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EMISSION LINES FROM JETS IN PLANETARY NEBULAE

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RESUMEN

Los perfiles de líneas de emisión provenientes de flujos colimados de alta velocidad, o jets, en nebulosas planetarias (NPs) tienen diversas características que indican la influencia de núcleos binarios y mecanismos de confinamiento magnético en su origen. En esta contribución se presentan varios casos que ejemplifican la complejidad de estos flujos en NPs.

ABSTRACT

Emission line profiles from collimated high-velocity outflows or jets in planetary nebulae (PNe) have diverse characteristics that indicate the influence of binary cores and magnetic confinement mechanisms in their origin. In this contribution, a number of cases are presented that exemplify the complexity of these outflows in PNe.

Key Words: **ISM: JETS AND OUTFLOWS — PLANETARY NEBULAE**

1. INTRODUCTION

Jets are usually found in objects such as quasars, active galactic nuclei, high energy binary systems and young stars, where the presence of an accretion disk and magnetic acceleration and collimation of the outflows plays a key role. However, these elements were not considered to be established components in planetary nebulae (PNe). Thus, the detection of collimated, high-velocity outflows or jets in planetary nebulae came as an unexpected result just a few years ago. The expansion velocities in these outflows run from several tens to a thousand km s^{-1}, with characteristic values around a few hundred km s^{-1} and kinetic energies in the order of 10^{45} erg. These jets are particularly prominent in low ionization emission lines, such as [N II] and [S II], as in YSOs. However, in PNe, contrary to the case of YSOs, the strong photoionized environment of the PN makes the discrimination of shocked regions (e.g., Dopita 1997).

The first bipolar collimated outflow with jet characteristics identified in a planetary nebula was found in NGC 2392 by Gieseking, Becker & Solf (1985), where they measured expansion velocities of the order of 200 km s^{-1}. Bipolar jets with much higher velocities have now been found in many other PNe. For example, in KjPn 8., López et al. (2000) found bipolar outflows exceeding 300 km s^{-1}. In MyCn 18, Bryce et al. (1997) found symmetric strings of knots expanding at observed radial velocities of 500 km s^{-1}. More recently, Borkowski & Harrington (2001) using the *HST*/STIS confirmed bipolar jets with speeds of 1200 km s^{-1} in the young PN He 3-1475.

Collimated outflows in planetary nebulae develop from the very earliest stages of formation, where bipolar molecular outflows are now routinely detected, and these influence in an important way the subsequent structural development of the nebular shell (e.g., Huggins et al. 2000). The *Hubble Space Telescope* has also revealed that starting in the proto-planetary stage they are observed not only as bipolar but in many cases also showing more complex characteristics such as poly-polarity and point-symmetry (e.g., Sahai & Trauger 1998).

In the ionized nebular stage, where more data are available, the presence of point symmetry has been shown to be a pervasive characteristic of collimated outflows in PNe. Point symmetry was originally introduced as a main morphological class by Stanghellini, Corradi, & Schwarz (1993) after noticing this peculiarity in a small group of PNe. However, point symmetry is actually a common characteristic in PNe that spans every morphological class (Guerrero, Vázquez, & López 1999; López 2000) .

In those cases of point symmetry where there is kinematic information, this morphological characteristic has been related to the action of a bipolar rotating, episodic jet or BRET (López, Meaburn, & Palmer 1993; López, Vázquez, & Rodríguez 1995). Although an alternative interpretation for some cases of point symmetry has been presented by García-Segura & López (2000) considering a steady tilt of the magnetic or stellar rotation axis with respect to the bipolar wind outflow (see also Franco

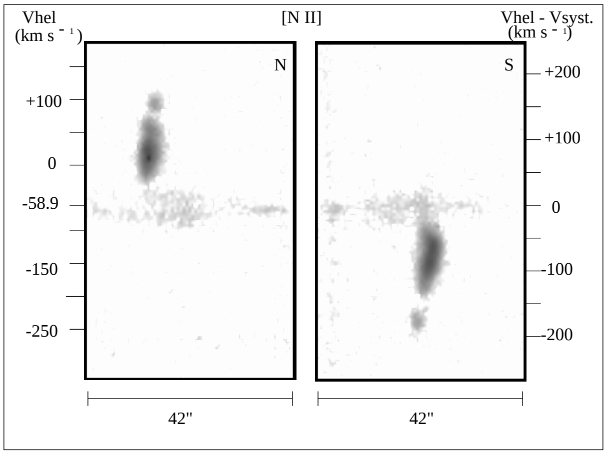

Fig. 1. P-V arrays for the [N II] $\lambda 6584$ Å line profiles from the north and south bipolar jets of Hb 4. The heliocentric radial velocity is marked on the left-hand side and $V_{\rm hel} - V_{\rm sys}$ on the right-hand side. The heliocentric systemic radial velocity $V_{\rm sys} = -58.9$ km s^{-1} (from López et al. (1997).

et al. 2002). Precession in a binary core can also produce point-symmetric structures.

BRETs and point symmetry indicate variations in the direction of the bipolar, collimated outflows. However, for the case of poly-polar nebulae, multiple, distinct, bipolar outflows are observed (e.g., López et al. 1998). The mechanism by which a PN can produce multiple bipolar ejections in different directions is still enigmatic.

In the following sections, some examples of emission line profiles observed in PNe jets are described.

2. THE INTERMITTENT JETS OF HB 4

Hb 4 is a PN with an elliptical core expanding at only $2V_{\rm exp} = 43$ km s^{-1}. López, Steffen, & Meaburn (1997) detected high velocities in the nebular line profiles from the elongated, ionized knots protruding symmetrically on both sides of the core. The line profiles in these collimated outflows are complex, with expanding radial velocities of ± 150 km s^{-1} with respect to the systemic radial velocity (see Figure 1) and detached emission regions at further extreme radial velocities (~ 200 km s^{-1}). In Hb 4 we are probably observing an intermittent outflow developing into episodic bipolar jets.

López et al. (1997) performed a detailed simulation of the observed line profiles from the jets in Hb 4 with a parameterized description of the emissivity and velocity field of the collimated outflows. In their simulated long-slit spectra the line profiles are reproduced by the emission from a bow-shock at

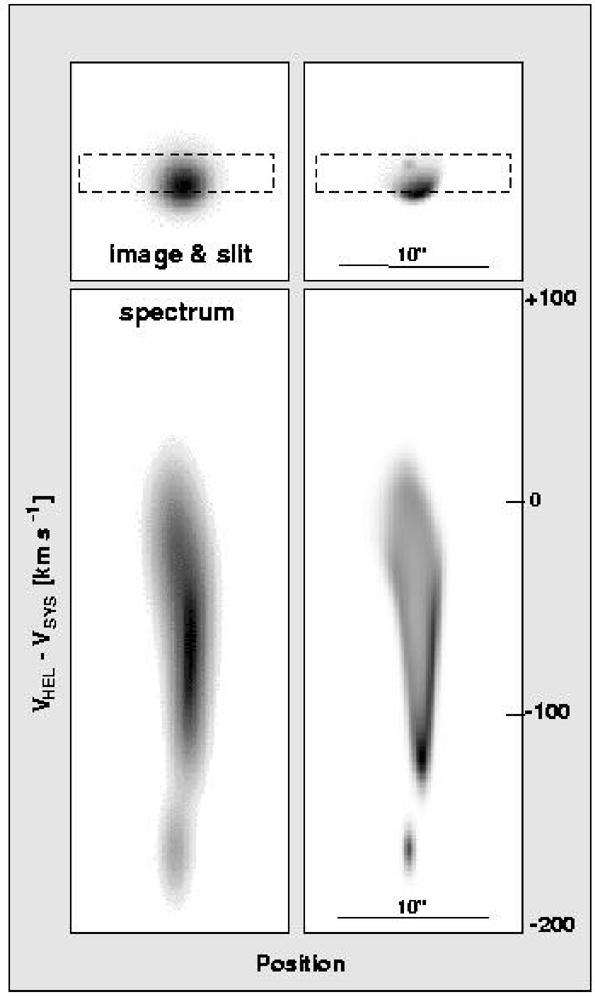

Fig. 2. Simulated images (top) and P-V diagrams (bottom) for the southern jet of Hb 4; shown in the left-hand side at a resolution of 1.″9 and 30 km s^{-1} and for values of 0.″5 and 15 km s^{-1} in the right-hand side, from López et al. (1997).

the head of the jet followed by a faster, dense component (see Figure 2).

3. POINT-SYMMETRIC OUTFLOWS, THE CASE OF IC 4634

IC 4634 is a PN with a striking point-symmetric structure (see Figure 3). Its morphology is also reflected in the velocity space where red-shifted and blue-shifted line profiles from the knotty, collimated outflows are both observed on either side of the nucleus (see Figure 4). The kinematics of the nebula shows evidence of discrete bipolar ejecta with progressive variable direction that produces both positive and negative velocities on each side of the bipolar outflow with respect to the systemic velocity.

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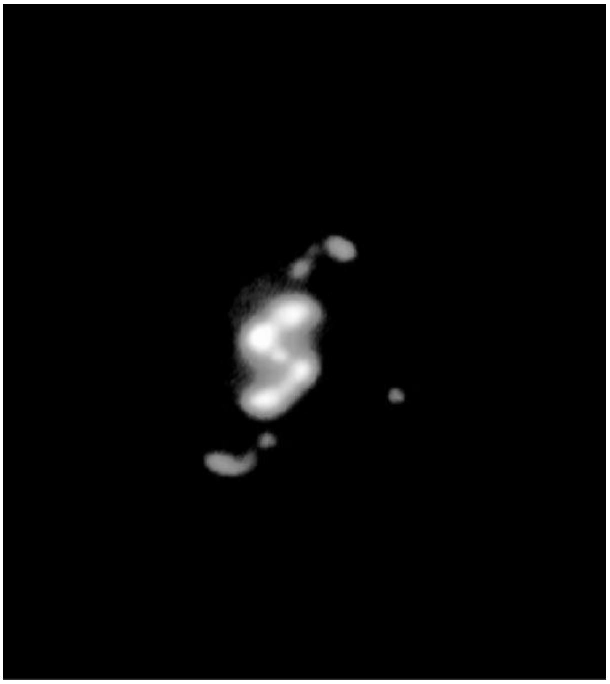

Fig. 3. A logarithmic [N II] image of the point-symmetric PN IC 4634 obstained under 0.″7 seeing.

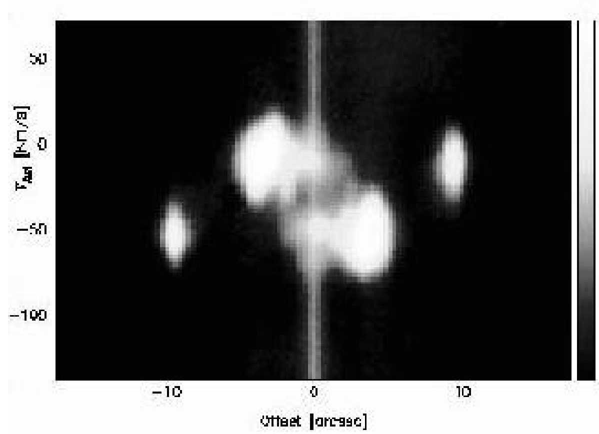

Fig. 4. P-V array for a slit running along the symmetry axis of IC 4634. Red-shidfted and blue-shifted emission with respect to the systemic radial velocity, on each side of the nebula, can be clearly appreciated as is the central expanding shell.

The velocity difference between the extreme blue-shifted and red-shifted components is $\sim$ 45 km s^{-1}. This behaviour is typical of a BRET (e.g., López et al. 1993) and can be interpreted as originating from a precessing or rotating source that produces the switching velocity signs in each of the bipolar outflows. An inner expanding shell, $\sim$ 2.″5 in radius has also been detected at the core and expanding at $\sim$ 25 km s^{-1}. The development of this expanding shell has most likely occured after the ejection of the point-symmetric knots.

4. MYCN 18 AND ITS HYPERSONIC, KNOTTY, BIPOLAR OUTFLOWS

MyCn 18 is a PN with a bright bipolar core. Bryce et al. (1997) found symmetric strings of knots emerging from the bright core, extending $\sim 1''$ on either side of the nucleus and expanding at the remarkable outflow speeds of $\pm$500 km s^{-1} with respect to it (see Figure 5). O'Connor et al. (2000) have further explored the extreme kinematics of this nebula. The velocity of these knots is proportional to their distance from the central star and there is also some degree of point/velocity symmetry, indicating that some pairs of knots have been ejected in opposing directions at the same speed (see Figure 6)

An additional peculiarity of this outflow is that the line profiles from the knots are very narrow, from 15 to 30 km s^{-1} FWHM, which indicates that they are visible due to the photoionization by the central star rather than shock excitation (see Figure 7). Other examples of PNe with extreme outflow velocities are He 2-111 (Meaburn & Walsh 1989), KjPn 8 (López et al. 2000) and He 3-1475 (Borkowski & Harrington 2000). In all these cases, outflow speeds range from 300 to 1200 km s^{-1}.

5. POLY-POLARITY AND JETS, THE CASES OF NGC 7026 AND KJPN 8

Poly-polar PNe are among the most enigmatic nebulae. A proto-typical example of this class is NGC 2440 (López et al. 1998). Another interesting example is the case of NGC 7026, where at least two distinct pairs of bipolar systems are detected, in addition to a well collimated jet. Figure 8 shows a logarithmic Hα + [N II] image of this bright nebula where two sets of bipolar lobes at the top and bottom of the nebula emerge at an angle of $\sim 45^\circ$ from each other. The jet is visible in south-east region.

A representative [N II] λ6584 Å line profile obtained slightly east from the center of the nebula and that exemplifies the global complex kinematics of the outflows in this object is shown in Figure 9. A section of the jet emerging in the southern portion of the nebula is also crossed by the slit in a region where the jet starts to accelerate. Further away from the nebula the jet reaches over 100 km s^{-1} with respect to the systemic velocity.

As a last example of the complex emission line profiles from collimated outflows in PNe, the case of KjPn 8 is presented in Figure 10, where a mosaic of [N II] λ6584 Å line profiles is shown (see López et

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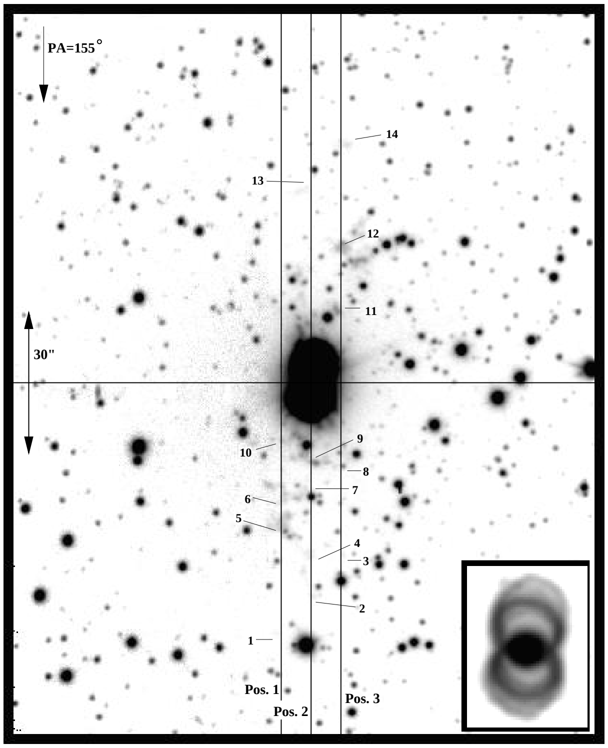

Fig. 5. A deep Hα + [N II] image of MyCn 18 where the extended, bipolar, knotty regions outside the bright core are apparent. An unsaturated image of the core is shown in the lower-right corner. Slits indicated are from the data reported by Bryce et al. (1997).

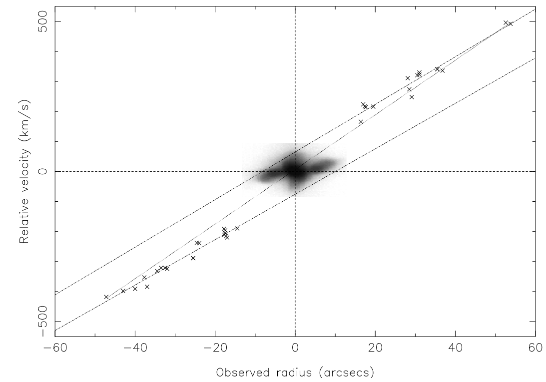

Fig. 6. The observed radial velocities of the high-speed knots in MyCn 18, relative to the systemic velocity, are plotted against the apparent angular distance of each knot from the central star. The grey-scale P-V profile at the center of the plot corresponds to the nebular core. From O'Connor et al. (2000).

al. 1997). These profiles correspond to slits oriented E-W and covering the full extent of the central region of this large nebula from north to south. These spectra describe the kinematics of one of the two sets of bipolar lobes of KjPn 8. The observed heliocentric radial velocities cover ± 220 km s^{-1} with respect to the systemic radial velocity. Their origin is collisional excitation and their similarity with some HH spectra is apparent. The bipolar outflows are angled at 30° to the plane and reach speeds of ~ 320 km s^{-1}.

6. FINAL REMARKS

The emission line profiles from jets in PNe are complex and have diverse characteristics. These outflows are formed since the early stages of development of the PN and have a profound influence in its subsequent evolution. Hydrodynamics alone cannot account for the range of phenomema observed in the collimated ouflows of PNe. Furthermore, the mass, mechanical momentum and kinetic energy contained

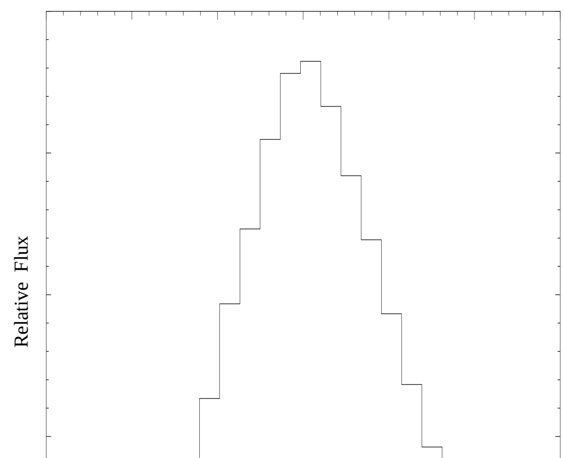

Fig. 7. The observed [N II] λ 6584 Å line profile from one of the high-speed knots in MyCn 18. Line profiles in these fast outflows are narrow. From O'Connor et al. (2000).

in these outflows is estimated to be in the range of 10^{28-32} g, 10^{37-40} g cm s^{-1} and 10^{44-46} erg, respectively (e.g., Bujarrabal et al. 2001) the latter values

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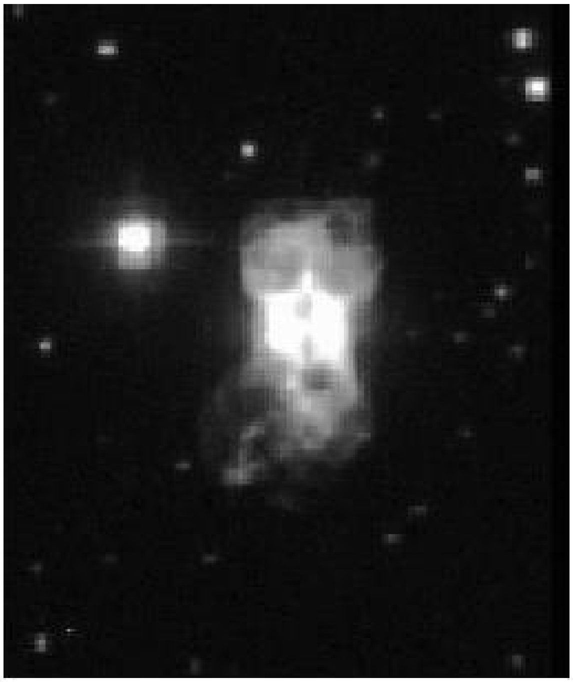

Fig. 8. A logarithmic Hα + [N II] image of poly-polar nebula NGC 7026.

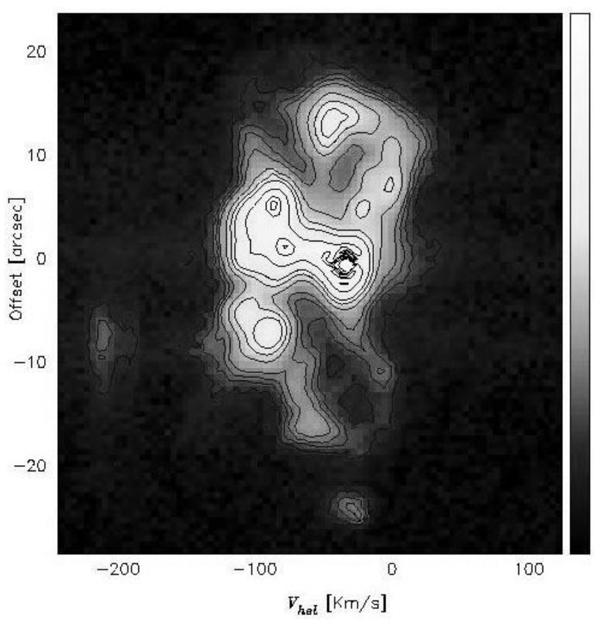

Fig. 9. A [N II] λ 6584 Å line profile of NGC 7026 from a slit oriented N-S, located slightly east from the core. The slit intersects part of the tilted northern and southern lobes. The knot at the bottom corresponds to a region where the slit intersects the emerging jet.

are beyond the energy budget that the central star can provide by its radiative power. In order to pro-

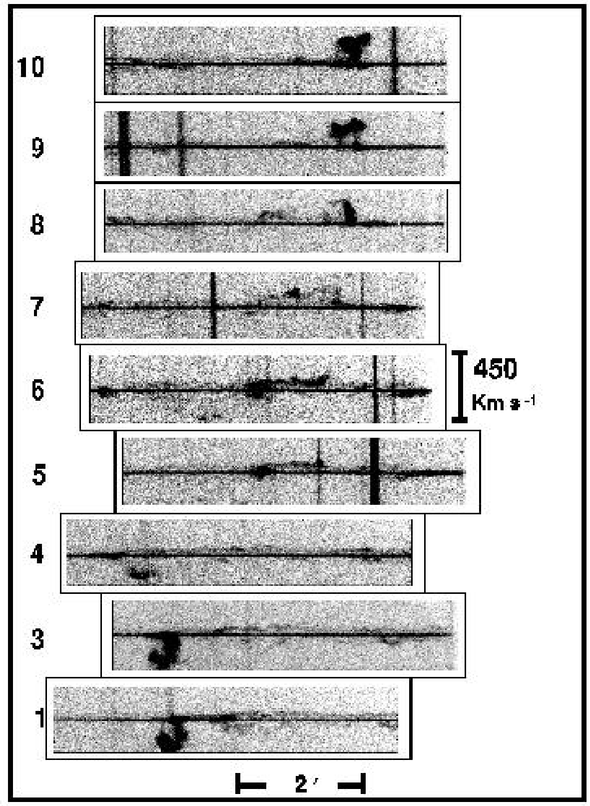

Fig. 10. The observed grey-scale PV arrays of [N II] λ 6584 Å line profiles across the youngest jets of KjPn 8. Receding radial velocities are to the top of each P-V array. From López et al. (1997).

duce the complex geometries and dynamic requirements that drive these outflows, it becomes necessary to include additional ingredients in the traditional hydro models, such as magnetic confinment and acceleration (e.g., Rózyzcka & Franco 1997; García-Segura & López 2000) and the influence of binary cores (e.g., Reyes-Ruíz & López 1999; Soker & Rapapport 2000). It is interesting to notice that in many respects, the presence of collimated outflows in different astrophysical objects show striking similarities and apparently common physical mechanisms.

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