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PROPERTIES OF BIPOLAR PLANETARY NEBULAE

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RESUMEN

Revisamos las propiedades de las Nebulosas Planetarias Bipolares (NPB). Damos una definición de la clase de las NPB, describimos sus características y los mecanismos de formación propuestos, y destacamos algunos aspectos específicos tales como la polarización, efectos de inclinación y su vínculo con las estrellas simbióticas.

ABSTRACT

In this paper the properties of Bipolar Planetary Nebulae (BPNe) are briefly reviewed. The class of BPNe is defined, their characteristics and proposed formation mechanisms are described, and some specific aspects—polarization, inclination effects, and their link to symbiotic stars—are highlighted.

Key Words: **BINARIES: SYMBIOTIC — PLANETARY NEBULAE: GENERAL — TECHNIQUES: POLARIMETRIC**

1. INTRODUCTION AND BASIC PROPERTIES

Planetary Nebulae (PNe) are produced at the end of the lives of most low- and intermediate-mass stars, when they exhaust their nuclear fuel and the core collapses, expelling the outer layers of the star—by an as yet unknown mechanism—which are then lit up by photoionization 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. For PNe the average WD mass is about $0.6\,M_\odot$, with associated cooling time of about 10^5 yrs. after which the star remnant fades away like a dying ember.

As a historic note, I find it remarkable that as long as 46 years ago, Deutsch (1956) in a paper entitled "The Dead Stars of Population I" already wrote:

> When a single massive [then $\geq 1.4\,M_\odot$] star reaches the state of maximum distension and begins to shed mass, the structure of the star will change in an unknown way. From what is presently known about the structure of a giant star it appears that, while the star is still in equilibrium, degeneracy is likely to set in near the center. In a late stage of development, one might imagine that a giant star already carries an embryonic white dwarf within itself. The non-degenerate mantle over this object will eventually become transparent in places. Then we may expect parts of the dissipating circumstellar envelope to be highly excited by the emerging white dwarf, and we may also expect intermittent glimpses of its continuous radiation. One may speculate that the combination variables represent the final stages in the birth of a white dwarf from the exhausted core of an M giant.

He predicts the formation of PNe from red giants, and their link with the "combination variables", which until recently were considered as possible candidates for single star symbiotics, a model that nowadays is no longer supported.[2]

The BPNe are a subset of the general group of PNe. There are various definitions of what BPNe are but here I will use the one formulated by Schwarz, Corradi, & Stanghellini (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 dumbbell shape. With this definition 12% of the objects in Manchado et al. (1996) are bipolar, 11% in Schwarz, Corradi, & Melnick (1992, hereafter SCM92), and 9% in Górny et al. (1999), the three major imaging catalogs of recent years. Overall about 10% of the ≈ 600 PNe with good narrow-band images are truly bipolar, and this is the group on which we concentrate in this paper.

That being bipolar is not just a morphological coincidence was shown by Corradi & Schwarz (1995), who showed that bipolars have properties that dif-

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[2] The term "symbiotic star" was coined by Merrill (1950) and was not yet well known in 1956.

fer significantly from those of the general PNe sample. They based their conclusions on a sample of 46 BPNe, listed their main properties, and showed images of all objects. They found that bipolars:

- Have a smaller scale height (z = 130 pc vs. 260 pc).
- Have hotter central stars (mean = 145 kK vs. 75 kK).
- Have nearer circular orbits in the Galaxy.
- Have He, N, & Ne overabundances.
- Have a higher mean $V_{\rm exp}$ (150 km s^{-1} vs. 15 km s^{-1}).
- Larger mean linear sizes (0.76 pc vs. 0.1 pc).
- Have more massive progenitors ($\geq 1.5\,M_{\odot}$).

Clearly, the bipolars come from a different population with differing physical properties.

Another indication of this fact was given by Stanghellini, Corradi, & Schwarz (1993), who investigated the correlations between the morphology of PNe and their loci in the HR diagram. They found that bipolars:

- Have a different mass distribution of central stars from those of elliptical PNe.
- Have a lower ratio of He II/H I Zanstra temperatures than ellipticals (1.3 vs. 1.8) and therefore a different optical depth.

We do note that the number of bipolars in their sample was small, leading to uncertain properties of their binned data.

Bipolars are the most asymmetrical PNe and their association with polarization is a natural one. Scattered light in an optically thin medium will produce linear polarization when there are global asymmetries present. As most stars are spherically symmetric and their integrated light is intrinsically unpolarized—what is usually measured is interstellar polarization—the question of at what point the onset of the major asymmetry takes place is as yet unanswered. There is some evidence that the presence and degree of intrinsic polarization increases with later type stars (Schwarz 1985, and references therein; Johnson & Jones 1991; Trammell, Dinerstein, & Goodrich 1993). The findings of these authors are that intrinsic polarization increases from near zero to a few percent in going from K- to late M-type stars, and about 75% of AGB stars are intrinsically polarized.

The processes responsible are not identified; for red supergiants the large convection cells proposed by Schwarzschild (1975) may work, as supported by the observations and modeling of Schwarz & Clarke (1984) and Clarke & Schwarz (1984). What is the mechanism in AGB stars? The majority of PNe are asymmetrical to some degree and the high incidence of polarization among AGB stars indicates that the onset of the asymmetry takes place early in the PNe formation process. The observed time variability of polarization poses a problem: the timescale is too short for major changes in the circumstellar material to happen. Also, if the asymmetries in PNe are due to binaries, a high proportion of PNe must have binary central objects. Perhaps only the more extreme asymmetrical objects are binaries, bipolars being the main contenders.

2. POLARIZATION AND M 2-9

M 2-9 is an extreme bipolar PN whose faint outer lobes were not discovered until Kohoutek & Surdej (1980) published prime focus plates of them, increasing the size of the nebula from about 40″ to 115″. The inner nebula has been studied in great detail by Carsenty & Solf (1983) and Carsenty (1983), and the *HST* image is well known. Movement in the inner nebula was recorded by Doyle et al. (2000) and is due to some particle beam or other "lighthouse" type effect since material movement would place M 2-9 at 50 pc, while its distance is 640 pc (Schwarz et al. 1997, hereafter SACR).

Figure 1 shows M 2-9 in Hα + [N II] light. The outer lobes are faint but clearly visible and show point symmetry, while the inner nebula has plane symmetry.

Spectroscopy of M 2-9 in Figure 2 has shown that *both lobes are red shifted*, which SACR explained by assuming dust scattering of the central object spectrum at near 90° angles.

Polarimetry has proved this to be the likely mechanism as the lobes are 60% polarized—shown in Figure 3—and such a high level of polarization can only be achieved by optically thin, near 90° scattering or non-thermal processes such as synchrotron radiation, the latter being extremely unlikely in this case.

By modeling the lobes as due to reflection, the inclination and space expansion velocity of M 2-9 were derived by SACR, and independently checked by using an asymmetrical phase function and the ratio of brightnesses from the lobe ends. Thus $i = 15°$ and $V_{\rm exp} = 164$ km s^{-1}. Using images taken over the period 1978 to 1995, SACR measured the expansion of the outer lobes to be 0.″051 per year (Figure 4). In combination with the expansion velocity this leads to a distance of 640 pc, a linear size of 0.37 pc, a dynamical age of 1200 years, and, using the spectral energy distribution (SED), a luminosity of 553 $L_{\odot}$.

This example clearly shows that polarimetry can make a small but crucial contribution; without the

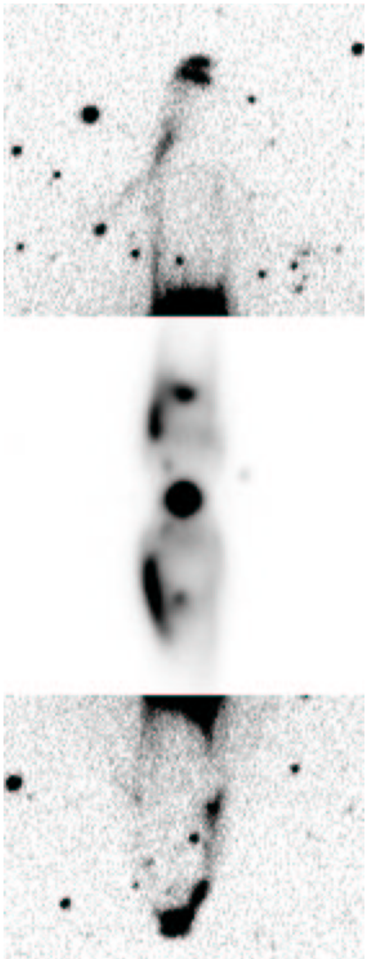

Fig. 1. The Hα + [N II] image of M 2-9 from SACR. Note the point symmetry of the outer lobes and the plane symmetry of the inner nebula. North is up, East to the left, and the length of the nebula is 115″.

convincing 60% polarization result, no referee would have accepted the dust scattering model for the outer lobes of M 2-9, and all the results presented would not have been confirmed.

3. ORIENTATION EFFECTS

Bipolar PNe have an added parameter that round PNe lack: their inclination on the sky as defined by the direction of the polar outflows i.e., by the bipolar lobes of the object. 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° points toward the observer.

Fig. 2. Long-slit spectrum of M 2-9. The spectrum runs horizontally, with blue to the left, the spatial axis is vertical with North up. Note that both outer lobes are red shifted, while the inner nebula shows the classical blue-red shifts of an inclined bipolar outflow.

If there is some equatorial density enhancement in bipolars, as suggested by various authors, for example Morris (1987), Icke, Balick, & Frank (1992), Corradi & Schwarz (1995), Schwarz, Corradi, & Mendez (2002), then some effect on their SEDs is expected. Consider a nebula in which the central star is surrounded by an equatorial torus of material containing gas and dust. This 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 torus. 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 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

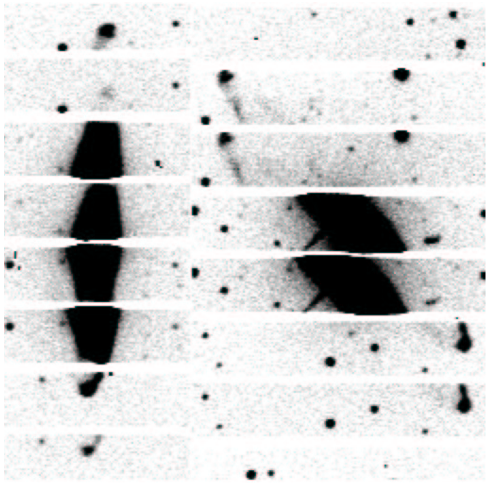

Fig. 3. Hα/[N II] polarization images of M 2-9 from SACR. The two images show alternate strips of orthogonally polarized light with the vectors vertical and horizontal. Note the large ratio between the N and S lobes in the left hand image and the near unity ratio in the right-hand image (with the instrument rotated by 45°) due to the very high polarization at *right angles to the line joining the poles of the object*.

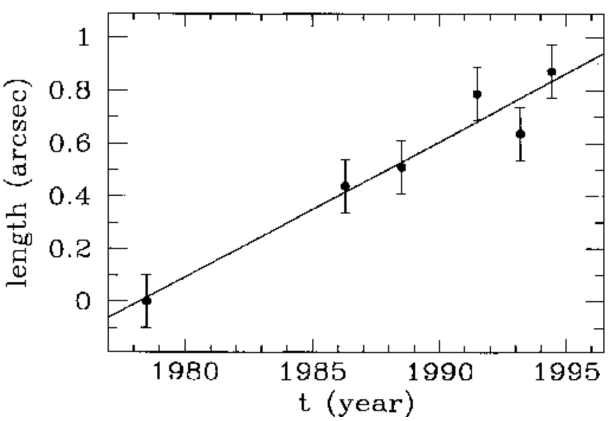

Fig. 4. The expansion of the outer lobes of M 2-9 over 16.25 years.

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 selected a sample of about 30 bipolars for which we have data on the *BVR*, *JHK*, and *IRAS* fluxes, plus a estimated inclination angle from optical images. By plotting the relative luminosity 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. In Figure 5 we show the observational effect of the inclination on fractional luminosities.

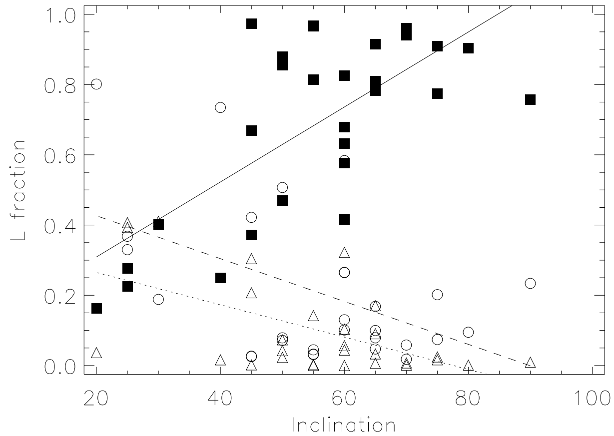

Fig. 5. The observed luminosity fractions in the visual (triangles; dotted line), NIR (circles, dashed line), and FIR (filled squares; solid line) as a function of inclination to the line of sight of a sample of bipolars. The lines are least squares fitted.

The result is clear: 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.

We made a simple model of a bipolar nebula: a star is surrounded by a toroidal density distribution ("donut"), which absorbs and 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 $100\,L_\odot$ stars with effective temperatures randomly distributed in the range 3800 to 6800 K, and a $1000\,L_\odot$ compact star with $25\,\mathrm{kK} \leq T_{\mathrm{eff}} \leq 100\,\mathrm{kK}$ with the equatorial torus at 400 K. The morphology and optical depth of the torus follow a simple law. The photometry—in the same three bands—of the resulting sample gives the distribution shown in Figure 6. Clearly, this is qualitatively quite similar to the observed distribution in Fig. 5.

The luminosity of the model-generated sample as a function of inclination is shown in Figure 7, 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). Figure 8 shows the relative model luminosity, that is the total luminos-

TABLE 1

OBSERVED LUMINOSITIES AND INCLINATIONS

Name	Inclination (°)	Distance (kpc)	Luminosity ($L_\odot$)
Inclination $\geq 45°$			
Sa 2-237	70	2.1	340
M 2-9	75	0.64	553
He 2-104	50	0.8	205
He 2-111	70	2.8	440
M 1-16	70	1.8	194
Inclination $\leq 45°$			
R Aqr	20	0.2	2800
BI Cru	40	1.8	3400

ity divided by the central object luminosity. This is not a directly observable quantity but gives an idea of what is going on in the model objects.

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 do show this effect, listed in Table 1, but the numbers are small.

In summary, 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.

4. LINKS WITH SYMBIOTICS

Symbiotics are binaries with a cool giant as primary and a compact secondary, usually a White Dwarf (WD), surrounded by a partially ionized gas and dust mixture. Their spectra show both emission lines and a cool + hot continuum; they are variable, and are divided into S types with a stellar photospheric spectrum, and D and D′ types, having the signature of respectively hot and cool dust. There are a few so-called yellow symbiotics, which have spectra showing the *G*-band. For an overview see Kenyon (1986).

The link between bipolars and symbiotics is strong. Of the D and D′ type symbiotics 40% have a nebula associated with them, and of the 14 nebulae found to date 5 are bipolar, or about 36% versus only 10% of PNe in general. Table 2 lists the name, symbiotic type, size and morphological shape of the discovered nebulae. BI Cru and AS 201 also have unresolved high-excitation nebulae associated with them, and possibly contain fossil PNe in the form of

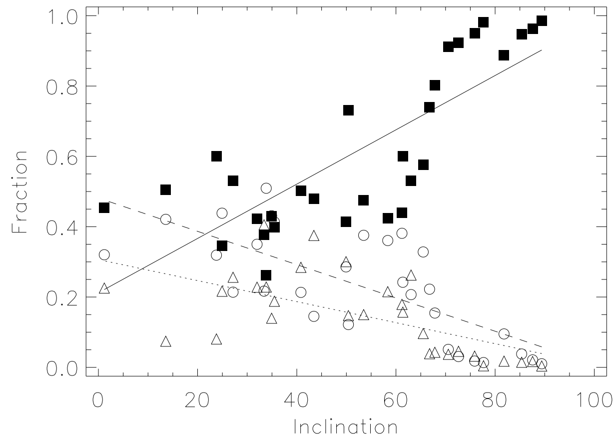

Fig. 6. The model generated luminosity fractions emitted in the visual (triangles; dotted line), NIR (circles, dashed line), and FIR (filled squares; solid line) as a function of inclination to the line of sight of a sample of bipolars.

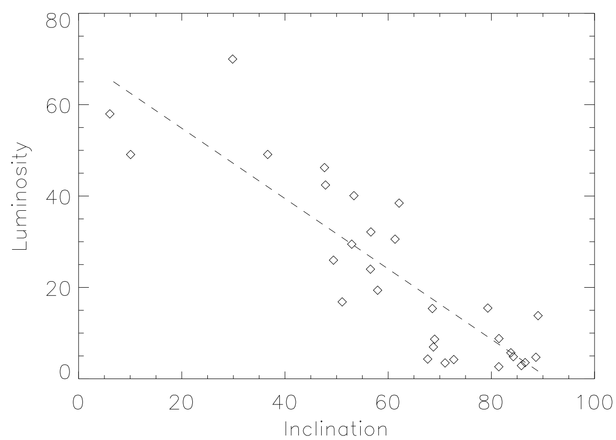

Fig. 7. Luminosities (arbitrary units) of the model generated sample as a function of inclination.

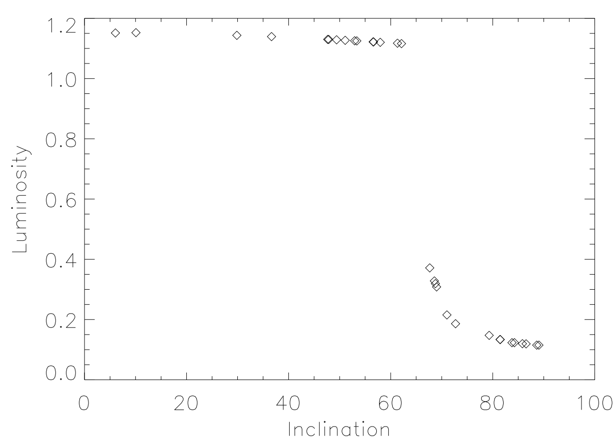

Fig. 8. Luminosities of the model sample as a function of inclination, relative to the stellar luminosity for a "donut" equatorial density distribution.

TABLE 2

PROPERTIES OF SYMBIOTIC NEBULAE

Name	Type	Size ($''$)	Shape
AG Peg	yellow	8	irregular
AS 201	D	13	elliptical
CH Cyg	S	150	jet+irreg.
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
He 2-147	D	5	ring
HM Sge	D	30	irregular
R Aqr	D	120	bip.+jet
RX Pup	D	4	bipolar?
V417 Cen	yellow	100	bipolar
V1016 Cyg	D	20	elliptical

the outer, low-excitation nebulae. These would be "post-PN nebulae" created in the binary in an evolutionary scheme as suggested by Schwarz & Corradi (1992).

M 2-9 needs a faint, hot, compact component to be able to ionize the observed [O III] line but has a luminosity too low for the necessary B0 ionizing star, as fixed by its distance of 640 pc. This is an argument for the binary nature of this object, and, as it combines a cool continuum with emission lines, it may be considered a symbiotic system. The very high-velocity Hα wings observed in M 2-9 by Balick (1989) also indicate its symbiotic nature, as many symbiotics have such winged profiles, usually ascribed to an accretion disk, where the inner, high-velocity parts of the disk provide the photons scattered out into the high velocity line wings.

The point symmetry can be naturally explained by precession in the binary. The material is ejected at different times during the precession period and hence results in a point-symmetric nebula.

Thus, most observed properties of bipolar nebulae are shared with symbiotic nebulae. A disk wind blowing into a fossil PN explains the observed nebulae of BI Cru, AS 201, He 1-104, and perhaps the Tc containing Ba stars. R Aqr and M 2-9 probably have precessing jets. He 2-104 and M 2-9 must have a hot, compact component to explain their spectra (respectively, a Mira plus high-excitation lines, and low luminosity but showing the [O III] line). Finally, there are many overlapping properties of both groups, SEDs, line shapes, IR properties, time variability, and the morphology of the nebulae.

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