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ENIGMATIC LOW-VELOCITY JET-LIKE FEATURES IN PLANETARY NEBULAE

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RESUMEN

Dentro de nuestro proyecto de investigación sobre las condiciones físicas, origen y evolución de las estructuras de baja ionización en las Nebulosas Planetarias, hemos identificado varios pares de estructuras tipo 'jet' altamente colimadas (Gonçalves et al. 2001). Aunque son muy parecidas a los 'jets' reales, curiosamente presentan velocidades de expansión muy pequeñas, o por lo menos no muy diferentes a las de las envolturas en las que se encuentran. Presentamos aquí nuestros datos sobre estos falsos 'jets' (Corradi et al. 1997, 1999) compárandolos con los modelos teóricos existentes sobre la formación de estructuras colimadas en NPs. Estos enigmáticos sistemas 'tipo jet' son difíciles de encajar en los escenarios teóricos que tratan de las estructuras colimadas en NPs.

ABSTRACT

We are developing a project aimed at studying the physical properties, origin and evolution of low-ionization structures in planetary nebulae. Within this project we have identified a number of pairs of highly collimated low-ionization jet-like features (Gonçalves et al. 2001). In spite of being very similar to real jets, they have the intriguing property of possessing expansion velocities which are very low, or at least not significantly different from, that of the shells in which they are embedded. In this contribution we discuss our data on these fake jets (Corradi et al. 1997, 1999) and compare them with existing theoretical models for the formation of collimated structures in PNe. These enigmatic jet-like systems are not easily accounted for within the theoretical scenarios that deal with collimated features in PNe.

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

1. PLANETARY NEBULAE WITH LOW-IONIZATION STRUCTURES

The main components of a planetary nebula—spherical and elliptical shells, bright rims, bipolar lobes, and halos—are better identified in the light of hydrogen and helium recombination lines, as well as in the forbidden [O III] lines. On the other hand, on usually smaller scales, the low-ionization structures (LISs) are features selected because they are prominent in low-ionization lines (particularly [N II]), fainter in Hα, and almost undetectable in [O III]. Of 50 planetary nebulae (PNe) known to contain LISs we find that 24% have real jets and 18% have jet-like LISs. The features we call *jet-like* systems are highly collimated filaments: (i) directed in the radial direction of the central star; (ii) which appear in symmetrically opposite pairs; and, at variance with real *jets*, (iii) move with relatively low expansion velocities (similar to those of the main shells in which they are embedded; see Table 1 of Gonçalves et al. 2001 for references). Table 1 illustrates the main characteristics of jet-like LISs in contrast with those of the real jets. Those PNe that will be discussed in this contribution are distinguished in the table by bold letters.

2. OUR DATA FOR JET-LIKE SYSTEMS

2.1. *K 1-2*

This PN is composed of a low surface brightness, elliptically shaped main nebula (see in Fig. 1 the morphology of the Hα emission), in addition to a low-ionization jet-like system (at P.A. = $-27°$ and well identified in both emission lines of Fig. 1). K 1-2 also contains another system of knots that appears (projected on the plane of the sky) almost perpendicular to the first one.

Its kinematics shows that the main elliptical shell has an expansion velocity of 25 km s^{-1} (determined from the splitting of the Hα line emission), and that the inner regions of the P.A. = 27° jet-like LIS share the expansion of the shell in which they are embedded. Note, however, that the tail of this system (the feature we called A$'$ in Fig. 1) has a peculiar velocity, which increases outwards—accelerating from

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TABLE 1

JETS VERSUS JET-LIKE LOW-IONIZATION STRUCTURES

Jets			Jet-like Systems			
Object	Kinem. ages[a]	Orientation[b]	Object	Kinem. data	Orientation[b]	Location[c]
Fg 1	older	40°	He 2-249	yes	0°	outside
Hb 4	younger	90°	**IC 4593**	yes	-	outside
He 2-186	-	-	**K 1-2**	yes	-	inside
IC 4634	-	-	M 3-1[d]	no	-	outside
K 4-47	older	-	NGC 6309[d]	no	-	outside
M 1-16	older	-	NGC 6751	yes	-	outside
NGC 3918	coeval	-	NGC 6881	yes	40°	outside
NGC 6210	younger	90°	NGC 7354[d]	no	-	outside
NGC 6543	younger	20°	**Wray 17-1**	yes	-	inside
NGC 6884	coeval	50°				
NGC 6891	coeval	0°				
NGC 7009	coeval	30°				

[a]Quoted kinematic ages are those of the jets as compared to those of the main nebular shells.

[b]Orientation column shows the approximate angle of the LISs with respect to the major axis of the main shell.

[c]The apparent location of the tip of the jet-like system with respect to the swept-up shell.

[d]M 3-1, NGC 6309, and NGC 7354 do not have kinematic data along the LISs, thus they cannot be classified as jets.

25 km s^{-1} at the shell position to 45 km s^{-1} at its outermost region (see Corradi et al. 1999 for a complete discussion of this object).

2.2. *IC 4593*

From the images in Figure 2 we see that IC 4593 has, in addition to its bright rim and asymmetrical shell, two systems of collimated LISs: a jet-like system (P.A. = $-41°$) and a pair of knots (P.A. = $-118°$). Resembling the case of K 1-2, also in this PN the two main pairs of LISs are almost mutually perpendicular. The spectra of IC 4593 allow us to determine, from the velocity field in various lines, the heliocentric systemic velocity as being 21 ± 3 km s^{-1} (Fig. 2). Along the jet-like system, labeled ABB' (P.A. = $-41°$) the measured velocities do not differ from that of the shell. Our analysis (Corradi et al. 1997) suggests that the low radial velocities measured for the jet-like system are not due to projection effects—as argued by other outhors (Harrington & Borkowski 2000)—thus showing that this is a real low-velocity jet-like system.

2.3. *Wray 17-1*

From the detailed discussion of Corradi et al. (1999), Wray 17-1 possesses a diffuse elliptical shell ([O III] emission) and two collimated low-ionization structures ([N II] and ratio images of Fig. 3). The jet-like system, at P.A. = $-28°$, has a direction (projected into the sky) completely different of that of the pair of knots (at P.A. = $-103°$). From the data on the kinematics of this object, also in Figure 3, we determined the expansion velocity of the main elliptical shell as being 28 km s^{-1}. As is shown in the position–velocity diagram, the jet-like system (except for its tail) is embedded in the 28 km s^{-1} shell and has radial velocities smaller or similar to those of the shell. Note, however, that the radial velocity of the tail A′ is very peculiar; there is a velocity gradient of 90 km s^{-1} between A′ and A. Considering that A and A′ are morphologically well aligned, we explain this gradient as an ionization effect (Corradi et al. 1999).

3. THEORETICAL IDEAS FOR THE ORIGIN OF JET-LIKE LIS'S

Theoretical models for the formation of collimated structures in planetary nebulae can be roughly grouped into two kinds: those based in the interacting stellar winds (ISW models) and those that consider the stellar and accretion-disk winds interaction (accretion-disk models). ISW models are

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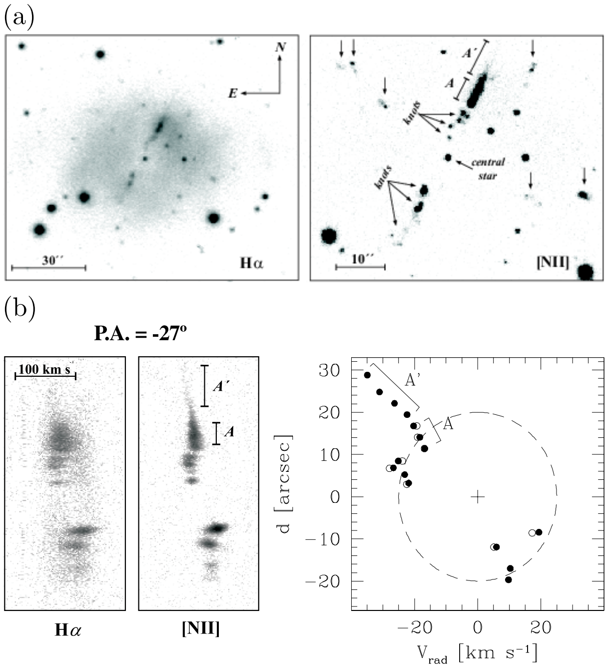

Fig. 1. (a) Hα and [N II] images of K 1-2. The left panel shows the diffuse elliptical Hα shell as well as the jet like-system. In the right panel is shown a closer view of the low-ionization features. The string of knots that forms the jet-like system and the filament (A, A′) are indicated. Arrows identify the other LISs of this PN. (b) Kinematics of K 1-2 . Left panel: spectra along the jet-like system indicating two different velocity regimes (regions A and A′). Right panel: position-velocity plot of the measured velocities corrected for the systemic velocity. Filled and open circles represent [N II] and Hα velocities, respectively. The dashed line shows the velocity field of the main shell.

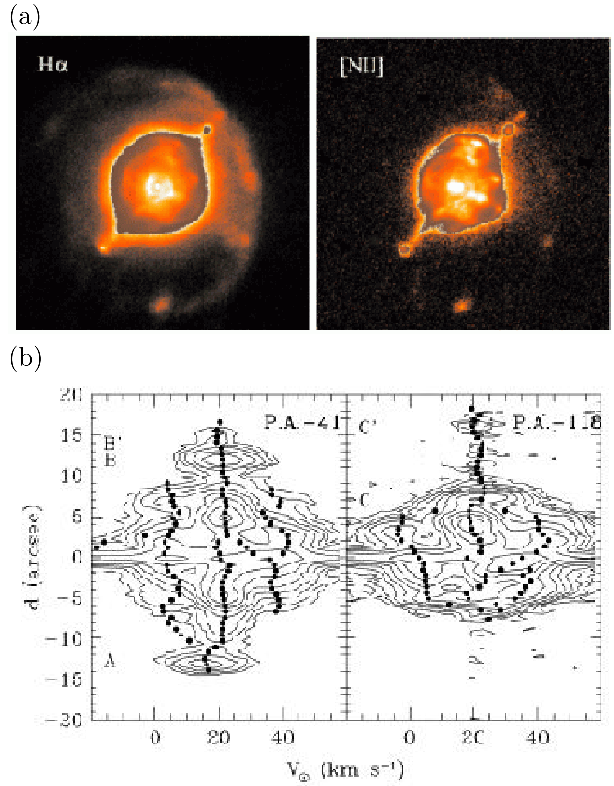

Fig. 2. (a) Hα and [N II] images of IC 4593. The left panel shows the inner rim and the asymmetrical shell, while the jet-like system is better identified on the right. The field of view is 45′′ × 45′′, with north at the top and east to the left. (b) [N II] position–velocity plots superposed on the contour plots of the observed spectra along the jet-like system (ABB') and along the pair of knots (CC'). Circles represent the measured heliocentric velocities.

related to the origin of collimated features in a single-star scenario, while the latter ones deal with processes occurring in binaries. The formation of jets by the ISW process was pointed out by Frank, Balick, & Livio (1996). Magnetohydrodynamical simulations of the ISW also proved to be successful in predicting some of the properties of the observed PNe with jets (García-Segura 1997; García-Segura et al. 1999). In particular, the observed linear relationship between the jet expansion velocity and the distance from the center is one of the predictions of the latter models, while new results of the stagnation zone jets also predict this velocity behavior (see Steffen & López, these proceedings). Jets originating from the interplay of the accretion disk and stellar winds in PNe have been investigated by, for instance, Soker & Livio (1994), Livio & Pringle (1997), and Reyes-Ruíz & López (1999). Generally, what all the above models predict is the formation of (i) two-sided highly collimated features with supersonic velocities larger than that of the main shell, (ii) kinematic ages similar to (ISW models) or older than (accretion-disk models) that of the main shell, and (iii) with an orientation that depends on the presence of precession, wobbling, or a misalignment between the main axis of the coupled system (Blackman, Frank, & Welch 2001; García-Segura, López, & Franco 2001).

On the other hand, the fake jets presented here are a bit more difficult to explain. Their main characteristic—the one that makes them different from genuine jets—is that their velocities are not peculiar with respect to the surrounding medium. Note that most jet-like systems are located (projected onto the sky) outside the swept-up shell of the host nebulae (as well as all the jets of Table 1; see also Table 2 of Gonçalves et al. 2001). However, for two of the cases we show here the

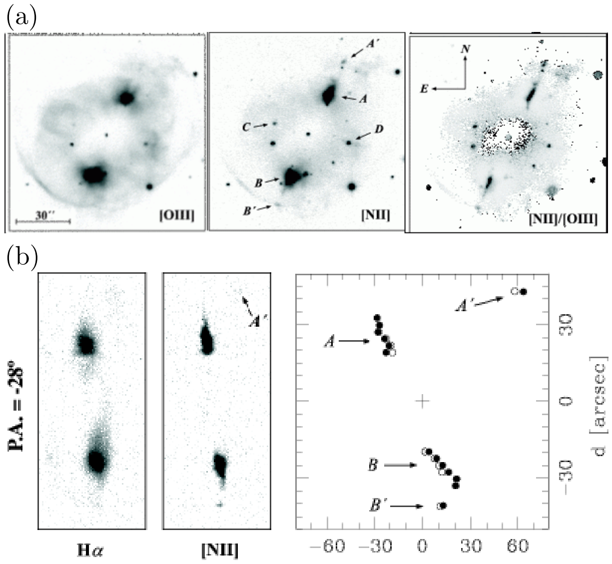

Fig. 3. (a) [O III], [N II], and [O III]/[N II] images of Wray 17-1. The main shell is easily seen in the left panel, while the jet-like system (AB, A′B′) and the pair of knots (CD) are better seen in the middle image. Note that the ratio image puts in evidence the high collimation of the LIS. (b) Spectra and PV plot of Wray 17-1, along the jet-like features (P.A. = −28°). Open and filled circles represent [N II] and Hα measured velocities, respectively, and are corrected for the systemic velocity of the nebula.

jet-like features are inside of the main shell. It seems that this property plays an important role when we try to compare observed properties and theoretical predictions. This is particularly true when we analyze certain details of the results found by Różyczka & Franco (1996)—the first paper proposing magnetized interacting stellar winds to produce jets in PNe—since their simulations show the formation of two pairs of well collimated flows (one pair per stagnation region, which are in the polar regions of the main shell), and in every pair one of the flows is of low velocity and directed toward the central star, and the other is of high velocity and expanding away from it. The stagnation zone jets of Steffen, López, & Lim (2002) appear to produce low-velocity collimated features as well. Note, however, that in both models the low-velocity jet-like systems develop inside the swept-up shell, and that this is not the case for four of the six PNe containing jet-like systems that are well studied (see last column of Table 1). Another important issue is the lifetime of the low-velocity features that would arise during the evolution of the interacting winds of the above cited models. Unfortunately, this information is not easily obtained from the observations since the useful comparison between kinematic ages of nebular components do not apply in this case. Therefore, the actual origin of the low-velocity jet-like system in PNe is clearly a challenge for further exploration.

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