pérez et al. (2006). Some were found to be non-radial pulsators, but no variability was found that could be attributed to a binary companion. Indeed, since 15–20% of PNe have post-CE CSPNe (Bond 2000; Miszalski et al. 2009a), then we would have expected ~ 5 – 7 post-CE [WR] CSPNe to have been found. These non-detections exclude the presence of post-CE [WR] binaries in the sample with MS companions since they would have produced a very large amplitude irradiation effect as in e.g. Corradi et al. (2011) and Miszalski et al. (2011a).

3 A new approach: RV monitoring of [WR] stars

RV monitoring is a tried and tested method to discover massive WR binaries (e.g. Foellmi et al. 2003), so there is no reason not to suspect it would work for [WR] stars. Our approach is to take several spectra of each object with a resolution of $\sim 2\text{\AA}$ and signal-to-noise > 40 in the continuum. We are using SpCCD on the SAAO 1.9-m telescope for the brightest targets and the Robert Stobie Spectrograph (RSS) on the Southern African Large Telescope (SALT) for fainter targets. We then follow the cross-correlation procedure of Foellmi et al. (2003) to derive the RV measurements. Initial results have been published in Manick et al. (2015). No periodic variability was found in PMR 2, Hen 2-99, NGC 5315, Hen 2-113 and Hen 3-1333, whereas we found periodic variability of 4.04 d in NGC 5189.

Additional higher quality SALT observations have since ruled out the previously suspected variability in Hen 2-99 and NGC 5315.

Figure 1 presents an updated RV curve for NGC 5189 containing 12 additional spectra, resulting in a revised period of 4.05 d, as well as our preliminary RV curve for PN G222.8–04.2. The measured RV amplitudes for NGC 5189 and PN G222.8–04.2 are 54 ± 4 and $184 \pm 8 \text{ km s}^{-1}$, respectively. As the orbital inclinations of both objects are unknown, we present a list of possible companion masses in Tab. 1. An evolved WD companion is most likely present in NGC 5189, similar to that in Fleming 1 (Boffin et al. 2012). In the case of PN G222.8–04.2, if the unusually high RV amplitude is not an artefact of the cross-correlation technique, then we may suspect the companion to be a subdwarf O/B-type star, perhaps similar to that found in NGC 6026 (Hillwig et al. 2010). Polarimetric observations and spatio-kinematic modelling (e.g. Sabin et al. 2012) would be desirable to constrain the inclinations of both objects.

Tab. 1: Companion mass estimates for a variety of orbital inclination angles assuming $M_1 = 0.6 M_{\odot}$.

i ($^{\circ}$)	M_2 (NGC 5189)	M_2 (PN G222.8–04.2)
30	1.30 ± 0.20	7.60 ± 0.70
40	0.80 ± 0.10	4.10 ± 0.20
50	0.59 ± 0.04	2.70 ± 0.10
60	0.50 ± 0.02	2.10 ± 0.10
70	0.44 ± 0.01	1.80 ± 0.10
80	0.42 ± 0.01	1.60 ± 0.03
90	0.40 ± 0.01	1.60 ± 0.04

4 Summary

We have started to conduct RV monitoring of several [WR] CSPNe to search for post-CE [WR] binaries. These binaries are needed to provide the first accurate distance-independent stellar parameters for [WR] stars, as well as to inform the still enigmatic formation scenarios regarding [WR] stars. We have increased the known sample of post-CE [WR] binaries to two with the discovery of a 4.05 d orbital period in NGC 5189 (Manick et al. 2015), an object long suspected of harbouring a binary CSPN (Phillips & Reay 1983) because of its peculiar morphology (Sabin et al. 2012). Its morphology is typical of post-CE PNe and in particular bears close resemblance to the post-CE PN NGC 6326 (Miszalski et al. 2011c). Furthermore, we have presented a preliminary RV curve for PN G222.8–04.2 that will form the basis of a more detailed study to be presented elsewhere.

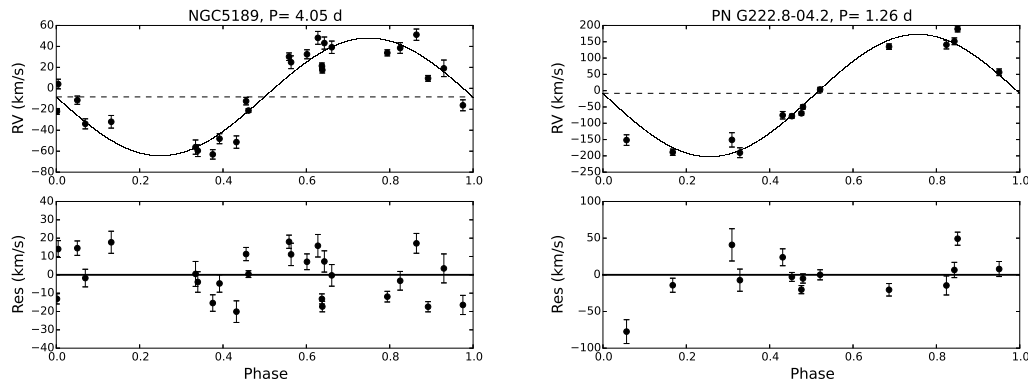


Fig. 1: SALT RSS RV curves of NGC 5189 (left upper panel, 26 epochs) and PN G222.8–04.2 (right upper panel, 14 epochs) fitted with circular orbits (solid curve). The residuals (lower panels) show a larger amplitude scatter than seen in non-[WR] post-CE CSPNe (e.g. Boffin et al. 2012), but is consistent with wind variability that is also encountered in massive WR RV curves (e.g. Foellmi et al. 2003). The larger residuals in PN G222.8–04.2 are probably the result of the cross-correlation method reacting to the high degree of line profile variability.

The anomalously large 4.05 d orbital period for NGC 5189 suggests that the orbital periods of other post-CE [WR] CSPNe may also be several days or months. This may be a result of the [WR] primary and its extended atmosphere requiring more space in its orbit. Such binaries can only be found from RV monitoring and much work remains to find them. If this is correct, then we would expect close binaries containing the progeny of [WC] stars, PG1159 stars, to have similarly wide orbits.

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References

- Balick, B. & Frank, A. 2002, *ARA&A*, 40, 439
- Boffin, H. M. J., Miszalski, B., Rauch, T., et al. 2012, *Science*, 338, 773
- Bond, H. E. 2000, in *Astronomical Society of the Pacific Conference Series*, Vol. 199, *Asymmetrical Planetary Nebulae II: From Origins to Microstructures*, ed. J. H. Kastner, N. Soker, & S. Rappaport, 115
- Ciardullo, R. & Bond, H. E. 1996, *AJ*, 111, 2332
- Corradi, R. L. M., Sabin, L., Miszalski, B., et al. 2011, *MNRAS*, 410, 1349
- De Marco, O. 2009, *PASP*, 121, 316
- De Marco, O., Hillwig, T. C., & Smith, A. J. 2008, *AJ*, 136, 323
- De Marco, O. & Soker, N. 2002, *PASP*, 114, 602
- Foellmi, C., Moffat, A. F. J., & Guerrero, M. A. 2003, *MNRAS*, 338, 360
- González Pérez, J. M., Solheim, J.-E., & Kamben, R. 2006, *A&A*, 454, 527
- Hajduk, M., Zijlstra, A. A., & Gesicki, K. 2010, *MNRAS*, 406, 626
- Hillwig, T. C., Bond, H. E., Afşar, M., & De Marco, O. 2010, *AJ*, 140, 319
- Ivanova, N., Justham, S., Chen, X., et al. 2013, *A&A Rev.*, 21, 59
- Jones, D. 2015, arXiv:1507.05447
- Manick, R., Miszalski, B., & McBride, V. 2015, *MNRAS*, 448, 1789
- Miszalski, B., Acker, A., Moffat, A. F. J., Parker, Q. A., & Udalski, A. 2008, *A&A*, 488, L79
- Miszalski, B., Acker, A., Moffat, A. F. J., Parker, Q. A., & Udalski, A. 2009a, *A&A*, 496, 813
- Miszalski, B., Acker, A., Parker, Q. A., & Moffat, A. F. J. 2009b, *A&A*, 505, 249
- Miszalski, B., Corradi, R. L. M., Boffin, H. M. J., et al. 2011a, *MNRAS*, 413, 1264
- Miszalski, B., Corradi, R. L. M., Jones, D., et al. 2011b, in *Asymmetric Planetary Nebulae 5 Conference*, 328
- Miszalski, B., Crowther, P. A., De Marco, O., et al. 2012, *MNRAS*, 423, 934
- Miszalski, B., Jones, D., Rodríguez-Gil, P., et al. 2011c, *A&A*, 531, A158
- Phillips, J. P. & Reay, N. K. 1983, *A&A*, 117, 33
- Sabin, L., Vázquez, R., López, J. A., García-Díaz, M. T., & Ramos-Larios, G. 2012, *Rev. Mexicana Astron. Astrofis.*, 48, 165
- Santander-García, M., Rodríguez-Gil, P., Corradi, R. L. M., et al. 2015, *Nature*, 519, 63
- Todt, H. & Hamann, W.-R. 2015, these proceedings
- Todt, H., Kniazev, A. Y., Gvaramadze, V. V., et al. 2013, *MNRAS*, 430, 2302
- Tovmassian, G., Yungelson, L., Rauch, T., et al. 2010, *ApJ*, 714, 178
- Udalski, A., Szymanski, M. K., Soszynski, I., & Poleski, R. 2008, *Acta Astron.*, 58, 69

Vikram Dwarkadas: I am a bit suspicious of the correlation between morphology and binarity. Are you saying that single stars should give only spherical (circular) PNe? Are there exceptions? Are there any nebulae which show jets and other structures where you did *not* find a binary? What does it mean?

Brent Miszalski: Yes, there have been some and these could potentially be wider binaries or mergers. That said, we've had considerable success finding new close binaries based on these trends, the strongest of which are jets, so they do seem to hold up to scrutiny.

Generally, it is believed that spherical/elliptical PNe are formed by single stars, but this has not been fully explored yet.

Gloria Koenigsberger: Among the light curves you showed, are there eclipses? Have radii been determined?

Brent Miszalski: Yes, several of the known systems have eclipses and many have been modelled

to determine accurate orbital parameters including stellar radii.

Norbert Langer: Even if the PNe show jets, couldn't the central stars be single? As many central stars are *very* short period binaries, one would expect that many others would have merged in the common envelope (CE) phase.

Brent Miszalski: Yes, that is a possibility covered by jet models, e.g. a shredded companion in Nordhaus et al. (2006). A merger would be consistent with non-detection of close binaries, but is exceptionally difficult to prove observationally.

Dany Vanbeveren: Lev Yungelson once claimed that finding one in a 1000 double WDs with a combined mass $\geq 1.4 M_{\odot}$ that will merge within a Hubble time will highly increase the probability that the double degenerate (DD) scenario is a very valuable scenario to form SN Ia. It is fantastic that you found the candidate.



Brent Miszalski (center) with Andy Pollock (left) and Victor Gómez-González (right)