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Review

Binary Central Stars of Planetary Nebulae

David Jones [1,2]

[1] Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain; djones@iac.es
[2] Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain

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Abstract: It is now clear that a vast majority of intermediate-mass stars have stellar and/or sub-stellar companions, therefore it is no longer appropriate to consider planetary nebulae as a single-star phenomenon, although some single, isolated stars may well lead to planetary nebulae. As such, while understanding binary evolution is critical for furthering our knowledge of planetary nebulae, the converse is also true: planetary nebulae can be valuable tools with which to probe binary evolution. In this brief review, I attempt to summarise some of our current understanding with regards to the role of binarity in the formation of planetary nebulae, and the areas in which continued study of planetary nebulae may have wider ramifications for our grasp on the fundaments of binary evolution.

Keywords: close binary stars; spectroscopic binary stars; planetary nebulae; jets; type Ia supernovae; chemically peculiar stars

1. Introduction

It is now beyond doubt that central-star binarity plays an important role in the formation and evolution of a significant number of planetary nebulae (PNe). However, the exact details and extent of this role are still uncertain. What fraction of planetary nebulae are the product of binary interactions? What is the role of the common envelope (CE)? What is the impact of a wide companion? How does binarity influence the nebular chemistry? These questions and others are critical for understanding planetary nebulae, but also have important ramifications in other fields ranging from the study of other evolved binary phenomena (including cosmologically-important type Ia supernovae [SNe] and stellar mergers). Exploiting these wider impacts will be key in justifying the work and, perhaps more critically (in the context of WorkPlaNS II, at least), the observing time needed to forward our understanding of binary stars in PNe.

2. Making the Case for Binaries (and Perhaps Planets?)

Binarity can and does have a strong impact on stellar evolution, often being key in the formation of a number of astrophysical phenomena previously interpreted as the products of single-star evolution [1]. Almost half of all solar-type stars exist in binaries or higher order multiples [2], while the binary fraction steadily increases with stellar mass [3,4]. When sub-stellar companions are considered, the average number of companions grows to be greater than unity for all possible masses of PN progenitor[1] [8]. Collectively, these values are far too large to ignore when considering the prior evolution of the observed population of PNe—given that so many low and intermediate mass stars have companions, one cannot assume that PNe are solely the product of single star evolution. Moreover, as will be highlighted later, PNe are often the immediate descendants of poorly-understood

[1] Note that I will not discuss the possible importance of planets further here. However, massive planets are likely to have a similar, albeit far weaker, influence on the evolution of their host star to that of a stellar mass companion [5–7].

binary interactions (like the common-envelope phase), meaning that they offer a truly unique window into binary evolution and the formation processes of other binary phenomena [9].

2.1. Common-Envelope Evolution

The most obvious way a binary companion can influence the evolution of a PN progenitor is via a CE phase, whereby the engulfment of the companion leads to the bipolar ejection of the nebular progenitor's envelope [10]. However, only binaries with orbital separations less than a few au could possibly evolve through a CE [9,11]. Therefore, while the binary fraction among stars with masses thought to be consistent with producing a PN might be 50% or more, only some 20% of these (i.e., 10% of all central stars) will actually experience a CE[2]. Furthermore, some fraction of these systems will not survive the CE (reaching merger without fully ejecting the primary's envelope). As such, it is interesting to consider that the fraction of PNe found to host a post-common-envelope (post-CE) central star is at least 12–21% [13], even higher than the total fraction expected to experience a CE, thus perhaps indicating that observable PNe are more easily formed via a CE than via a single-star evolution (i.e., not all intermediate-mass stars produce an observable PN [14]).

It is clear that understanding CE evolution is critical in understanding PNe (or at least a significant fraction thereof). However, it is also important to emphasise that post-CE PNe themselves represent a critical tool with which to understand the CE phase and, thus, other post-CE phenomena.

2.1.1. Pre-Common Envelope Evolution

The nebulae themselves are thought to represent the ejected CE. This has two major consequences for their use in studying the CE:

1. They are the only systems where one can directly study the ejection morphology and kinematics[3].
2. The short-lived nature of the nebulae means that the central star systems have not yet had time to relax (the thermal timescales of both components are much longer than the visibility time of a PN), and are thus "fresh-out-of-the-oven" of the CE.

With respect to the first point, the statistical correlation between bipolar, nebular symmetry axes and the orbital planes of their post-CE central stars has already been demonstrated [18], thus confirming the expectation that the CE is ejected preferentially in the orbital plane. However, the exact details of the process, and how such a wide variety of post-CE morphologies (ranging from double-shelled [19] through to highly filamentary [20]) can form, are still highly uncertain.

The observed prevalence of jet-like structures in post-CE PNe does provide strong indication that accretion must occur around the time of the CE (before, during and/or after). This connects well to the second point above, where detailed studies of post-CE central stars, via combined light- and radial velocity curve modelling, have shown that in the vast majority of cases main-sequence secondaries are highly inflated [21]—likely as a consequence of accretion. Additional evidence for such accretion is also found in the chemical contamination of the low-mass main-sequence companion in the Necklace nebula [22]. The Necklace presents with a pair of bipolar jets, likely formed during the same mass-transfer episode which led to the contamination of the secondary. Furthermore, based on their kinematical ages, these jets are found to pre-date the central nebular region thus indicating that the mass transfer must have occurred just prior to entering the CE [23]. Support for pre-CE mass transfer is similarly found in the spectacular bipolar, rotating, episodic jets of Fleming 1 (PN Fg 1),

[2] This fraction is extremely dependent on both mass [4] and metallicity [12] but, even accounting for more massive progenitor stars which are more likely to be found in binaries close enough to experience a CE, the total fraction probably doesn't increase that much given that such stars are less abundant.

[3] One might also say that the envelope ejection can also be studied directly in stellar mergers (e.g., luminous red novae [15]). However, these represent "failed" CEs, in which the envelope was not completely ejected and thus led to a merger [16,17]. Post-CE PNe are instead the products of "successful" CE ejections.

where both their kinematical age and associated precession period imply that they were formed before the CE spiral-in [24].

2.1.2. The Abundance Discrepancy Problem

It has recently become clear that short-period, post-CE central stars are strongly linked to large abundance discrepancy factors [25] (the ratio of nebular abundances in recombination lines, ORLs, to those in collisionally-excited lines, CELs). These elevated abundance discrepancies are strongly linked to the presence of a second, lower-temperature, higher-metallicity gas phase in the host PNe [26]. Spatially-resolved studies of the distribution of ORL and CEL emitting gas have indicated that this second, metal-enriched gas phase is generally found to be centrally concentrated [27], perhaps suggestive of some form of reprocessing event late in the CE ejection [28] particularly given that the abundance patterns in this gas are rather nova-like [29]. One of the biggest tests of this hypothesis will be the kinematical study of the enriched gas phase, with preliminary studies (comparing ORL and CEL kinematics across different chemical species) indicating that the two gas phases do, indeed, display discrepant kinematics [30,31]. In any case, understanding the origin of the second gas phase and how it relates to evolution of the central binary represents an important step towards fully understanding the physics at work in the CE.

2.1.3. Ionised Masses

Measuring the total mass of a PN is challenging, with masses scaling with the inverse of the distance squared (where distances to PNe have always been problematic [32]). Furthermore, much of the ionised mass is "hidden" in extended low-surface-brightness haloes, meaning that they are almost always underestimated [33]. Nonetheless, as the CE should be associated with a vastly increased mass-loss rate (as a significant fraction of the envelope is ejected in a single episode rather than via a slow stellar wind), one would (in principle) expect post-CE PNe to present greater, but at least similar, masses than the general PN population. However, recent studies have shown that the contrary appears to be true, with post-CE PNe presenting with appreciably lower ionised masses than the general population [26]. Ref. [34] have speculated that this could be due to: a significant fraction of the envelope mass being accreted onto the companion (likely prior to the CE occurring, see Section 2.1.1), that a significant amount of envelope material falls back into a circumbinary disk (perhaps with some reaching the central stars and being reprocessed, thus providing a possible link to the abundance discrepancy problem detailed in Section 2.1.2 [34]), or that the CE is not a single, one-off ejection perhaps as outlined by [35]. Alternatively, the "missing mass" could be the result of an earlier mass-loss/ejection episode similar to those seen in the simulations of [36].

2.1.4. Double-Degenerates and Type Ia Supernovae

Some 20% or so of post-CE central stars show photometric variability associated with tidal deformations known as ellipsoidal modulation [37]. To date, every ellipsoidally-modulated post-CE central star subjected to detailed study has proven to comprise two evolved stars (i.e., two white dwarfs) [38]. As such, this fraction likely represents the tip of the iceberg in terms of such double-degenerate (DD) systems, given that only those that have very short orbital separations are photometrically variable—indeed a number of further DD systems have been detected only through their radial velocity variability [24].

The apparently high fraction of DD, post-CE central stars could have wider implications given that the mechanism by which such systems form has been the subject of much debate [39]. As both stars are evolved, it was previously believed that these systems must have experienced consecutive CE events (one for each star)—where the orbital shrinkage from the first CE could make surviving a second CE challenging (depending on the components of the system). It now seems more likely that such post-CE DDs avoid the first CE via a phase of stable, non-conservative mass transfer allowing the system to survive a CE when the second component evolves to fill its Roche lobe [40].

Understanding the formation (and formation rates) of compact DD stars is of particular interest as the merger of such systems represents one of the key pathways towards type Ia supernovae (SNe) [41]. Indeed, two of the strongest candidate DD type Ia SN progenitor systems are found inside PNe [42]. The primary alternate pathway (though others have been proposed, i.e. the core-degenerate scenario [43]), known as the single-degenerate scenario (whereby a white dwarf accretes material from a nearby companion until it exceeds the Chandrasekhar limit) is also connected to the study of post-CE PN central stars, with the central star of IPHASX J195424.6+205252 (V458 Vul) constituting one of the strongest candidate progenitors for that pathway [44]. The fact that both single- and double-degenerate pathways bear such a strong relation to PNe is further emphasised by the finding that of a number of type Ia SNe explode in circumstellar environments that may be consistent with a remnant PN [45,46].

Ultimately, further constraining the population of post-CE central stars (DDs and otherwise) will likely reveal important clues towards understanding the origins of cosmologically-important type Ia SNe.

2.2. Wider Binaries

Thus far, I have focused on the CE and post-CE PNe but, as previously mentioned, a majority of solar-type binaries are too wide to experience a CE. This does not mean, however, that they will simply evolve as single stars—many systems will be wide enough to avoid the CE but still experience appreciable interaction, perhaps in the form of wind Roche lobe overflow[4] [48] or via some form of companion-reinforced attrition process (CRAP; [49]). The precise range of orbital separations over which these processes can operate, as well as their impact on the properties of a subsequent PN, are highly uncertain, however recent studies have begun to reveal a population of wider binary central stars [50].

Of the definitively non-post-CE, binary central stars, only a handful have had their periods measured (via long-term radial velocity monitoring)[5], with the longest (NGC 1514) being a little over 9 years [52]. Even with such a long orbital period, the impact of the central binary is highlighted by the presence of a pair of infrared-bright rings, similar to those observed in other binary phenomena (e.g.; Hen 2-104—a symbiotic star, and SN 1987A—a type II supernova, [53]). Among the others is LoTr 5, the secondary star of which is a Barium star—defined as a G–K-type star showing unusually high abundances of s-process elements in its spectrum, the standard formation model of which is the accretion of s-process-enhanced material from an evolved primary via wind Roche lobe overflow [54]. Indeed, several other PNe have been found to have Barium star central star (e.g., [55]), but which have yet to have their periods measured, and all have bipolar and/or ringed PN morphologies consistent with significant binary-induced shaping [56].

3. Pre-Planetary Nebulae

Much of the discussion at WorkPlaNS II was of pre-PN—objects in the short-lived phase between the end of the AGB and the post-AGB central star reaching a temperature sufficient to ionise the surrounding envelope. Such objects are often ignored when discussing the importance of binarity in the formation and evolution of PNe – principally because, to date, no bona-fide post-CE PPN[6] has been discovered despite many years of diligent observation [58,59].

Recently, HD 101584 has received much attention as a post-AGB star with an apparently post-CE companion, that is surrounded by a bipolar circumstellar nebula which would certainly be

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4 Wind Roche lobe overflow could even cause the orbital separation to reduce, possibly leading to a CE phase [47].

5 A number of further wide-binary central stars have been found, either via chemical contamination of their companions (for example, the Barium stars as mentioned later) or via companions resolved with space-based observations [51], for which the orbital periods have not been measured.

6 The central star of the Calabash nebula (OH 231.8+4.2) likely has an A-type companion, but the orbital characteristics are uncertain [57].

morphologically consistent with binary-induced shaping (though perhaps not energetically so [60,61]). However, the binary classification of the central star is principally based on the ruling out of a pulsational origin for the observed variability by [62], due to their measured radial velocity amplitude (3.0 $\pm$ 3.4 km s^{-1}) and period (218 days). However, ref. [63] derive a significantly-shorter period (144 days) and also refute the claim that the star itself is of late B-type, rather finding that it is an early F-type (while others find it to be late A-type). Collectively, the uncertainties on the periodicity, spectral type and amplitude, might mean that pulsation should not be so-readily ruled out as the cause of the observed variability (as is the case for the numerous variables studied by [64,65]). Furthermore, even if the system is proven to be a binary, the purported period(s) is not entirely consistent with those observed for the general post-CE population (which are normally of the order of a day or shorter). This might mean that the system avoided a full-blown CE event, perhaps via the launching of jets and a so-called grazing envelope evolution [35].

Beyond HD 101584, there are other similar candidates where the properties of the nebulae are seemingly only consistent with a binary evolution of their central stars [66–68]. However, as demonstrated by the handful of wider non-post-CE binaries detected in PNe (see Section 2.2), these may not necessarily be the products of a CE. Indeed, the central star of M 2-9 has been shown to be a symbiotic-like system with a period of 86 $\pm$ 5 year [69], where the lighthouse-like variability in the highly bipolar nebula is likely the product of a rotating, collimated jet launched by the binary.

Ultimately, the lack of observed post-CE central stars in pre-PNe is still somewhat troubling given the relatively large fraction observed among the general PN population. It has been suggested that the discrepancy could be a consequence of the CE phase itself, whereby post-CE evolution could be accelerated with respect to single star (or wider binary) evolution, meaning that post-CE binaries spend less time in the pre-PN phase and become fully-fledged PNe earlier [9]. Finally, the similarities between the properties of some pre-PNe and galactic luminous red novae, which are the product of a CE in which the two stars merged [15], possibly hint that a significant number of pre-PNe may be the product of CE mergers and would thus not contain a surviving post-CE binary central star.

4. Conclusions

I have attempted to review some of the unique aspects of binary evolution related to PNe, both in terms of their importance in understanding the formation and evolution of PNe but also the areas in which PN-related research will likely have wider impacts for the binary star community. The mutual exploitation of these overlaps, as well as continued and fomented collaboration between the PN and binary evolution communities, will be extremely important in justifying future work in the field (both theoretical and observational).

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