Do post-common envelope objects form a distinct subset of PNe?

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Summary. A new Hα surface brightness – radius (SB–r) relation has proved to be a useful statistical distance indicator for planetary nebulae. Known close binary PNe with reliable primary distances are shown to inhabit a distinct locus in SB–r space. Comparing the ionized masses of this sample with a volume-limited ensemble of PNe with the same range of surface brightness leads to the conclusion that post common-envelope (CE) PNe have systematically lower ionized masses than 'normal' PNe. Post-CE PNe are also morphologically distinct from the majority of elliptical PNe. A comparison of optical and near-infrared colors of the central stars of PNe in a volume limited sample leads to an estimated binary fraction of 52 – 58 per cent, similar to the known binary fraction of G-type main-sequence stars. Close binaries form a subset of these so we conclude that only a minority (12 – 33 per cent) of PNe have passed through a CE phase.

Key words: stars: AGB and post-AGB; stars: binaries: general; planetary nebulae: general

1 Introduction

The question of binarity as being an essential ingredient for the production of PNe is a hot topic at present, though its role in shaping PNe is considered (in at least some cases) to be on much firmer ground (for reviews, see [3, 40]). Recent studies have suggested that the binary fraction amongst PN central stars may approach unity [12], but this fraction is based on a small number of objects. In order to better estimate the proportion of close binaries amongst PN central stars, and to understand their role in PN evolution, a volume-limited sample of PNe is necessary. We have compiled a detailed database of 'potentially nearby' PNe and for many of these objects have obtained new global fluxes in Hα and [O III]. A secondary distance indicator, the Hα surface brightness – radius (SB–r) relation, has been developed to estimate distances for the PNe for which no primary (individual) distance estimate exists; further details are provided in [20, 21]. As a result, we have defined a volume-limited sample of PNe within 1.0 kpc (presently $n = 56$), and a less complete 2.0 kpc sample

(n = 197). Ten nearby nebulae traditionally classified as PNe have been shown to be Strömgren zones in the ambient ISM, rather than true PNe (e.g. Sh 2-174, DeHt 5, Sh 2-68, RE 1738+665, HDW 5, PG 0108+101, PG 0109+111, Hewett 1, and PHL 932) [10, 20, 33]. These nebulae no longer contaminate our volume-limited sample.

2 Low-mass PNe in SB–r space

Low-mass PNe will plot along the lower bound of the broad trend seen in Hα SB-r space (Figure 1). Many of these have several characteristics in common and form a distinct subset of PNe [27]. For the purposes of our study we have defined very high excitation PNe as showing strong He II λ4686 emission, specifically F(He II)$\geq$ 0.75 F(Hβ) *and* very weak or absent [O II], [N II] and [S II] lines. These PNe are optically thin, generally have round, simple elliptical, or amorphous (filled-center) forms, higher than average expansion velocities ($>$ 30 kms^{-1}), and ionized masses, $M_{\rm ion} \leq 0.25\ M_\odot$. Their central stars (CS) are hot ($T_{\rm eff} > 100$ kK), luminous relative to the nebular flux, and still in the nuclear burning phase. The scale height of the group is $|z| \simeq 300$ pc, considerably higher than the mean for all local PNe ($|z| =$ 210 pc [21]), suggesting that the progenitors are of low mass ($<$1.5 $M_\odot$). This nicely explains both the low shell mass and the slow rate of CS evolution.

We also found that the region of SB–r space populated by optically thin, high-excitation PNe is shared with close binary objects. In other words close-binary PNe are also of low mass. To elucidate this, we analyze the properties of the 23 close-binary PNe given by [13]. Abell 35 was omitted from this list, as it has a demonstrably wide binary companion [22], as was NGC 6302 since the evidence for binarity is weak [43]. The bipolar PN Sh 2-71 has also been omitted as the true CS has been misidentified in the literature till now (see Figure 2). We retained LoTr 5 and NGC 1514, even though the orbital periods are unknown, as they have rather amorphous morphologies. Finally, NGC 1360 has been included as it is morphologically similar to Abell 65, a known close binary PN, and radial velocity variations have been reported [2]. This gives a sample of 21 objects, of which 11 have reliable primary distances. These PNe, listed in Table 1, are also used as calibrating objects for a 'low-trend' SB–r relation [20], which is used to find distances to the remaining objects given in [13].

Known close binary PNe show a somewhat restricted range of Hα surface brightness ($S_{\rm H\alpha} = -2.5$ to -6.2 erg cm^{-2}s^{-1}sr^{-1}) compared to the full observed range for all PNe (+0.2 to $-$6.7). In other words, PNe of highest SB are not known to host close-binary nuclei. This has been traditionally interpreted as a selection effect [9]. The average ionized mass of local, non-close binary PNe (selected for SB within the same limits shown by close-binary PNe) is 0.64 ± 0.5 $M_\odot$. However, the average ionized mass for the objects from Table 1 is 0.17 ± 0.13 $M_\odot$, or 0.13 ± 0.08 $M_\odot$ if HFG 1 is excluded (due to a less reliable ionized mass). This result confirms what is apparent from the distinct locus of post-CE objects in SB–r space; that the known post-CE PNe have systematically lower ionized masses than other PNe of similar SB. This observation extends the conclusion of [4] based on Abell 63.

Furthermore, post-CE nebulae seem to show quite distinctive filled-center, bipolar, or toroidal morphologies, but not the more typical double-shelled forms [9]. All

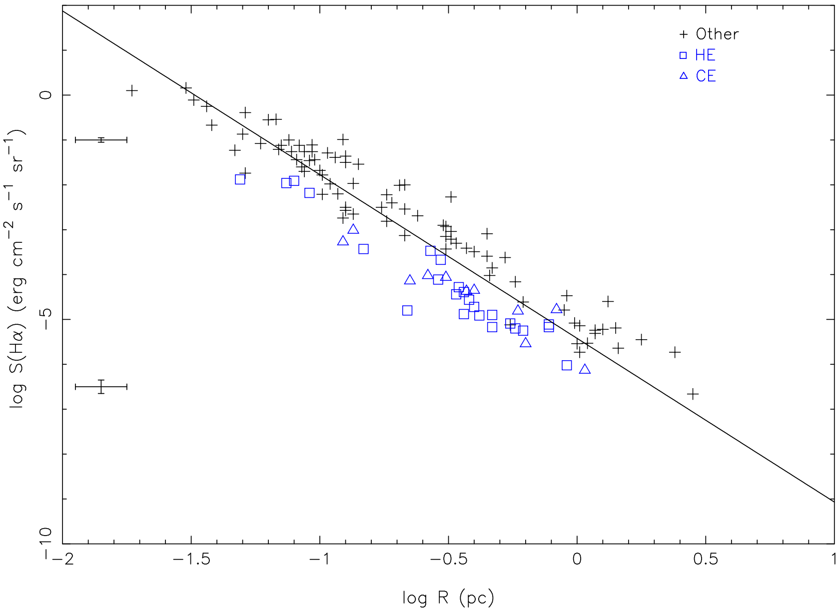

Fig. 1. New Hα SB – r relation, which extends nearly 7 dex in SB, is based on a large sample of 118 calibrating PNe. Common-envelope (CE) PNe (blue triangles) have lower masses and define a separate trend in *SB–r* space, coincident with high excitation (HE) PNe (squares). Other calibrating PNe are marked with crosses. The line is a least-squares bisector fit [26] to the entire sample, and representative error bars are shown.

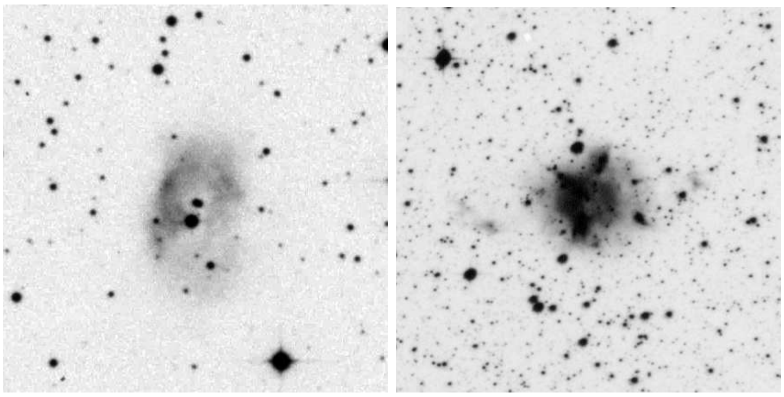

Fig. 2. Left: Blue DSS image of the bipolar PN Sh 2-71. The bright star near the center of the PN is considered to be the CS in the literature. A much better candidate is a faint 19th mag star at the exact center, just NW of the bright star. It is barely visible on this image. Right: UKST Hα+[N II] image of the remarkable point-symmetric PN Longmore 16. Both images are 5′ wide, with NE at top left.

in all, the known close binary PNe have a distinct spectrum of properties, which differentiate them from the more common 'typical' PNe.

Table 1. Known post-CE nebulae with reliable distances. Ionized masses are calculated from our measured diameters and fluxes, and assuming a volume filling factor of 0.4 [21].

PN	Distance (kpc)	Method	Reference	Ionized Mass ($M_\odot$)
Abell 46	1.7 ± 0.6	1	[39]	0.14
Abell 63	2.4 ± 0.4	1	[4]	0.08
BE UMa	2.0 ± 0.4	2	[19]	0.2:
DS 1	0.73 ± 0.07	2	[15]	0.26
HFG 1	0.6 ± 0.3	3	[16]	0.5:
LoTr 5	0.5 ± 0.2	3, 4, 5	[1, 21, 41]	0.13
NGC 1360	0.37 ± 0.10	5, 6	[1, 21]	0.13
NGC 1514	0.37 ± 0.15	3	[21]	0.03
NGC 2346	0.9 ± 0.2	3, 7	[21]	0.06
SBS 1150+599A	18 ± 5	6	[42]	0.17
SuWt 2	1.6 ± 0.4	3	[21]	0.06

Distance method: 1. Eclipsing binary; 2. Reflection effect model; 3. Spectroscopic parallax; 4. Wilson-Bappu relation; 5. Trigonometric parallax; 6. Gravity method; 7. Extinction distance.

3 Where are the binaries?

If all PNe are the product of CE evolution, there should be direct observational evidence for binary companions. There are several techniques used to discover or infer the presence of a binary companion. Briefly, they are: (1) direct imaging for resolved companions, (2) measuring cyclical photometric variations (sensitive to close binaries with orbital periods shorter than a few days), (3) radial velocity variability with a definite periodicity, (4) detecting composite spectra (evidence for both cool and hot components), and (5) using optical and near-infrared (NIR) photometry to infer the presence of an unresolved cool companion.

The known close binaries summarized by [13] were primarily found via photometric monitoring. However, this technique has selected for bright CS in faint PNe, and seems to be biased *a priori* to finding binaries (note that the mean absolute magnitude of the close binary sample is significantly brighter than the mean of the non-close binary sample in the solar neighborhood [21]). Indeed, the local sample is ideal to gauge the true fraction of binary companions. We estimate there are 56 PNe with $D \leq 1.0$ kpc, including eight known wide binaries discovered from direct imaging, namely NGC 246, NGC 3132, NGC 6853, NGC 7008, Abell 7, Abell 31, Abell 35, and EGB 6 [6, 8, 11, 22, 30]. Note that the companion(s) of NGC 6853 may not be physical [11].

Looking in the near-IR for signatures of cool companions has been productive [44]. By comparing reddening-corrected colors with the intrinsic colors of a 100kK DA white dwarf [5], the presence or absence of a cool companion can be inferred. The 2MASS survey provides accurate photometry to $J \simeq 16$, $K_s \simeq 14.7$. As long as the CS is brighter than these limits, then the detection threshold for a CS companion is a spectral type of ~M0 V – M8 V, depending on the luminosity of the true nucleus. Since most local PNe are highly evolved with CS on the WD cooling track, the practical limit is towards the *fainter* end of this range. For the local PNe, only the K0 V secondary in NGC 246 is resolved in 2MASS data. Of the rest, NGC 3132 and Abell 35 have colors dominated by the brighter companion, and the remaining five CS *all* show a NIR excess compared to that expected from the optical magnitudes. If not already discovered as visual binaries by direct imaging, these stars would all be strongly suspected of binarity based on optical-NIR colors.

Of the seven likely close binary PNe within $D = 1.0$ kpc (of which four are bona fide, with known orbital periods), only the CS of NGC 6337 has inadequate data. Of the remaining six, five are either dominated by the cooler companion or show an excess at J, H and/or K_s. The exception is NGC 1360, and we emphasize that binarity has *not* been proven for this object as yet. At any rate the limit is not particularly stringent; the companion, if present, has a spectral type later than M2 V. The return rate of using optical/NIR colors in finding known companions shows that this is a highly effective technique of inferring binarity at arbitrarily close separations.

Of the remaining PNe in the local volume, NIR data is wanting for 18 objects due to the faintness of the CS. Another three local PNe have a suspect CS identification, which might be taken as evidence of a likely companion, but are not considered further at this point, while three more have uncertain optical photometry. Of the 19 others which have adequate optical and NIR data, four show an excess at J, $H$and/or K_s. These are Ton 320, already shown to have an NIR excess by [25], plus Longmore 16, EGB 9 and HbDs 1. The last object has been monitored photometrically [24] but no variations were found. Lo 16 is an especially promising candidate for photometric follow-up, due to its unusual point-symmetric morphology (Figure 2). In summary, considering the 33 local PNe with adequate data, the *total* binary fraction is 52% – 58%, and depending on the exact assumptions made, the total close-binary fraction is 12% to 33%, somewhat greater than, but in formal agreement with the estimate of 10% to 15% based on photometric variability [7].

3.1 Are there undetected companions to PN central stars?

Optical/NIR colors should be effective at detecting the majority of unresolved CS/red dwarf binaries. Since the observed binary fraction is slightly over half, and the close binary fraction lower still, there needs to be a large number of faint brown dwarf (BD) or cool WD companions present *if binaries are needed to generate PNe.* However, this seems unlikely based on BD detection statistics. Recall the 'Brown Dwarf Desert' [23, 34], whereby solar-type stars (i.e. PN progenitors) have an almost total absence of BD companions within 5 AU, the upper separation limit for a CE phase to occur during AGB evolution.

Confirmatory statistics are provided by WDs [17, 18], the descendents of PN nuclei. The turnover in the companion star frequency distribution is approximately M3.5 V, the same as for field red dwarfs [17], and consequently BDs are found to be rare around WDs (see Farihi 2007, these proceedings). The percentage of double-degenerate systems is also too low [35] to readily account for the lack of observable companions.

Alternatively, a single CS may be a merger product, a point argued at this meeting, but this is again considered unlikely. BDs are very rare at close separations around WDs, but the fraction is not nil. One has been found to be in a short period orbit around a WD [36]; this system must be the result of CE evolution, therefore it is apparent that even *substellar* companions can survive a CE phase. So it seems unlikely that merger events are frequent enough to explain away the nearly 50% of nearby central stars which do not appear to have a detectable companion. Occam's razor suggests that single stars can make PNe.

4 On the Galactic population and birth rate of PNe

A recent novel way of predicting the total number of Galactic PNe has been presented by [37]. This study used a population synthesis model to predict a total Galactic PN population of 46,000 ± 13,000 PNe, which disagrees with their preferred observationally determined estimate of 8000 objects (R $\leq$ 0.9 pc). They conclude that only some of the stars thought to be able to make PNe, actually do so, namely close binaries. Similarly, [38] have predicted a population of 5000 ± 1600 PNe if they result from CE evolution, which is in tolerable agreement with the observations.

Based on the column density of PNe in the solar neighborhood, [20] give an estimate of the total Galactic population of 28,000 PNe, which however, includes senile PNe with radii $>$ 1.0 pc. We can repeat this calculation using only nearby PNe with $R \leq 0.9\,\mathrm{pc}$ to estimate a local disk column density of 13.0 kpc^{-2}. Extrapolating to the whole Galaxy leads to a total of ~13,000 PNe ($R \leq 0.9\,\mathrm{pc}$), which is in between the predictions of [37, 38]. Our resulting PN birthrate is $0.8 \pm 0.3 \times 10^{-12}$ pc^{-3}yr^{-1}, fully consistent within the errors with the WD birthrate of $1.0 \pm 0.25 \times 10^{-12}$ pc^{-3}yr^{-1} [32].

We note that recent work on the low-mass end of the initial-final mass relation (IFMR) [29] hints at a revision of the lower mass bound for PN production; if the lower limit of a PN progenitor is closer to $1.5\,M_{\odot}$ (compared to 0.9 $M_{\odot}$), this will substantially decrease the number of PNe predicted by the population synthesis model [37], and bring it into closer agreement with the observations. Especially interesting is the data from the old metal-rich cluster NGC 6791; an average initial mass of 1.16 $M_{\odot}$ is found to produce an average WD mass of only 0.51 $M_{\odot}$ [29]. However, a CS below a minimum mass of $\sim 0.55\,M_{\odot}$ is considered to evolve too slowly to ionize a PN before it disperses into the interstellar medium (see the discussion in [37]). Furthermore, most of the lower mass WDs in NGC 6791 evolved directly from the extended horizontal branch [28], a consequence of super-solar metallicity, further reducing the pool of potential PN progenitors. Further observational data to refine the low-mass end of the IFMR (and any metallicity dependence) is urged.

5 Conclusions and Future Work

Close binary (post-CE) PNe form a distinct trend in SB-r space, shared by optically-thin, high-excitation PNe. Post-CE PNe have low ionized masses and seem to show quite distinctive amorphous, bipolar, or toroidal morphologies, but not the more typical double- and multiple-shelled forms [9].

Since the sample size is still relatively small, there is urgent need to continue the search for close-binary nuclei via time-series photometry and/or radial velocity monitoring (though these methods are difficult for faint CS). Deep $(U)BVRIJHK(L)$ photometry of *all* CS in the solar neighborhood sample is needed to ultimately get a better handle on the intrinsic binary fraction of PN nuclei. First steps towards these goals are underway as part of the Planetary Nebula Binary (PlaNB) project (De Marco, these proceedings). New deep imaging surveys becoming available now or in the near future should have an impact by producing extensive new optical and NIR datasets (e.g. UKIDSS, VHS, SkyMapper), while new radial velocity surveys aimed at fainter CS are planned. In the meantime, the present data suggest a central star binary fraction (52% to 58%) comparable to that seen in sun-like stars [14, 31], and presumably F-type stars, which are the progenitors of at least the lower mass CS. Post-CE nebulae are a fraction of these and are in the minority: our best estimate at present is 12% to 33% of all PNe.

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