Binarity and Symbiotics in Asymmetrical Planetary Nebulae

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Abstract. We show that there are strong links between certain types of asymmetrical Planetary Nebulae (PNe) and symbiotic stars. Symbiotics are binaries and several have extended optical nebulae all of which are asymmetrical and ≥ 40% are bipolar. Bipolar PNe are likely to be formed by binaries and share many properties with symbiotic nebulae (SyNe). Some PNe show point symmetry which is naturally explained by precession in a binary system. M2-9 has both point and plane symmetry, and has been shown to have a binary central object. We show that inclination on the sky affects the observed properties of bipolar nebulae due to enhanced equatorial densities, and compare observations of a sample of BPNe with a simple model. Good agreement is obtained between model predicted and observed IR/optical flux ratios and apparent luminosities, which further confirms the binary hypothesis.

1. Introduction

Planetary Nebulae (PNe) are formed and live briefly at the spectacular end of the lives of most low- and intermediate mass stars. The outer layers of these stars are expelled when their cores collapse after having used up their core fuel and switching off the nuclear furnace that through radiation pressure kept gravity at bay. These tenuous outer layers are then lit up by photo-ionization caused by the heating up of the collapsing core. The White Dwarf (WD) that remains cools, following a “Schönberner track” in the HR diagram on which the cooling time depends critically on the WD mass, with massive stars evolving much faster than lower mass objects. For PNe the average WD mass is about 0.6 M⊙, with associated cooling time of about 10^5 yrs. after which the star remnant fades away like a dying ember.

This scenario was essentially predicted by Deutsch(1956) in a paper called “The Dead Stars of Population I”. He links the formation of PNe to the last phase of red giants, and makes the connection with the so-called “combination variables” which are now known to be the symbiotic stars\(^1\), systems with partially ionized gas and dust surrounding a binary containing a hot, compact star and a cool giant.

\(^1\)The term ”symbiotic star” was coined by Merrill (1950) and was not yet disseminated well in 1956.
The classical picture of a PN as a “circle with dot in the middle” has now been superseded by the rich complexity of observed morphologies, and it is accepted that most PNe are asymmetrical. A smaller fraction of PNe shows extreme asymmetries: the bipolar and point-symmetric PNe. Related are the symbiotic nebulae (SyNe) which have a high proportion of bipolar and other strongly asymmetric nebulae.

2. Bipolars and Symbiotic Nebulae

Bipolar PNe (BPNe) are a sub-set of the general group of PNe. There are various definitions of what BPNe are but here I will use the one formulated by Schwarz et al. (1993), noting that this is one of the more restrictive definitions. A PN is bipolar when it has an aspect ratio larger than unity and has a “waist” i.e. it has well defined lobes and an overall dumb-bell shape. With this definition 12\% of the objects in Manchado et al. (1996) are bipolar, 11\% in Schwarz et al. (1992), and 9\% in Górný et al. (1999), the three major imaging catalogs of recent years. Therefore about 10\% of the ≈600 PNe with good narrow-band images are truly bipolar.

Bipolarity is not just a morphological coincidence. Bipolar PNe have properties that differ significantly from those of the general PNe sample as was first reported by Corradi & Schwarz (1995). They used a sample of about 50 objects to show that: BPNe have a smaller scale height (z = 130 pc vs. 260 pc); hotter central stars (mean = 145 kK vs. 75 kK); nearer circular orbits in the Galaxy; He, N, & Ne overabundances; higher mean $V_{\text{exp}}$ (150 kms$^{-1}$ vs. 15 kms$^{-1}$); larger mean linear sizes (0.76 pc vs. 0.1 pc); & more massive progenitors ($\geq 1.5 M_\odot$ vs. $1.0 M_\odot$). Another piece of evidence comes from Stanghellini et al. (1993) who investigated correlations between the morphology of PNe and their CS loci in the HR diagram. They found that bipolars have a different mass distribution of central stars from those of elliptical PNe, and a lower ratio of HeII/III Zanstra temperatures than ellipticals (1.3 vs. 1.8) and therefore a different optical depth. These results are based on a small sample of objects but again physical properties correlate with morphology. We conclude that BPNe come from a different population with different physical properties.

Bipolars are among the most extreme asymmetrical PNe, something they have in common with some of the SyNe that have been discovered. We list the known SyNe in Table 1. We put M2-9 in Table 1 since according to Balick 1989 the object is probably symbiotic. Note that 6 SyNe are bipolar or 40\% of the total, cf. 10\% of PNe. He2-147 is possibly bipolar too, the outflow having left the now visible ring. This would increase the bipolar SyNe fraction to 47\%. This firmly links binarity with bipolarity. Note that 5 out of the 7 SyNe with known expansion velocities have $V_{\text{exp}} \geq 100$ km/s with an average $V_{\text{exp}} = 232$ km/s, similar to the bipolars. Sa2-237 (Schwarz et al. 2002), M2-9 (Schwarz et al. 1997), BI Cru (Schwarz & Corradi 1992) and He2-104 (Corradi & Schwarz 1995) are all binaries, because these objects need a hot central source to excite the observed [OIII] line but have low luminosities. Other evidence shows that they have an evolved cool star (a Mira in He2-104 and BI Cru) so the central objects are symbiotic-like binaries.
Table 1. Symbiotics with optical nebulae. Given are: name, type, size of nebula, shape description, aspect ratio (AR), and the maximum expansion velocity. D and S are dusty and photospheric types resp. (Kenyon 1986), Yell indicates yellow symbiotics with the G band in their spectrum.

| Name      | Type | Size (") | Shape     | AR  | max 2V_{exp} |
|-----------|------|----------|-----------|-----|--------------|
| AG Peg    | Yell | 8        | irregular |     |              |
| AS 201    | Yell | 13       | elliptical| 1.3 | 16           |
| BI Cru    | D    | 150      | bip. + jet| 8   | 280          |
| CH Cyg    | S    | 32       | jet + irreg.| 1   |              |
| H 1-36    | D    | 1.5      | unresolved | -   |              |
| H 2-2?    | S    | 1.4      | unresolved | -   |              |
| HBV 475   | S    | 0.4      | irregular | -   |              |
| He 2-104  | D    | 95       | 2 bip. + jet| 10  | 250          |
| He 2-147  | D    | 5        | proj. ring| 2.2 | 100          |
| HM Sge    | D    | 30       | irregular | 2.5 |              |
| M2-9      | D    | 115      | bipolar   | 12  | 328          |
| R Aqr     | D    | 190      | bip. + jet| 6   | 200          |
| RX Pup    | D    | 4        | bipolar?  | -   |              |
| V417 Cen  | Yell | 100      | bipolar   | 2   | 10           |
| V1016 Cyg | D    | 20       | elliptical| 2   |              |

There is also evidence that the bipolars A79, He2-428, and M1-91 are binaries (Rodríguez et al. 2001).

Summarizing: SyNe have 4 times more bipolars than normal PNe; average $V_{exp} = 140$ km/s as for bipolars; average $z = 133$ pc as for bipolars; bipolar SyNe have average $z = 98$ pc; most have [NII] as strongest line as do bipolars. So SyNe share many properties with bipolar PNe and are known to be binaries.

We note that the aspect ratio - which is a measure of the degree of asymmetry or bipolarity - is correlated with $V_{exp}$ in SyNe. Figure 1 plots this for the 7 SyNe for which both values are known. One expects this behavior if the degree of collimation is related to the outflow velocity.

Bipolar PNe have a preferred direction and this should produce observable effects due to their orientation on the sky. In the next section we investigate this.

3. Inclination effects in bipolar nebulae

PNe are randomly oriented in the Galaxy according to Corradi, Aznar & Mampaso (1998), and therefore the number distribution of observed bipolar axes on the sky should follow a sin(i) law, where i is the inclination to the line of sight. An inclination of 90° is associated with a bipolar with its lobes in the plane of the sky, 0° means the lobes point toward the observer. If there is an equatorial density enhancement in bipolars, as suggested by e.g. Morris (1987), Icke, Balick, Frank (1992), Corradi & Schwarz (1995), Schwarz, Corradi, Méndez (2002), then some effect on their observed Spectral Energy Distributions (SEDs) and
The equatorial “torus” will produce an increased extinction toward the central star when this is viewed at an inclination nearer 90°, because the stellar light passes through more of the material. Some of the shorter wavelength light is absorbed and re-emitted as FIR radiation, increasing the relative contribution to the luminosity in the IRAS bands. Viewed pole-on, the same object will show the central object, basically un-reddened plus the torus, and the overall spectrum will be bluer.

The other mentioned effect is the variation of the luminosity with orientation. Pole-on objects will be apparently over-luminous, due to the fact that we see both the central star plus the re-radiated emission from the torus, while equator-on nebulae will have a lower observed luminosity since only the edge of the torus is seen. Random inclination statistics assure that the mean luminosity over all directions is constant and no energy conservation laws are violated.

We have collected a sample of 29 bipolars for which we have data on the BVR, JHK, and IRAS fluxes, plus an inclination angle estimated from optical images. By plotting the relative luminosities in the BVR, JHK, and IRAS bands (that is relative to the sum of the luminosities in those three bands) we should see such effects, if they exist. The model predicts that the IRAS luminosity should increase with the inclination angle, and the other two bands should decrease.

We made a simple model of a bipolar nebula: a star is surrounded by a toroidal density distribution (“donut”) which absorbs & re-radiates 15% of the stellar flux. We then run this model for a random sample of nebulae with their inclination angle histogram distributed on the sky as sin(i). We generate binaries containing 100 L⊙ stars with effective temperatures randomly distributed in the range 3800–6800 K, and a 1000 L⊙ compact star with 25 kK ≤ Teff ≤ 100 kK with the equatorial torus at 400 K. The morphology and optical depth of the torus luminosities is expected. The equatorial “torus” will produce an increased extinction toward the central star when this is viewed at an inclination nearer 90°, because the stellar light passes through more of the material. Some of the shorter wavelength light is absorbed and re-emitted as FIR radiation, increasing the relative contribution to the luminosity in the IRAS bands. Viewed pole-on, the same object will show the central object, basically un-reddened plus the torus, and the overall spectrum will be bluer.

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Figure 2. The observed fractional fluxes in the visual (triangles; dotted line), NIR (circles, dashed line), and FIR (filled squares; solid line) as a function of inclination to the line of sight of a sample of bipolars. The lines are linear regressions.

Figure 3. The model generated fractional fluxes in the visual (triangles; dotted line), NIR (circles, dashed line), and FIR (filled squares; solid line) as a function of inclination to the line of sight of a sample of bipolars. The lines are linear regressions.

follow a simple law. We generate fractional fluxes as for the observational case and compare.

Figures 2 & 3 show respectively the observed distributions of fractional fluxes and the model generated data. It is clear that the model and observations are at least qualitatively in agreement. The IRAS fluxes increase with inclination angle, the NIR, and visual bands decrease. This lends strong support to the idea that bipolars indeed have an equatorial density enhancement, and therefore are binaries.

The luminosity of the model generated sample as a function of inclination is shown in Figure 3, and shows the expected decrease with inclination angle. Pole-on objects are super-luminous –since we see the central object plus re-radiated emission from the torus– while in or near the plane of the sky they are sub-luminous (star absorbed and only partially re-radiated toward the observer).
An observational check of this model prediction is more difficult as distances are not known to most objects. The few objects for which we have reasonably hard distance determinations are listed in Table 1, and they indeed show this effect. The small number of objects urge caution when interpreting this.

There is a tendency for bipolars to be observationally selected nearer the plane of the sky, i.e. with high inclination angles. This is due to the fact that they have been mainly discovered by their morphology and that is only recognized when they are not too far from the plane of the sky, enhancing the sin(i) bias further. Bipolars should therefore tend to have lower luminosities than the average for PNe. This seems to be borne out by the observations, but also here, care should be taken with small number statistics.

In summary, bipolar PNe have much in common with SyNe; both types of objects have binary central sources, and the concept of bipolars having an equatorial density enhancement seems well established and model data, based on randomly oriented nebulae, give a good fit to the observations. The degree of asymmetry as measured by the aspect ratio of the nebulae correlated positively with outflow velocity, as expected if the collimation mechanism plays a role in defining the maximum velocities.
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