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## **Spatio-kinematic modelling: Testing the link between planetary nebulae and close binaries**

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**Abstract.** It is widely believed that central star binarity plays an important role in the formation and evolution of aspherical planetary nebulae, however observational support for this hypothesis is lacking. Here, we present the most recent results of a continuing programme to model the morphologies of all planetary nebulae known to host a close binary central star. Initially, this programme allows us to compare the inclination of the nebular symmetry axis to that of the binary plane, testing the theoretical expectation that they will lie perpendicular - to date, all have satisfied this expectation, indicating that each nebula has been shaped by its central binary star.

As a greater sample of nebulae are modelled, it will be possible to search for trends connecting the parameters of both nebula and central binary, strengthening our understanding of the processes at work in these objects. I will discuss some of the more obvious comparisons, and their current statuses, as well as the obvious links to common envelope evolution.

### **1. Introduction**

Planetary nebulae (PNe) are glowing shells of gas ejected by intermediate mass stars at the end of their lives. The most widely accepted explanation for their formation is described by the Generalised Interacting Stellar Winds Theory (GISW Theory, see, e.g., review by Balick & Frank 2002). Under this scheme, PNe are formed from the snowplough-like interaction between two stellar winds. In order to form an aspherical PN, one of these winds is required to be aspherical. Three main possibilities have been considered for the origin of this aspherical wind: (a) Stellar rotation, (b) Magnetic fields, and (c) Central star binarity. Of these, only central star binarity has stood up to theoretical investigation (de Marco 2009). The levels of stellar rotation required to produce significant wind asphericity were found to be too high (Bond & Livio 1990), while magnetic fields were found to be too short-lived in single star systems (Nordhaus et al. 2007).

For binary central stars, the shaping effect is expected to be greatest in those systems that have passed through a common-envelope (CE) phase. Here, it is the ejected CE which goes on to form the required asphericity, as it is preferentially expelled in the orbital plane of the binary (Nordhaus & Blackman 2006). Therefore, any PNe formed

Table 1. A table of PNe, with well studied binary central stars, that have been the subject of detailed spatio-kinematic study.

PN	Morphology	References
Abell 41	open-ended bipolar with equatorial torus	Jones et al. (2010b)
Abell 63	barrel-like with bipolar “end-caps”	Mitchell et al. (2007)
Abell 65	double-shelled bipolar	Huckvale et al. (2011)
		Huckvale et al. (in prep.)
HaTr 4	Elliptical with equatorial torus	Tyndall et al. (2011)
		Tyndall et al. (in prep.)
NGC 6337	Torus without bipolar lobes, jet-like corkscrew outflow	García-Díaz et al. (2009), Hillwig et al. (2010)
Sp 1	end-on bipolar	Mitchell (2007), Jones et al. (in prep.)

from a post-CE central binary is predicted to display a bipolar morphology, the symmetry axis of which is aligned perpendicular to the plane of the central binary.

While central star binarity remains the strongest contender for the origin of aspherical planetary nebulae, observational evidence is lacking. In recent years, the effort to find the observational support for the so called *Binary Hypothesis* has gathered pace, mainly through the search for new binary central star systems (Miszalski et al. 2009; Corradi et al. 2011; Miszalski et al. 2011a,b; Jones et al. 2011; Boffin et al. these proceedings), which now number  $\sim 50$  (c.f.  $\sim 3000$  known Galactic PNe). With the relatively rapid rate of discovery of new binary central star systems, it is now important to begin to try to relate the properties of the host PNe to those of their central stars.

In these proceedings, I will detail the results of an on-going investigation to determine the morphologies of all PNe known to host binary central stars, with the aim of relating those morphologies to the parameters of the central binary stars (particularly testing the expected perpendicular alignment between nebular symmetry axis and binary plane).

## 2. Determining the morphologies of planetary nebulae

The orientation and morphology of a PN cannot be determined from imagery alone as projection effects result in a degeneracy between shape and inclination (i.e. a bipolar nebula viewed “end-on” will appear to be circular/spherical, see, e.g. Kwok 2010). This degeneracy can only be circumvented by spatio-kinematic modelling of the PN based on both imagery and spatially resolved spectroscopy of the nebula (see figure 1). Detailed explanation of the techniques used can be found in Jones et al. (2010a,b).

It is important to note that spatio-kinematic modelling reveals not only the general morphology of the PN, but also the orientation of the nebular structure with respect to the line of sight. This inclination to the line of sight is an important parameter as it can be compared to the inclination of the orbital plane (of the central binary, determined by modelling of photometric and/or radial velocity measurements of the system), in order to test the expected perpendicular alignment, and therefore examine whether the PN has been shaped by its central binary.

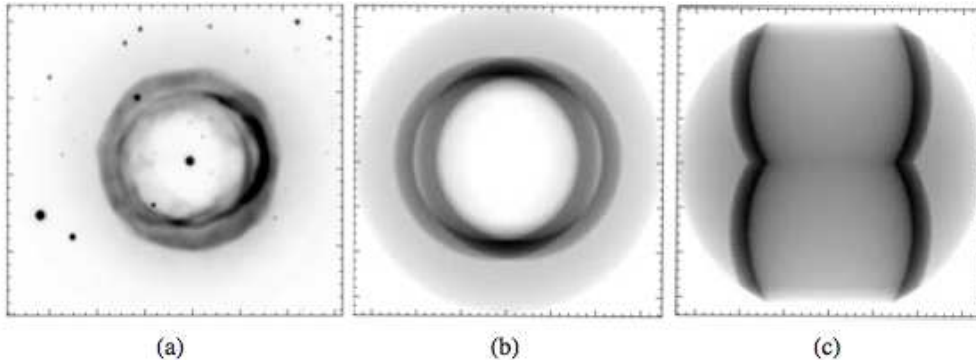


Figure 1. Image and model of Sp 1. (a) Shows the observed image of Sp 1, an apparently spherical/circular PNe, (b) shows the model at the observed inclination and (c) at an inclination of  $90^\circ$  (Note: images not to same scale). This PNe is a good example of the need for spatio-kinematic modelling due to the degeneracy between morphology and orientation in imagery.

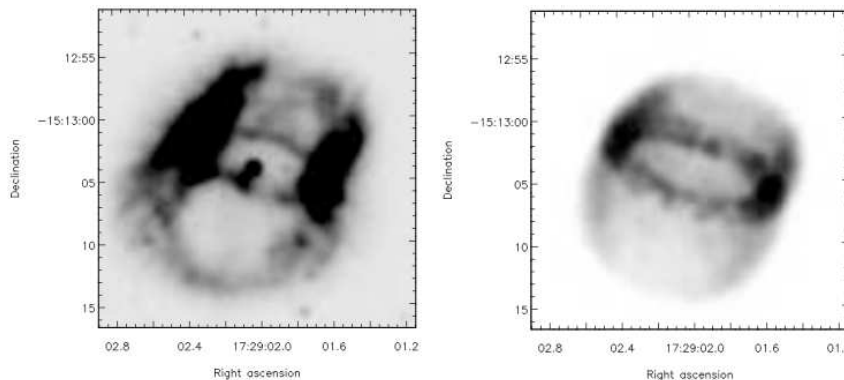


Figure 2. An image of Abell 41 (left) and the Jones et al. (2010b) model (right).

### 3. The sample

To date, only six PNe with well-constrained binary central stars (i.e. with known orbital inclinations) have been subjected to detailed spatio-kinematic study. However, each of the six PNe has been shown to follow the expected anti-alignment between nebular symmetry axis and binary orbital plane, indicating that each of the PNe has been shaped by its central binary. The PNe studied along with a description of the derived morphology is presented in table 1. Examples of the observed and modelled morphologies of Sp 1 and Abell 41 are shown in figures 1 and 2, respectively.

### 4. Results

As detailed in section 3, all of the six PNe, which have been subjected to detailed study of both central binary system and nebular morphology, have been shown to follow the expected perpendicular alignment between nebular symmetry axis and binary orbital

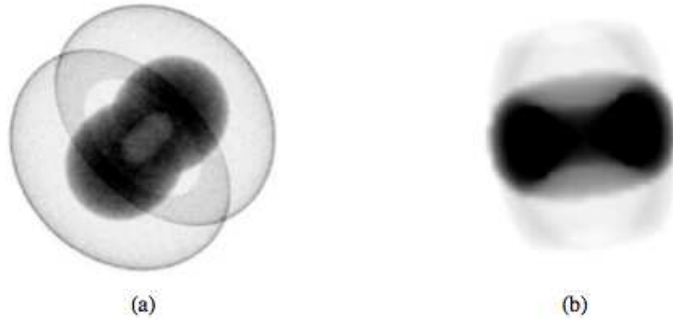


Figure 3. Spatio-kinematic models of (a) Abell 65 (Huckvale et al. 2011, in preparation) and (b) HaTr 4 (Tyndall et al. 2011, in preparation).

plane. The fact that *all* of the sample display this perpendicular alignment indicates that each PNe has been shaped in some way by its central binary - strengthening the candidacy of central star binarity as the most important factor in the shaping of aspherical PNe. Although some common features do appear among the PNe (equatorial rings, polar outflows), it is clear that each of the PNe studied is morphologically very different (see e.g. the modelled morphologies of Abell 65 and HaTr 4, shown in figure 3), indicating that understanding the exact shaping mechanism(s) will not be trivial!

#### 4.1. Expected correlations?

As the number of PN systems subjected to detailed study increases it will become possible to search for correlations between the orbital parameters of the binary central stars and the morphological parameters of their host PNe. The most obvious correlations to examine are between the period of the central star, which should be related to the orbital angular momentum deposited in the ejected CE, and the nebular morpho-kinematics. Examining the relationship between binary period and degree of collimation of the nebular lobes (characterised by a factor I have called  $\phi$ , which is the ratio of maximum lobe radius and waist radius), one might expect the most highly collimated PNe (high  $\phi$ ) to host the shortest period binaries (as more orbital angular momentum deposited in the CE will cause a high over-density in the binary plane, creating the tight waist of the collimated PN). Orbital period is plotted against the collimation in figure 4a (ETHOS 1, a seventh PNe for which the relevant data is available, has also been included - see Miszalski et al. 2011a), showing no strong correlation. However, the most collimated PNe do exhibit the lowest orbital periods, indicating that a correlation may be found with the addition of further data points.

If, as current theories predict, the ejected CE goes on to form the waist of the subsequent PNe, one might expect to find a correlation between the equatorial expansion velocity of the PNe and the orbital periods of their central binary stars (as lower periods require more angular momentum to be transferred to the CE, possibly ejecting it at higher velocity). These two parameters are plotted in figure 4b (including a further 3 PNe for which the relevant data is available - ETHOS 1, The Necklace, & NGC 6778 - see Miszalski et al. 2011a, Corradi et al. 2011 and Maestro et al. 2004, respectively), again showing no apparent correlation. However, the greatest equatorial expansion ve-

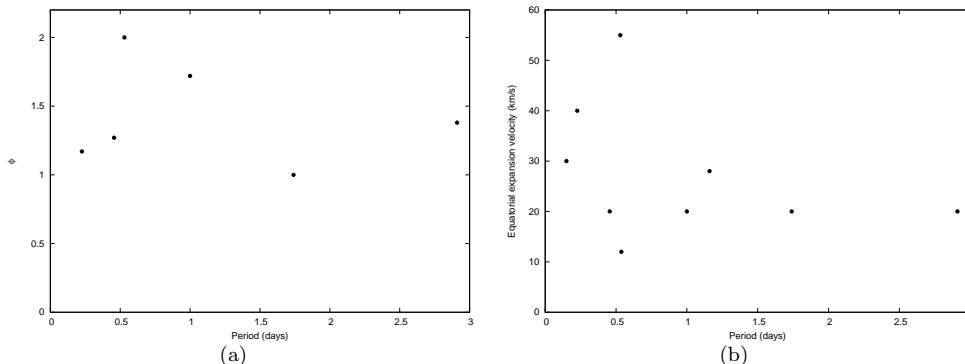


Figure 4. Plots of central star orbital period versus (a) collimation factor,  $\phi$ , and (b) equatorial expansion velocity for the PNe in this study.

locities are found in PNe with the shorted orbital period central stars, hinting that a possible correlation may be found with the addition of further data points.

#### 4.2. Pre-CE polar outflows?

Table 2. The kinematical ages of PNe, with binary central stars, and their observed polar outflows (see text for references).

PN	PN age (yrs kpc <sup>-1</sup> )	Polar outflow age (yrs kpc <sup>-1</sup> )
Abell 63	3500 ± 200	5200 ± 1200
ETHOS 1	900 ± 100	1750 ± 250
The Necklace	1100 ± 100	2350 ± 450
NGC 6337	~ 9200	~ 1000

ETHOS 1 (Miszalski et al. 2011a), The Necklace (Corradi et al. 2011), NGC 6337 (García-Díaz et al. 2009) and Abell 63 (Mitchell et al. 2007) all display extended polar outflows in the form of jets or end-caps, which have been kinematically studied. Interestingly, in three out of the four systems (ETHOS 1, The Necklace & Abell 63) the polar outflows are found to be older than the central PN. Currently, the only explanation for this discrepancy is for the polar outflows to have formed *before* the central binary entered the CE phase, possibly at the onset of mass transfer. Furthermore, in each of these systems the polar outflows are found to be approximately ~1000 years older than the central PNe (see table 2), which is consistent with the expected lifetime of the CE phase (Webbink 2008).

#### 5. Discussion and conclusions

Each of the PNe studied shows the expected perpendicular alignment between PN and binary orbital plane, indicating that central star binarity has played an important role in

the shaping of the PNe. These results indicate that central star binarity may indeed be the most important factor in the formation of aspherical PNe - a key unsolved problem in the PN community.

Too few PNe have been subjected to detailed study to be able to determine strong correlations between the parameters of nebula and central binary, however the results so far are certainly encouraging enough to warrant continued investigation.

Probably the most striking result to come from this work, particularly in a binary context, is that polar outflows in PNe may originate from before the CE phase, meaning that PNe may be used as a tool to constrain the mass-loss leading up to the CE phase *as well as* the ejection of the CE itself.

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