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Post-common-envelope planetary nebulae

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Abstract. Close-binary central stars of planetary nebulae offer a unique tool with which to study the critical and yet poorly understood common-envelope phase of binary stellar evolution. Furthermore, as the nebula itself is thought to comprise the ionised remnant of the ejected common envelope, such planetary nebulae can be used to directly probe the mass, morphology and dynamics of the ejecta. In this review, I summarise our current understanding of the importance of binarity in the formation of planetary nebulae as well as what they may be able to tell us about the common-envelope phase – including the possible relationships with other post-common-envelope phenomena like stellar mergers, novae and type Ia supernovae.

Key words: binaries: close – planetary nebulae: general – stars: jets

1. Introduction

It is now almost half a century since Paczynski (1976) first proposed the common-envelope (CE) scenario as the most viable pathway towards the formation of close binaries with an evolved component. Since then, the evidence for the importance of the CE has only grown, however key aspects of the processes at work remain enigmatic (Ivanova et al., 2013). At the time, Paczynski (1976) already recognised the importance of planetary nebulae (PNe) in understanding the CE phase, stating *"Observational discovery of a short period binary being a nucleus of a planetary nebula would provide very important support for the evolutionary scenario"*, and the first example was discovered that same year by Bond (1976). Subsequent studies of post-CE planetary nebulae (PNe) have already taught us much about the CE and they continue to represent a key tool with which to shed light on this critical phase of binary evolution (Jones, 2020).

From the perspective of the PN community, the principal interest in CE evolution is the ease with which it can explain the wide range of aspherical morphologies observed in PNe (Balick & Frank, 2002; García-Segura et al., 2018;

De Marco et al., 2022). However, until recently, there was a reluctance to accept that binarity was the primary shaping mechanism in PNe due to the lack of known binary central stars. In the early 2000s, only 16 post-CE PNe were known (a couple of which have since been shown to be wide binaries, false associations or non-PNe) leading to the estimate that roughly 10% of PNe hosted close binary stars (Bond, 2000). Exploitation of wide-field surveys, like OGLE, Kepler and TESS, has since led to an explosion of new discoveries (Miszalski et al., 2009; Jacoby et al., 2021; Aller et al., 2024), taking the total now to over 100 known post-CE central stars[1]. These studies have placed a hard lower limit on the binary fraction of 20%, while other probes (such as radial velocities, composite spectra and infrared excesses) have provided much higher estimates (perhaps as high as 80%; De Marco et al., 2004; Douchin et al., 2015).

The minimum 20% post-CE fraction already has one critical implication for our understanding of PNe – it is likely that some stars which our textbooks would say should produce an observable PN, in fact, do not. Simply put, based on the main sequence binary fraction and period distribution, one would not expect as many as 20% of all low- and intermediate-mass stars to experience a CE phase, let alone survive one without merging. The implication being that, if binaries appear over-abundant, then some single stars previously believed to be PN progenitors must not lead to observable PNe. Clearly, with such a large uncertainty on the true post-CE binary fraction in PNe (20–80%), it is similarly uncertain just what fraction of these single-star PN progenitors will not lead to PNe. However, there are indications that it may indeed be significant. Population synthesis studies have found that perhaps around one fifth of expected PN progenitors due not lead to observable PNe (potentially consistent with only binaries leading to PNe; Moe & De Marco, 2006), while as many as 50% of central stars exhibit properties that are inconsistent with single-star evolutionary tracks (Weidmann et al., 2020).

As a result of conservation of angular momentum during the ejection, the CE is always expected to be preferentially deposited in the orbital plane of the binary thus leading to nebular symmetry axes which lay perpendicular to this plane. While only nine PNe have been the subject of sufficiently detailed study to constrain both their nebular inclinations and central binary orbital inclinations, the correlation is striking and entirely consistent with the CE shaping each and every one (Hillwig et al., 2016). Indeed, the probability of finding such an alignment in these PNe by chance has been shown to be less than one in a million (Munday et al., 2020). Nonetheless, there is significant morphological diversity, even among this sample, meaning that, while the CE has clearly played a role in their shaping, the exact processes at work may vary appreciably (Hillwig et al., 2016).

Thus, it now seems beyond doubt that CE evolution is a critical aspect of PN formation and evolution, even though the precise details of this are still the

[1]A regularly updated list is maintained by the author at `http://drdjones.net/bCSPN`.

subject of active research (Jones & Boffin, 2017; Boffin & Jones, 2019). But, perhaps of greater interest for the wider astronomical community, we are now in a position to use post-CE PNe to try and understand the CE phase itself. The nebular material in these PNe is thought to comprise the ejected CE, offering a unique opportunity to study the ejecta directly (CE ejecta can also be observed in luminous red novae, but these represent "failed" CE events, where the stars merged before fully ejecting the donor's envelope). Furthermore, the short-lived nature of PNe ($\tau \sim$30 kyr) means that post-CE central stars of PNe have not yet had time to adjust their chemical and physical properties following the CE ejection. As such, post-CE PNe are an invaluable tool with which to study the CE phase leading to potentially interesting conclusions for a wide-range of other post-CE phenomena.

2. Pre-CE mass transfer

The first step towards using the population of post-CE central stars of PNe to try and understand the CE phase is to constrain the properties of individual post-CE central stars. Most have been discovered through their photometric variability meaning that only their orbital periods are known. In order to determine the properties of the stars themselves (masses, temperature, radii), one must obtain follow-up observations that allow for simultaneous modelling of light and radial velocity curves (e.g., Jones et al., 2022), and/or spectral analysis using model atmospheres (Hillwig et al., 2017).

While the number of central stars with well-constrained properties remains relatively small, principally due to the painstaking nature of the required follow-up observations and the complications of the modelling, one can already draw remarkable conclusions. Where the companion to the nebula progenitor is a main-sequence (MS) star, they are always[2] found to be inflated (often by a factor of $\times$2–3) with respect to isolated MS stars of the same mass (Jones et al., 2015). This inflation is almost certainly due to accretion, with further signposts of this accretion coming from the chemical contamination observed in the companion of the central star of The Necklace nebula (Miszalski et al., 2013).

Accretion during the CE phase is expected to be minimal (Sandquist et al., 1998), so it is probable that the accretion onto the companion happens before CE. Further evidence for accretion prior to the CE comes from the kinematical ages of the polar outflows observed in some post-CE PNe. These polar outflows, thought to be tracers of the mass transfer/accretion, are generally found to predate the ejection of the central nebula (and thus the ejection of the CE) by a few hundred to a few thousand years (Corradi et al., 2011; Miszalski et al.,

[2]Except the companion to the central star of PN M 3-1, which was found by Jones et al. (2019) to be of a normal size but extremely close to filling its Roche lobe (this system will be discussed more in section 5).

2011). It seems likely that this pre-CE mass transfer might be associated with a period of wind Roche-lobe overflow which could last for several thousands of years as indicated by the jets observed in Fleming 1 (Boffin et al., 2012).

It is important to note that there is little to no inflation observed in the MS companions of more evolved post-CE binaries (indeed these systems are excellent probes of the mass-radius relationship of late-type MS stars; Parsons et al., 2018). This might, at first, appear puzzling when one takes into account that the thermal timescales for these stars are too long for them to have relaxed back to a normal state. However, models predict that for intermediate values of accretion efficiency and rate, the response of fully convective stars is to become partially convective (Prialnik & Livio, 1985), and it is thus the convective layer formed in the outer envelope which expands rather than the star as a whole. The relaxation of this convective layer can then occur on a much shorter timescale (Jones et al., 2022).

3. Conditions to experience (and survive) a CE

The characterization of post-CE central stars has revealed a dearth of early type-companions (Brown et al., 2019). This is consistent with the idea that large mass ratios are required to initiate unstable Roche lobe overflow and thus a CE event (Pavlovskii & Ivanova, 2015). The same characterization efforts have also revealed a number of candidates to have experienced the CE while on the red giant branch (RGB). These stars are analogous to subdwarf B binaries (e.g., Schaffenroth et al., 2015) and serve as a clear demonstration that RGB CE events can both be survived (without merging) and produce an observable PN (Jones et al., 2022).

A handful of central stars have been shown to have white dwarf companions, being detected either by radial velocity variability (Boffin et al., 2012) or photometric variability due to tidal deformations (Santander-García et al., 2015) – as opposed to the sinusoidal photometric variability due to irradiation which is typical for MS companions. If one extrapolates from this to assume that all central stars showing photometric variability due to tidal deformations are double degenerates (DD; Hillwig et al., 2010), then a very significant fraction of all post-CE central stars are DD (particularly when one takes into account that these systems should be harder to detect due to the low amplitudes of variability for most configurations). These DD post-CE central stars may have formed through two consecutive CE phases (Nelemans & Tout, 2005), but their properties are more consistent with having avoided a CE when the first component evolved off the asymptotic giant branch (AGB), with the mass transfer at this stage being stable due to the initial mass ratio being close to unity (Woods et al., 2012). Understanding the frequency and properties (namely masses and orbital periods) of DD central stars of PNe will likely have important implications for the constraining the pathways towards type Ia supernovae (Santander-García et al., 2015).

4. The missing mass problem

In the single-star scenario, the bright central shells of PNe contain only a small fraction of the mass that originally comprised the progenitor's envelope, with the vast majority residing in a very low surface brightness halo (Villaver et al., 2002). In the case of a CE event, the entirety of the donor's envelope is expected to be ejected on a very short timescale, subsequently forming the PN. Thus one would expect post-CE PNe to be significantly more massive than their single star counterparts, however Santander-García et al. (2022) showed that, in fact, there is very little difference between the masses of the two populations. Furthermore, studying the observed masses of four PNe for which data of the central stars permits the reconstruction of the CE phase and an estimation of the envelope mass, they found that the masses of the PNe represent only a fraction of the envelope masses of the donors (roughly 60% for the two DD systems analysed, but as low as 1% for Abell 63 which has a MS companion). This brings into question whether the nebulae surrounding post-CE central stars are indeed the ejected CE or rather the product of some much later phase of mass-loss when the CE has already dissipated (Corradi et al., 2015).

5. Nebular abundances and the link to novae

There are obvious links between post-CE PNe and novae, in particular the discovery of an ancient PN surrounding nova V458 Vul (Wesson et al., 2008a). However, there are also other less obvious connections. The central star of PN M 3-1 was found by Jones et al. (2019) to have a MS companion which is very close to Roche-lobe filling. This means that as the system evolves there is potential for mass transfer from the companion onto the central star in the relatively near future, possibly leading to a nova eruption inside the expanding PN similar to that of Nova V458 Vul.

Further connections between post-CE PNe and novae are found in their abundance patterns, with some of the shortest period central stars being associated with extreme abundance discrepancy PNe (Wesson et al., 2018). The abundances in these PNe are discrepant by a factor of five or more depending on whether they are derived using recombination lines or collisionally-excited emission lines. These discrepancies indicate the presence of a second (often centrally-concentrated) high-metallicty gas phase in these PNe (García-Rojas et al., 2016), where the abundances of this second gas phase are similar to those observed in neon novae (Wesson et al., 2008b).

6. Pre-PNe and the link to luminous red novae

Pre-PNe are thought to represent the intermediate phase between the central star having left the AGB but not yet being hot enough to fully ionise the surrounding nebula. As such, one might expect to find a similar post-CE fraction inside pre-PNe to that found in PNe. However, despite years of dedicated study, no post-CE central star has been found inside a pre-PN (see Hrivnak et al., 2011, 2017, 2022, 2024, and many, many more). This is perhaps indicative that the CE leads to a shortened pre-PN phase (reducing the likelihood of discovery) or even that pre-PNe and post-CE PNe represent distinct evolutionary pathways.

Intriguingly, the ejecta properties of luminous red novae – a class of transients associated with CE mergers – are strikingly similar to those of pre-PNe (Kamiński et al., 2018), offering a potential explanation for the dearth of surviving post-CE binaries in pre-PNe. However, it must be highlighted that much progress has been made linking the morphologies of pre-PNe with wide stellar companions (Decin et al., 2020), several of which are known in both pre-PNe (e.g., Sánchez Contreras et al., 2004) and PNe (e.g., Jones et al., 2017).

7. Conclusions

Binary evolution (both CE and wider) plays a key role in the formation of a significant fraction, perhaps the majority, of PNe (some might even argue all!). This makes PNe an important test bed with which to study binary stellar evolution – in particular the poorly understood CE phase, which has been demonstrated to be responsible for at least one fifth of all PNe. The fact that post-CE PNe should be among the youngest observable post-CE systems, potentially allowing for direct observations of both the ejected envelope and the surviving post-CE binary, furthermore makes them a unique probe of the CE.

The observed population of post-CE PNe confirms the theoretical expectations that the CE is preferentially ejected in the orbital plane of the binary and that a relatively large initial mass ratio is required in order for unstable mass transfer to occur. There are also strong indications of pre-CE mass transfer which can chemically contaminate the companion (now the favoured hypothesis for the formation of carbon dwarfs; Whitehouse et al., 2021) as well as (temporarily) causing their radii to grow. However, not all properties of post-CE PNe are so easily understood – the so-called missing mass problem, and the origins of a second chemically-enriched gas phase in high abundance discrepancy nebulae are particularly puzzling. The resolution of these puzzles will undoubtedly further our understanding of the CE phase as well as of other CE progeny.

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