The Kinematics of Point-Symmetric Planetary Nebulae:
Observational Evidence of Precessing Outflows

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Abstract. The discovery of collimated outflows associated to point-symmetric features in Planetary Nebulae has proliferated in recent years. The systematic variation of radial velocity that many of them show strongly suggests a uniform rotation or precession of the ejection direction. Although several physical processes have been invoked, the formation mechanism of precessing collimated outflows in PNe is currently an intriguing but unresolved problem.

1. The Point-Symmetry Morphology

Point-symmetry in Planetary Nebulae (PNe) was introduced as a main morphological class by Corradi, Schwarz, & Stanghellini (1993) as: “those objects [...] whose morphology shows no other symmetries than point-reflection about the central source”. The increasing discovery of point-symmetric components in PNe has made clear that point-symmetry in PNe span nearly all the morphological classes and evolutionary stages. Among the many different point-symmetric features now recognized to be common in PNe, it can be quoted:

- The ansae or FLIERs (Fast Low-Ionization Emission Regions), which appear to be outflows departing from the tips of the major axis of elliptical PNe (e.g. Balick et al. 1998).
- The straight elongated jets or string of knots, as in Hb 4 (López, Steffen, & Meaburn 1997b) and NGC 3918 (Corradi et al. 2000).
- The marked point-symmetric brightness of the bipolar lobes of certain bipolar PNe, as is the case of Hb 5 (e.g. Riera 1999).
- The multiple bipolar outflows at different position angles and with different degrees of collimation reported in the quadrupolar PNe M 2-46 and M 1-75 (Manchado, Stanghellini, & Guerrero 1996) or in the poly-polar PN NGC 2440 (Pascoli 1987; López et al. 1998).
- The multiple point-symmetric pairs of components found at different position angles and distances to the center of the PN. Such is the case of the collimated outflows in NGC 6543 (Miranda & Solf 1992; Harrington & Borkowski 1995), and Fleming 1, the prototype of BRET (Bipolar Rotating Episodic jet) (López, Meaburn, & Palmer 1993), that shows a string of knots bent in opposite directions on both sides of the central nebula.

The peculiar spatial distribution of the pairs of knots in these PNe is specially interesting, as it strongly suggests rotation in the direction of the ejection. I will focus on these PNe.
2. Kinematics of Point-Symmetric PNe: Point-Symmetric Outflows

At the same time that the sample of PNe with point-symmetric components has been growing, kinematical information on a significant number of these PNe has been obtained. Information on the kinematics of point-symmetric morphological components of PNe is very valuable, as it provides us with information of the motions along the line of sight. This can be combined with the 2-D spatial distribution to construct a spatio-kinematic model.

Table 1. The Kinematics of Point-Symmetric PNe

| Object       | $v_r$ [km s$^{-1}$] | FWHM  [km s$^{-1}$] | References |
|--------------|---------------------|--------------------|------------|
| NGC 6543     | 25–40               | 10                 | 1          |
| IC 4634      | 30–35               | ...                | 2          |
| He 2-186     | 100                 | ...                | 3          |
| Fleming 1    | 7–75                | 17–26              | 4          |
| He 3-1475    | 425–870             | 150–400            | 5,6,7      |
| Hu 2-1       | 2–56                | 16–29              | 8          |
| NGC 6210     | 5–21                | ...                | 9          |
| IC 4593      | 3–100               | 12–20              | 10,11      |
| KjPn 8       | ~0–220              | 100–280            | 12         |
| MyCn 18      | 200–500             | 20–40              | 13         |
| NGC 6881     | 1–9                 | 13–19              | 14         |
| He 1-1       | 9–43                | ...                | 15         |
| PC 19        | 30–35               | ...                | 15         |
| Pe 1-17      | 2–24                | ...                | 15         |
| NGC 6884     | 14–38               | 18                 | 16         |
| NGC 6572     | 7–38                | 17                 | 17         |
| K 1-2        | 10–20               | 11–20              | 18         |
| Wray 17-1    | 15–70               | ...                | 18         |
| K 3-35       | 20                  | 27                 | 19         |
| M 1-16       | 250                 | 230                | 20         |
| M 2-46       | 25–40               | ...                | 21         |
| NGC 2440     | 100–150             | ...                | 22         |

(1) Miranda & Solf 1992; (2) Schwarz 1992b; (3) Hajiian et al. 1997; (4) López, Meaburn, & Palmer 1993; (5) Riera et al. (1995); (6) Bobrowsky et al. 1995; (7) Harrington 1999; (8) Miranda 1995; (9) Phillips & Cuesta 1996; (10) Corradi et al. 1997; (11) O’Connor et al. 1999; (12) López et al. 1997a; (13) Bryce et al. 1997; (14) Guerrero & Manchado 1998; (15) Guerrero, Vázquez, & López 1999; (16) Miranda, Guerrero, & Torrelles 1999; (17) Miranda et al. 1999; (18) Corradi et al. 2000; (19) Miranda et al. 2000; (20) Schwarz 1992a; (21) Manchado, Stanghellini, & Guerrero 1996; (22) López et al. 1998

Table 1 compiles the list of point-symmetric PNe with multiple pairs of components for which valuable kinematical information is available. The quadrupo-
lar and poly-polar PNe M 1-16, M 2-46, and NGC 2440 have been included. The measured radial velocities and line widths are given in columns 2 and 3 respectively.

In most of the cases, the radial velocities in Table 1 are in the range $0 - 50$ km s$^{-1}$. These are the typical velocity shifts reported in FLIERs (e.g. Balick et al. 1994) and in straight elongated jets. Real expansion velocities must be larger because projection effects. On the other hand, KjPn 8, MyCn 18, and He 3-1475 show quite noticeable large radial velocities that may correspond to deprojected expansion velocities larger than $1000$ km s$^{-1}$.

The line width is typically $10 - 20$ km s$^{-1}$. The narrow line width, together with the high expansion velocity and small spatial extension, prove that these structures are collimated outflows. There are only two cases (KjPn 8 and He 3-1475) in which the width is larger than $100$ km s$^{-1}$ revealing important dynamical effects.

Finally, one of the most important result from all these observations is that the spatial distribution of morphological components is related to systematic variations of their radial velocities in most of the cases. The term “bipolar outflow”, commonly used in PNe, can therefore be generalized to “point-symmetric outflow” in these PNe.

3. Precession in Planetary Nebulae

The coupled variations of the spatial distribution and radial velocities of pairs of point-symmetric knots strongly suggest a systematic rotation of the ejection direction. Precession, the uniform change in orientation of an axis around a fixed axis, is a very appealing phenomenon, as it involves very peculiar physical scenarios that will be described in §4. In the past, precession was invoked in order to explain the helical structures reported in NGC 6543 (Münch 1968) and NGC 7293, the Helix Nebula (Fabian & Hansen 1979), and the overlapping bipolar structures of the poly-polar PN NGC 2440 (Kaler & Aller 1974; Pascoli 1987). More recently, different numerical simulations (Raga, Cantó, & Biro 1993; Raga & Biro 1993; Cliffe et al. 1995; Cliffe, Frank, & Jones 1996) have shown that precessing jets can reproduce the morphological structure of point-symmetric PNe.

In a precessing collimated outflow, the variations of the radial velocity and spatial position are determined by the following parameters:

- The aperture angle of the precession cone, $\Phi$.
- The inclination of the precession axis with the line of sight, $i$.
- The precession period, $T$, or rotation rate, $d\omega/dt$.
- The expansion velocity, $v_{\text{exp}}$.
- The distance to the PN, $d$.
- The initial position angle of the ejection, $\omega_o$.

Depending on these parameters, the morphology and variation of radial velocity may be very different. For small inclination angles with the line of sight, a double helix or spiral is expected. This is the case of NGC 6884 (Miranda et al. 1999). Variations of the radial velocities are small, but change systematically with the position angle or distance (Figure 1-top). If the inclination angle increases, so the radial velocity differences do. Such is the case of He 1-1 (Figure 1-bottom),
Figure 1. [top] Relative variation of the radial velocity, distance and position angle [left], and spatial distribution [right] of the point-symmetric knots of NGC 6884. [bottom] Relative variation of the radial velocity versus distance [left], and spatial distribution [right] of the knots of He 1-1. In both cases, the lines represent the results of a ballistic precessing jet model (see Table 2 for further details on the specific precession parameters and expansion velocity).
with a large inclination angle, but a smaller aperture angle than NGC 6884 (Guerrero et al. 1999). A large inclination and small aperture angle produce a loop-like structure, as is observed in NGC 6881 (Guerrero & Manchado 1998) or an S-shaped structure, as in He 3-1475 (Borkowsky, Blondin, & Harrington 1997).

It is interesting to note that the steady increase of the radial velocity with distance has been reported for Fleming 1 (López et al. 1993) and MyCn 18 (Bryce et al. 1997). A ballistic precessing outflow can reproduce this behavior, but only for large inclination and aperture angles, and very restrictive initial ejection direction. An alternative explanation has recently been proposed by García-Segura et al. (1999) and will be discussed in more detail in §4.

Using the uniform precessing ballistic model above outlined, the precession parameters ($\Phi$, $v_{\text{exp}}$, $i$, and $T$) can be worked out by fitting the observational data. Figure 1 shows the fit to the data of NGC 6884 and He 1-1. The available precession parameters are summarized in Table 2 where $\Delta t$ stands for the fraction of the period, $T$, that the ejection lasted. Although these estimates are subject to uncertainties in the distance, assumptions in the model, and resolution of the observations and model fitting to them, the wide range of parameters is real. Interestingly, the ejection lasts only a fraction of the period in all the cases.

| Object       | $2 \times \Phi$ | $v_{\text{exp}}$ | $T$     | $\Delta t$ | Remarks   |
|--------------|-----------------|------------------|---------|------------|-----------|
| NGC 6881     | 44              | 11               | 3 800 $\times d$ | 0.8        |           |
| NGC 6884     | 120             | 55               | 500     | 0.6        |           |
| Fleming 1    | 180             | 85               | 195 000 | 0.08       | BRET model|
| He 1-1       | 130             | 110              | 100 000 | 0.14       |           |
| MyCn 18      | 180             | > 1000           | 4 700   | 0.11       | BRET model|
|              | 160             | 1000             | 9 500   | 0.07       |           |
| He 1-1       | 70              | 75               | 250 $\times d$ | 0.4        |           |
| NGC 6543     | 26–70           | 40–200           | 500–25 000 | 0.25–0.45 |           |
| M 2-46       | > 53            | 25–40            | > 18 500 | ...        |           |

There are still many point-symmetric PNe with kinematical information for which the available data do not allow to perform an accurate determination of the precession parameters. These are the cases of those PNe in which only two pairs of point-symmetric components are detected (for example, NGC 6543). In such cases, the parameter space can be restricted using additional constraints provided by a detailed morphological description. Therefore, the combination of ground-based high-dispersion spectroscopic observations with high spatial resolution HST WFPC2 narrow-band images can make a dramatic improvement in the spatio-kinematic modeling.

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1 This completely justify the simplification of a BRET model in which the ejection direction rotation is limited into a plane.
4. Physical Scenarios

Several models have been proposed to explain the formation of precessing jets in PNe. They can be grouped into three different categories:

- **Hydrodynamical focusing + wobbling instabilities.**
  It has been proposed that weakly collimated bipolar outflows in PNe are focused into jets by oblique radiative shocks (Frank, Balick, & Livio 1996). Borkowski et al. (1997) used a similar mechanism to explain the formation of the symmetric pairs of knots observed in He 3-1475 invoking additional hydrodynamical instabilities and/or asymmetries of the confining medium. While this mechanism might work for He 3-1475, it seems difficult to apply to precession motions characterized by large aperture angles. In addition, it seems quite unlikely that such instabilities may reproduce the point-symmetric distribution of pairs of knots.

- **Magnetic collimation around a precessing star.**
  The magnetic tension may also be able to produce collimated flows or jets (Różycka & Franco 1996). Using this scenario, García-Segura (1997) explains the formation of point-symmetric structures by adding a rotating star whose rotation axis is misaligned to the magnetic field. Although the resulting morphology (and presumably the kinematics) in this model results disturbed by the confining medium, the motion can still be interpreted as a precessing jet if the density of the ejection is larger than that of the confining medium. More recently, García-Segura et al. (1999) have shown that magnetic collimation can naturally reproduce the high velocity and steady increase of radial velocity observed in MyCn 18 and Fleming 1.

- **Precessing or wobbling accretion disks.**
  Livio & Pringle (1996; 1997) have suggested that instabilities in an accretion disk during a common envelope phase may cause it to wobble. The short fraction of the period for which precession is observed in PNe does not allow to reject this mechanism. Similarly, precession of the inner portion of an accretion disk has also been proposed by Morris & Reipurth (1990) to explain the point-symmetry observed in IRAS 09371+1212, and by Manchado et al. (1996) to explain the formation of quadrupolar PNe.

5. Summary and Conclusions

1. The kinematics of point-symmetric pairs of components in PNe exhibit systematic variations of the observed radial velocities coupled with the spatial distribution. These are compatible with a uniformly precessing episodic ballistic jet in most of the cases.

2. The properties of the ejection show a wide range of values:
   \[ 500 \text{ yr} < T < 2 \times 10^5 \text{ yr} \]
   \[ 22^\circ < \Phi < 80^\circ \]
   \[ 11 \text{ km s}^{-1} < v_{\text{exp}} < 1000 \text{ km s}^{-1} \]

3. The ejection of material lasts for a fraction (0.1 – 0.8) of the precession period.
At this moment, there is no definite answer to the question of what mechanism (probably involving binary stars or magnetic fields) produces point-symmetric outflows in PNe, but it is clear that precession or uniform rotation of the ejection direction is present in these PNe. Further observations (combining high-dispersion spectroscopic observations and high-resolution narrow-band images) are required to perform a detailed characterization of point-symmetric outflows in PNe. The spatio-kinematic models of a larger sample of such outflows would help to constrain the precession properties and to restrict the formation processes.

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