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THE KINEMATIC SIGNATURE OF A BINARY CENTRAL STAR IN THE COLLIMATED EJECTIONS OF PLANETARY NEBULAE

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RESUMEN

Se piensa que en la formación de muchos de los flujos colimados observados en las nebulosas planetarias están involucradas, de alguna manera, estrellas binarias. Dado que la detección de estrellas centrales binarias puede ser difícil observacionalmente, el uso de métodos indirectos para inferir la presencia de una binaria se presenta como una alternativa interesante. Recientemente se ha sugerido que una diferencia entre la velocidad sistémica de un flujo colimado bipolar y la velocidad sistémica de la envoltura principal es una evidencia directa de movimiento orbital. Presentamos y discutimos este método y mostramos datos de Hu 2-1 e IC 4846, dos nebulosas planetarias con múltiples componentes colimadas, en las que se observan diferencias claras entre esas dos velocidades sistémicas. Los parámetros orbitales que se deducen en Hu 2-1 e IC 4846 son típicos de binarias interactuantes y sugieren que el origen de los flujos colimados en estas dos nebulosas planetarias es un disco de acrecimiento alrededor de una compañera.

ABSTRACT

Binary stars are believed to be involved in some way in the formation of many collimated outflows observed in planetary nebulae. The direct detection of binary central stars is observationally difficult, so that indirect methods offer an interesting alternative for inferring the presence of a binary. It has been recently proposed that a difference between the systemic velocity of a collimated (bipolar) outflow and that of the main shell is direct evidence for orbital motion. We present and discuss this method and show data of Hu 2-1 and IC 4846, two planetary nebulae with multiple collimated components, in which the aforementioned systemic velocities clearly differ from each other. The orbital parameters estimated in Hu 2-1 and IC 4846 are typical of interacting binaries and suggest that the origin of the collimated outflows in these two planetary nebulae is an accretion disk around a companion.

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

1. INTRODUCTION

Collimated outflows appear to be a natural result of the transition from AGB stars to planetary nebulae (PNe). Even though collimated outflows have been extensively observed in the last few years (e.g., López 2002), their origin is still matter of debate. In addition to the first scenarios to explain the formation of these outflows (Morris 1987; Soker & Livio 1994; Soker 1996; Mastrodemos & Morris 1998), recent MHD calculations and simulations have opened new interesting alternatives (García-Segura 1997; Franco 2002; Frank 2002). However, the idea that binary stars play an important role in the formation of these outflows continues to be present in the different scenarios, either by the formation of a disk around the AGB star, or by the production of a misalignment (precession or wobbling) of the collimation axis.

Binary stars are known in only a small number of PNe, including wide binaries with separations $\sim 10^2$–10^4 AU and close binaries with orbital separations of a few solar radii, which are probably the result of common-envelope evolution (Ciardullo et al. 1999; Soker 1999; Bond 2000). It is also expected that binary central stars exist with intermediate separations of few to few tens of AU. These kind of binaries are of particular interest because, at such separations, interaction between the stars is possible, providing an ideal scenario for a rich and varied phenomenology. Direct detection of such binaries in PNe is difficult given current observational capabilities. However, the properties of a PN should contain information about the nature and evolution of its central star. Indirect methods based on the analysis of the nebula may be a valuable alternative to infer the presence of a binary central star.

2. SYSTEMIC VELOCITIES AND ORBITAL MOTION

Recently, Miranda et al. (2001a, hereafter MT-GVG) and Miranda, Guerrero & Torrelles (2001b,

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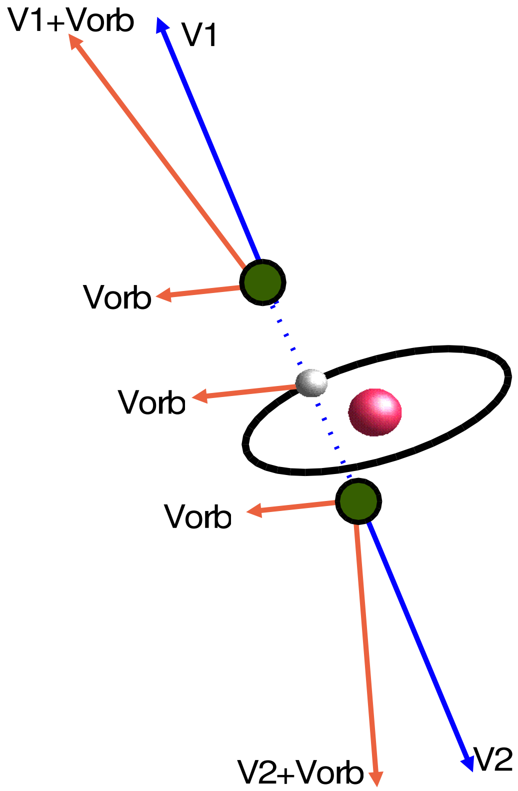

Fig. 1. Velocity components involved in the ejection of a bipolar collimated outflow from a single star (dark arrows) and from binary star (light arrows). $V_1 = V_2$ is the ejection velocity of the outflow and $V_{\rm orb}$ is the orbital velocity at the time of ejection. The observer is to the left.

hereafter MGT) have suggested that a difference between the systemic velocity of the collimated (bipolar) outflows and that of the main nebular shell is direct evidence for orbital motion in the ejection source. In Figure 1 we illustrate the cases of a bipolar outflow ejected from a single star and from a binary star. If $V_1 = V_2$ is the ejection velocity of the outflow, in the case of a single star we obtain

$$V_{\rm sys}(\text{outflow}) = 0.5(V_1 + V_2) = V_{\rm sys}(\text{shell}), \qquad (1)$$

where the systemic velocity of the bipolar outflow $V_{\rm sys}$(outflow) (defined as the centroid velocity of the bipolar outflow) coincides with the systemic velocity of the shell $V_{\rm sys}$(shell) (defined as the centroid velocity of the emission lines from the main shell). In the case of a binary star, the velocity component due to orbital motion $V_{\rm orb}$ should be considered in addition to the ejection velocity and we get

$$\begin{aligned} V_{\rm sys}(\text{outflow}) &= 0.5\,[(V_1 + V_{\rm orb}) + (V_2 + V_{\rm orb})] \\ &= V_{\rm sys}(\text{shell}) + V_{\rm orb}. \end{aligned} \qquad (2)$$

This simple equation illustrates the relationship between $V_{\rm sys}$(outflow), $V_{\rm sys}$(shell) and $V_{\rm orb}$ (see MTGVG for a detailed discussion). If we consider the inclination of the orbit i and the orbital phase angle at the time of the ejection γ, we obtain

$$V_{\rm sys}(\text{outflow}) - V_{\rm sys}(\text{shell}) = V_{\rm orb}\cos\gamma\cos i. \qquad (3)$$

Therefore, a difference between $V_{\rm sys}$(outflow) and $V_{\rm sys}$(shell) can be considered as direct evidence for orbital motion and, hence, for a binary central star. It should be pointed out that a lower limit for $V_{\rm orb}$ is obtained and, therefore, upper limits for the orbital separation and period can be estimated.

Measurements of $V_{\rm sys}$(outflow) and $V_{\rm sys}$(shell) can be obtained with high resolution spectroscopy. In principle, differences of $\geq$ 2–3 km s^{-1} may be easily detected if the emission line profiles are symmetric enough to allow a clear definition of the systemic velocities. On the other hand, systemic velocity differences may also be due to different interactions with surrounding material, different ejection velocity or different ejection angle for each of the bipolar components of an outflow. Before the systemic velocity difference can be attributed to orbital motion, other possibilities have to be ruled out. This can be done, for instance, by measuring the distance of each component in a bipolar outflow with respect to the central star of center of the nebula. The components of a bipolar outflow should be located symmetrically with respect to the central star if the systemic velocity difference is due to orbital motion whereas in other cases difference positions may be expected. In fact, a detailed and careful analysis of each particular PN is necessary to measure differences in systemic velocities and to exclude other possibilities, apart from orbital motion, as the origin of such differences.

3. COLLIMATED OUTFLOWS AND SYSTEMIC VELOCITIES IN HU 2-1 AND IC 4846

Figure 2 shows [N II] images of Hu 2-1 and IC 4846, two PNe with multiple collimated bipolar outflows in which systemic velocity differences have been detected (MTGVG; MGT).

Hu 2-1 is a bipolar PN. The main shell consists of an equatorial toroid and two point-symmetric lobes, which also present noticeable departures from axisymmetry. An inner point-symmetric shell is

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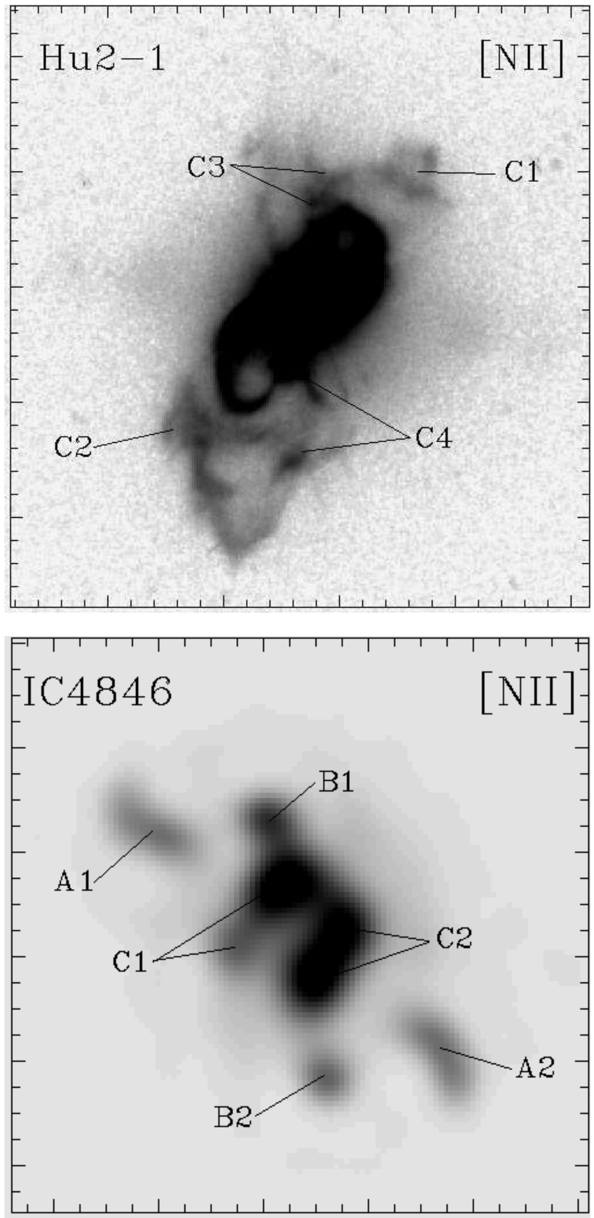

Fig. 2. (Top:) [N II] image of Hu 2-1 obtained with the HST (Progam ID: 6347, PI: Borkowski & Harrington). The size of the field shown is 11″ × 12″. The two bipolar pairs of compact knots (C1–C2 and C3–C4) are indicated. (Bottom:) [N II] image of IC 4846. The size of the field shown is 12″ × 12″. The pairs of collimated components(A1–A2, B1–B2, C1–C2) are indicated.

also observed. Two pairs of bipolar knots C1–C2 and C3–C4 exist in Hu 2-1 (MTGVG). C1 and C2 are located at 3.″0 from the central star, C3 and C4 are located at 2.″5. High-resolution, long-slit spectra of Hu 2-1 in the [N II] 6583 Å line are shown in Figure 3 at the position angle (PA) of

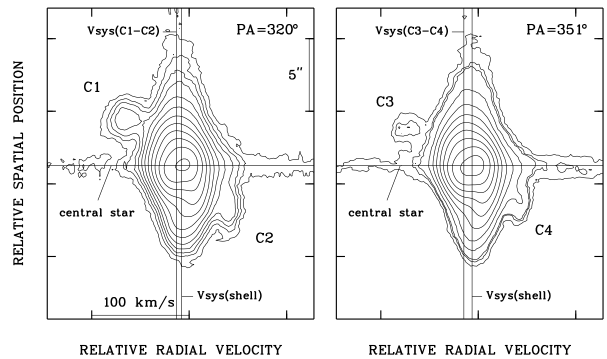

Fig. 3. Position-velocity maps of the [N II] 6583 Å emission line from Hu 2-1 at two position angles of the slit. The bipolar pairs of knots C1–C2 and C3–C4 are labeled (see Fig. 1). The systemic velocity of the bipolar outflows [$V_{\rm sys}$(C1–C2) and $V_{\rm sys}$(C3–C4)] and that of the main shell [$V_{\rm sys}$(shell)] are indicated with vertical lines (see text).

C1–C2 (PA 320°) and C3–C4 (PA 351°). Emission from C1–C2 and C3–C4 can be easily separated by their relatively large Doppler shift from emission from the main shell. In the long-slit spectra (Figure 3), it can be immediately recognized that the velocity centroid of C1–C2 and C3–C4 is displaced with respect to the velocity centroid of the emission from the main shell. The (LSR) systemic velocities deduced for the bipolar knots and main shell are: $V_{\rm sys}$(C1–C2) = 29 km s^{-1}, $V_{\rm sys}$(C3–C4) = 26.5 km s^{-1} and $V_{\rm sys}$(shell) = 34.5 km s^{-1}. $V_{\rm sys}$(C1–C2) and $V_{\rm sys}$(C3–C4) are almost identical to each other within the absolute errors in the long-slit spectra ($\simeq \pm$ 1.2 km s^{-1}). In addition, $V_{\rm sys}$(C1–C2) and $V_{\rm sys}$(C3–C4) differ by 5.5 and 8 km s^{-1} from $V_{\rm sys}$(shell) and these values are much larger than the relative errors ($\simeq \pm$ 0.15 km s^{-1}).

IC 4846 consists of a slightly elliptical shell, an attached circular shell and three pairs of point-symmetric components (A1–A2, B1–B2, and C1–C2) which most probably represent collimated outflows (Fig. 1; MGT). In fact, A1–A2 can be interpreted as bipolar precessing jets. In Figure 4 we show long-slit spectra of the [N II] 6583 Å emission line from IC 4846 at three different PAs. The (LSR) systemic velocities of the outflows and the emission centroid are: $V_{\rm sys}$(A1–A2) = 158 km s^{-1}, $V_{\rm sys}$(B1–B2) = 164 km s^{-1}, $V_{\rm sys}$(C1–C2) = 163 km s^{-1}, $V_{\rm sys}$(shell) = 168 km s^{-1}. $V_{\rm sys}$(B1–B2) and $V_{\rm sys}$(C1–C2) are almost identical to each other and differ by $\simeq$ 3 km s^{-1} from $V_{\rm sys}$(shell). This difference is comparable to the absolute errors in velocity. However, $V_{\rm sys}$(A1–A2) presents a noticeable difference of 10 km s^{-1} with

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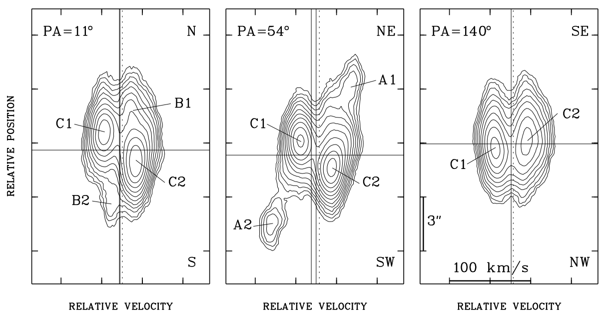

Fig. 4. Position-velocity maps of the [N II] 6583 Å emission line from IC 4846 at three position angles of the slit (upper left). The bipolar outflow components are labeled (see Fig. 1). Continuous vertical lines indicate the systemic velocity of the different outflows. Dashed vertical line indicates the systemic velocity of the emission centroid (see text).

respect to $V_{\rm sys}$(shell). It is worth noting that A1–A2 present an identical increase of the radial velocity from 36 km s^{-1} at the minimum angular distance up to 52 km s^{-1} at their tips. These values are quoted with respect to $V_{\rm sys}$(A1–A2). If they were quoted with respect to $V_{\rm sys}$(shell), a systematic shift of 20 km s^{-1} would exist between A1 and A2 all along the features.

4. INTERACTING BINARIES IN HU 2-1 AND IC 4846

Following equation (3), the systemic velocity differences between the bipolar knots C1–C2 and C3–C4 in Hu 2-1 and of A1–A2 in IC 4846 and the systemic velocity of their respective main shells can be interpreted as a result of orbital motion in a binary central star. In B1–B2 and C1–C2 in IC 4846, the difference between their systemic velocities and $V_{\rm sys}$(shell) is comparable to the errors and we cannot conclude whether this difference is real. Before orbital motion can be accepted as explanation for the systemic velocity difference, other possibilites should be ruled out. In the case of Hu 2-1, the two knots in each pair C1–C2 and C3–C4 are located at the same distance from the center. The same is true for A1–A2 in IC 4846, which exhibit a near-perfect point symmetry in the images and an identical radial velocity variation along their length (Fig. 1; see also above). These results rule out alternative explanations for the differences in systemic velocity in terms of deceleration of the knots, different ejection velocities, different angles, or a combination of these. Therefore, we conclude that the systemic velocity difference is due to orbital motion and that a binary central star exists in the two PNe.

Taking into account that the equatorial plane of Hu 2-1 is tilted by $\simeq 37°$ with respect to the line of sight (Miranda 1995; MTGVG) and assuming that the inclination of the orbit coincides with the equatorial plane of the nebula, a lower limit to $V_{\rm orb}$ of $\simeq 10$ km s^{-1} is obtained in Hu 2-1, identical to that obtained in IC 4846. With this value for $V_{\rm orb}$, and assuming a mass for the binary of $\leq 3\,M_\odot$ and circular orbit, the orbital separation is ≤ 30 AU and the period is ≤ 100 yr.

The systemic velocity difference is not the only argument supporting the existence of a binary central star in Hu 2-1. More arguments are (see MTGVG): the observed point symmetry of the lobes and inner shell; the departure from axisymmetry in the bipolar lobes; the detection of mass ejection towards the equatorial plane of the nebula; and the off-center position of the central star. In fact, the *HST* images reveal that the central star is displaced by $\simeq 0\farcs05$ from the center of the toroid and inner shell, along the minor nebular axis (MTGVG). Following Soker, Rappaport, & Harpaz (1998), this displacement suggests an eccentric binary with orbital separation and period of $\simeq$ 7–80 AU and $\simeq$ 15–500 yr, respectively, which are compatible with those obtained from the systemic velocity difference.

A further interesting aspect of Hu 2-1 is that the systemic velocity of the two pairs of knots is almost identical to each other. This suggests that collimated ejection occurs at a particular orbital phase and may be related to the periastron passage, where mass transfer is expected to increase (Mastrodemos & Morris 1999; see also Soker 2002).

The estimated orbital parameters link the central stars of Hu 2-1 and IC 4846 with interacting binaries. Some symbiotic stars present bipolar shells and collimated outflows and a relationship between symbiotic Miras and some PNe has already been suggested (Corradi et al. 1999). In these binary systems, accretion may be effective at relatively large orbital separations (Mastrodemos & Morris 1999). Therefore, the most probable origin for the collimated outflows in these two PNe is an accretion disk around a companion. Moreover, the whole formation of Hu 2-1 and IC 4846 may be a result of different physical processes in the evolution of interacting binaries.

5. CONCLUSIONS

We propose that differences between the systemic velocity of the collimated outflows and the systemic velocity of the main nebular shell in a PN can be interpreted as direct evidence for orbital motion in the central star. We discuss this method, briefly analyzing its capabilities and possibilities. Hu 2-1 and

IC 4846 are two PNe with multiple collimated outflows, in which a systemic velocity difference of $\simeq 10\ \mathrm{km\,s^{-1}}$ is observed. An analysis of the spatio-kinematic properties of the collimated outflows in these two PNe allows us to conclude that the systemic velocity difference is due to orbital motion and that a binary star should exist at the center of Hu 2-1 and IC 4846. With a simple binary model, estimates for the orbital separation of ≤ 30 AU and orbital period ≤ 100 yr are obtained assuming a mass for the binary $\leq 3\,M_{\odot}$. These orbital parameters suggest that the central stars of Hu 2-1 and IC 4846 are interacting binaries. If so, the origin of the collimated outflows in these two PNe is an accretion disk around a companion. Evidence is also found that the collimated outflows in Hu 2-1 are ejected at a particular orbital phase that may be related to the periastron.

A detailed analysis of the systemic velocities in more PNe with collimated outflows may reveal binary stars with orbital separations in the range of a few AU to several tens AU, which could be interacting binaries. In this cases, an accretion disk scenario appears as the most promising one for the origin of collimated outflows.

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Alberto Noriega-Crespo, Luis Miranda, José María Torrelles, & Jorge Cantó. (Photo: J. A. López.)

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