JETS AND BRETS IN PLANETARY NEBULAE

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1. Introduction

The presence of high-velocity, collimated outflows in planetary nebulae (PNe) has been observationaly established in recent years. Furthermore, these collimated outflows, or jets, are usually found to be symmetric with respect to the nucleus. In some cases, their morphology and spatial distribution indicates episodic outbursts and rotation of the symmetry axis. In these cases, the **b**ipolar, **r**otating, **e**pisodic je**ts** are identified as BRETs. The existence of bipolar jets in PNe has been considered perplexing since the mechanisms for their formation are unclear. However, substantial progress in their study has been made in the last few years, from both theoretical and observational grounds. Consequently, new results in the field are rapidly coming out, as it can be noticed from the number of related works in this symposium. We still need to reach solid answers in many aspects of this field, but its influence in the study of PNe has already modified the traditional views of PNe shaping and evolution. The main characteristics of some of these phenomena are discussed here, together with prototypical cases, including a compilation of PNe with BRETs charateristics.

2. The nomenclature of bipolar, collimated outflows in PNe

In contrast to the field of recent star formation, where optically detected collimated outflows are regularly termed jets and their leading fronts are identified with Herbig-Haro objects, the unexpected discoveries of similar features in PNe have led over the years to different terminologies. A wide range in collimation conditions (3-20), speeds (50 - 350 km s^{-1}) and morphologies, as well as unclear conditions for the onset of jet activity, have all contributed to a certain amount of confusion into the field. In some cases the structural differences seem real, in others these may just be a

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consequence of the lack of observational data of high enough quality. This apparent diversity in the characteristics of collimated outflows in PNe has produced the following main generic terms (see also Mellema 1996).

Ansae or FLIERS- The ansae found in a subgroup of mainly elliptical PNe are associated with regions of lower ionization and higher velocities than the surrounding medium (Balick *et al.* 1994). Typical cases are NGC 7009, NGC 3242 and NGC 6826. The ansae or FLIERS are usually single, symmetric pairs of condensations with filamentary tails, they are found close to the nebular cores and with typical opposite velocities of $\sim$ 50 km s^{-1}. Recent HST observations of some of these objects suggest the presence of bow shocks and mass-loaded flows. These results are causing a rapid evolution of previous concepts on FLIERS (see the contributions by Balick, Frank and collaborators in this symposium).

Straight symmetric jets- Elongated, structures protruding symmetrically from the core are observed in objects such as K 1-2 (Bond & Livio 1990) and Wray 17-1 (Corradi *et al.* 1996). These 'straight' jets may turn out to be knotty when observed at high spatial resolution. For example, in the case of Hb 4 (López *et al.* 1997b), opposite radial velocities in the order of 150 km s^{-1} have been detected in the jets with complex line profiles that indicate the presence of two or more internal shocks. Substantial effects due to ablation of (symmetric) clumpy structures by the stellar wind could also be present, resembling bipolar jets, for in some of these cases cometary shapes are observed, reminiscent of the ablated polar knots in Abell 30 (Borkowski *et al.* 1995; Meaburn & López 1996).

BRETs- The BRET prototype is Fleming 1 (López *et al.* 1993a, 1993b; Palmer *et al.* 1996) where clear evidence of the action of a bipolar, rotating episodic jet has been detected. This object is characterised by symmetric strings of episodic or time dependent velocity and direction ejections. From kinematical data, an ejection speed of 85 km s^{-1}, an angular rotation of $7''$ per year or 10.2×10^{-13} rad s^{-1}, and a time since the ejection of the outer globules of $1.6\times\ 10^4$ years have been calculated in this case. The ionized mass in the ejected globules has been estimated in the range of 6×10^{-4} to 1.2×10^{-3} $M_\odot$, with scale sizes of $2.8 - 3.5 \times 10^{17}$ cm.

Another dramatic example of a BRET is the bizarre planetary nebula KjPn 8 (López *et al.* 1995). This is the bipolar PN with the largest angular extent known to date ($14' \times 4'$), which may only indicate its proximity. This object presents symmetric pairs of groups of knots oriented at different position angles, within its extensive bipolar halo. López *et al.* (1997a) find direct kinematical evidence of the action over 1700 yrs of a rotating, or wobbling, bipolar episodic jet, with a speed of $\simeq$ 320 km s^{-1} and angled at $\simeq 30°$ to the plane of the sky. This BRET has formed two diametrically opposed groups of collisionally ionised knots at the apices of the extensive

NW and SE outflows, where the line profiles have all the characteristics of being generated behind bowshocks formed as the episodic jet ploughs into the walls of the bipolar cavities.

Point-symmetric Nebulae- Schwarz *et al.* (1992), found in their sample of southern PNe a number of objects with morpholgies ruled by apparent point-symmetry. Subsequent kinematical studies of some of these cases, such as He 2-186 and IC 4634 (Corradi & Schwarz 1993) led to the interpretation of these data as the result of bipolar and rotating episodic flows.

Poly-polar Nebulae- Some PNe show remarkable poly-polar structures, as is the case of NGC 2440 (López *et al.* 1997c), where multiple bipolar outflows at different position angles and degrees of collimation suggest a history of episodic ejections, where the orientation of the symmetry axis and the conditions of the collimating agent have changed in time. Further similar examples have been discussed recently by Manchado *et al.* (1996) for a group of quadrupolar PNe, where pairs of bipolar lobes with an apparent common center but with different orientations of their corresponding symmetry axes have been detected; a BRET-type mechanism has been invoked to explain the general features observed in them.

The interpretations that different authors have given independently to their data, converge into a main, basic underlying process, this is the action of episodic ejections involving rotation of the symmetry axis. Thus, BRETs do not seem to be confined to the strict realm of highly collimated, high-velocity outflows (jets). Different initial conditions, as yet not understood, seem to be responsible for the generation of extensive and compact configurations, with different rotation rates and degrees of collimation in PNe.

'Invisible' jets- In addition to the diverse cases of high-velocity, collimated outflows where their presence is betrayed by morphological elements, there are objects which do not show any morphological evidence of being hosts to these features. One example is NGC 2392, (Gieseking *et al.* 1985), where the detection of its high-velocity bipolar outflow was an unexpected finding made by means of spatially resolved spectroscopy. It is likely that more similar cases exist that have not yet been detected.

3. Models

There is observational evidence indicating that jet activity starts during the very early stages of formation in a planetary nebula. Examples that point us in this direction are transition objects or very young PN as He 3-1475, Hu 1-2, M 1-92 and IRAS 09371+1212 (see table 1 for references to these objects). In addition, all the current collimation models develop these structures during the proto-planetary nebula phase or right after the onset of the fast wind. It is less clear, though, for how long a PN can keep active collimated outflows, but several $\times 10^3$ to 10^4 years are estimated lifetimes for the outer structures in some cases (e.g. Palmer et al 1996) with intervals between episodic outbursts of the order of a several hundred to a few thousand years (see also Cliffe *et al.* 1996)

Collimating mechanisms in PNe can be currently distinguished into three main categories. These are, firstly, those that invoke the existence of an accretion disk, formed following the common envelope phase of a close binary system (e.g. Soker and Livio 1994, Soker 1996, Livio these proceedings). Secondly, magneto-hydrodynamic (MHD) models that consider a single, rotating star where the fast wind carries a sufficiently strong field to produce a toroidal configuration that drives a magnetic collimation (Rozyczca & Franco 1996, Garcia-Segura *et al.* 1996 and this symposium), in these cases the polar regions blow out due to the strong magnetic tension, forming jets. Thirdly, hydrodynamic models based on the interacting winds theory (e.g Icke *et al.* 1992). In a recent modification of the latter, relatively low velocities for the fast wind (~ 200 kms^{-1}) are considered in the simulations, producing a hot bubble that is momentum driven, leading to stronger focussing in an elliptical nebula.The post-shock fast wind is redirected by streams sliding along the walls of the elliptical cavity, eventually converging to produce symmetric, collimated outflows that seem to match well the main characteristics of ansae (Mellema 1996; Frank *et al.* these proceedings).

As for the mechanisms to produce rotating jets in PNe, Raga and Biró (1993) have studied ballistic jet models where the coupled effects of direction and time variability are taken into account. Their numerical results show striking similarities with the main properties observed in BRETs, such as in Fleming 1. In addition, Clifee *et al.* (1995) have developed 3-D numerical simulations postulating the presence of a precessing, episodic jet. The case of Fleming 1 is also convincingly reproduced here and the model is generally applicable to point-symmetric PNe. Also recently, Livio & Pringle (1996) have considered the effects of radiation induced self-warping instabilities in accretion disks, concluding that the timescales on which these instabilities occur are of the right order to produce observable wobbling,

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symmetric jets. Adittionaly, Rozyczca & Franco (1996) have suggested that the changes in the direction of the jets, as observed in BRETs, may be due to temporary missalignments of the stellar rotational and magnetic axes.

4. Planetary Nebulae with BRETs characteristics

In the following table it is presented a list of objects that show morphological characteristics of BRETs; when supporting kinematical evidence is also available this is indicated in the table. This list is bound to be incomplete since only the more obvious cases have been included. Likewise, additional observations on several of them, particularly regarding their kinematics, are needed to confirm their nature as BRETs. This list should however serve as a source reference in the study of these peculiar objects. The numbered references are indicated directly in the general reference section.

TABLE 1. Planetary Nebulae with BRETs characteristics

Object	Kinematics	Refs.	Object	Kinematics	Refs.
Fleming 1	yes	1,2,3	M 1-75	—	15
He 1-1	—	23	M 1-92	—	17
He 2-141	—	4	M 2-46	yes	15
He 2-186	yes	10	M 3-1	—	5
He 2-429	—	23	NGC 2440	yes	18
He 2-1312	—	5	NGC 3918	—	4
He 3-1475	yes	6,7	NGC 5307	—	24
Hu 1-2	yes	8	NGC 6210	yes	19
IC 4593	yes	10	NGC 6309	—	5
IC 4634	yes	10	NGC 6326	—	4
I 09371+1212	—	11,12	NGC 6337	—	4
J 320	—	5	NGC 6543	yes	20,21
KjPn 8	yes	13,14	NGC 6881	yes	22
K 3-24	—	15	PC 19	—	23
M 1-16	yes	16	Pe 1-17	—	23

5. Future Work

The origin of the displacements in the symmetry axes of some objects, the apparent episodic nature of the ejections and the causes of their collimation and acceleration are a fertile field of investigation. The excitation conditions and ionic abundances seemingly present in these features are perplexing in some cases, where enhanced low ionization line emission has yielded not

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only apparent overabundance of nitrogen but also sulfur(!), as in NGC 3242, M1 -75 (see Riera *et al.* this symposium) and KjPn 8 (Vázquez *et al.* 1997). The relevance of flows in the clumpy environment of PNe (Dyson 1993) is just starting to be considered in depth. Photoionization models including the effects of radiative shocks should find a wide range of applicability.

The different types of collimated outflows in PNe should not be regarded as independent phenomena; currently this differentiation is, to a large extent, a consequence of the lack of high quality data on many of them and of our ignorance on the mechanisms that produce these structures. Substantial progress in these areas is to be expected in the coming years.

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