STEADY TWIN-JETS ORIENTATION: IMPLICATIONS FOR THEIR FORMATION MECHANISM

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ABSTRACT

We compare the structures of the jets of the pre-planetary nebulae (pre-PNe) CRL618 and the young stellar object (YSO) NGC 1333 IRAS 4A2 and propose that in both cases the jets are launched near periastron passages of a highly eccentric binary system. The pre-PN CRL618 has two "twin-jets" on each side, where by "twin-jets" we refer to a structure where one side is composed of two very close and narrow jets that were launched at the same time. We analyze the position–velocity diagram of NGC 1333 IRAS 4A2, and find that it also has the twin-jet structure. In both systems, the orientation of the two twin-jets does not change with time. By comparing these two seemingly different objects, we speculate that the constant relative direction of the two twin-jets is fixed by the direction of a highly eccentric orbit of a binary star. For example, a double-arm spiral structure in the accretion disk induced by the companion might lead to the launching of the twin-jets. We predict the presence of a low-mass stellar companion in CRL618 that accretes mass and launches the jets, and a substellar (a planet of a brown dwarf) companion to the YSO NGC 1333 IRAS 4A2 that perturbed the accretion disk. In both cases the orbit has a high eccentricity.

Key words: planetary nebulae: general – stars: AGB and post-AGB – stars: pre-main sequence – stars: winds, outflows

Online-only material: color figures

1. INTRODUCTION

Many planetary nebulae (PNe) are thought to be shaped by jets that are launched from a binary companion (Soker & Livio 1994; Sahai & Trauger 1998; see the review by Balick & Frank 2002), in particular, two opposite dense clumps/bullets (also called ansae or FLIERS) are thought to be formed by jets (Soker 1990). Understanding the properties of the jets and the conditions for their formation is relevant to other astrophysical systems as well, such as young stellar objects (YSOs) that share some similar properties with some PNe (Lee & Sahai 2004). Examples include the well-collimated jets from Hen 2-90 that are composed of a chain of bullets that are similar to jets from some YSOs (Sahai & Nyman 2000), and the similar morphology of the PN KjPn 8 (for a recent study of this PN, see Boumis & Meaburn 2013) and the bipolar structure of the recently discovered YSO Ou4 (Acker et al. 2012; R. Corradi et al. 2013, in preparation). In the present study, we focus on the pre-PN CRL618 recently analyzed by Balick et al. (2013), and compare the two opposite *"twin-jets"* with those in the YSO NGC 1333 IRAS 4A2 (hereafter IRAS 4A2). By *twin-jets* we refer to two narrow and close jets (or bullets) that are launched at the same time. Lee et al. (2003) already compared CRL618 with the YSO HH 240/241. Lee et al. (2003) and Lee & Sahai (2003) were aiming at the flow structure of a single narrow jet (or bullets), while we are aiming at explaining the presence of two close jets (or bullets), i.e., twin-jets.

Balick et al. (2013) imaged CRL618 (PN G166.406.5) on few occasions from 1998 to 2010, and followed its evolution. The pre-PN CRL618 contains two close narrow main lobes (finger-shaped outflows) on opposite sides of the center (Trammell & Goodrich 2002). The lobes themselves show substructures that, as we see later, are observed also in IRAS 4A2. By jets we will also refer to very brief jets that are called bullets.

The opposite twin-jets in CRL618 are not exactly aligned with each other. The projected angle between the east twin is 20°, while that of the west twin is 12°. We are not aiming to explain the structure of the narrow lobes (see Lee & Sahai 2003; Lee et al. 2003, 2009; Balick et al. 2013), but rather we examine the presence of twin-jets. Balick et al. (2013) find that a brief ejection of bullets can account for the structure of CRL618. In Section 2, we discuss the properties of the bullets. In Section 3, we compare the non-identical twin-jet structure of CRL618 with that of YSO IRAS 4A2. In IRAS 4A2 the image does not reveal the twin-jets, but rather we had to carefully examine the position–velocity (P–V) maps to identify this structure. In Section 4, we speculate on a simple model to account for the formation of twin-jets.

2. THE BRIEF BULLET EJECTION IN CRL618

Based on the observations and numerical simulations of CRL618 as performed by Balick et al. (2013) and Lee & Sahai (2003), we can construct the following plausible set of properties for the four lobes (two opposite twin lobes) observed with the *Hubble Space Telescope*. The age of the lobes is $\sim$100 yr, implying that the bullets were launched within a much shorter time period. For our modeling this time will be very brief, $\tau_b \simeq 0.1$ yr. Balick et al. (2013) simulated the evolution of a bullet of mass $2.4 \times 10^{-5}\, M_\odot$ and with a velocity of 300 km s^{-1}. We take the typical bullet initial mass to be $M_b \sim 5 \times 10^{-5}\, M_\odot$, and the total mass in the four jets (that have more than four bullets) to be in the range $M_{4j} \sim 2$–$5 \times 10^{-4}\, M_\odot$. If the mass in the jets is $\sim$0.1 of the mass that was accreted onto a companion, then the accreted mass and the accretion rate are $M_{acc} \sim 3 \times 10^{-3}\, M_\odot$ and $M_{acc} \sim 0.03\, M_\odot$ yr^{-1}, respectively.

The energy of the accretion process that can be channeled to jets (bullets) and radiation, assuming accretion onto a main-sequence star, is $E_{ILOT} \simeq 0.5\, G\, M_\odot\, M_{acc}/R_\odot \simeq 5 \times 10^{46}$ erg. Radiation can come from the accretion process and from the interaction of the bullets with their surroundings. Some ingredients of the model were discussed in the past in other

contexts. Soker & Rappaport (2000) considered the interaction between asymptotic giant branch (AGB) winds and high-momentum jets that are blown simultaneously, and Blackman et al. (2001) pointed out that accretion power in PN progenitors can be relatively steady and powerful.

Soker & Kashi (2012) suggested that some structures in some PNe are formed by a brief energetic event lasting weeks to years that can be observed as an intermediate luminosity optical transient (ILOT). An event with an energy of few $\times$ 10^{46} erg lasting few months can in principle be classified as an ILOT similar to some ILOTs suggested for PNe (Soker & Kashi 2012). However, if dust obscures the inner several $\times$AU, such an event will not be detected as an ILOT.

It should be noted that we refer only to the four lobes studied by Balick et al. (2013) and Lee & Sahai (2003), and not to the massive molecular fast outflow, $M_{mol} \sim 0.1 \, M_\odot$ (Sánchez Contreras et al. 2004), that is closer to the center (Kastner et al. 2001; Cox et al. 2003; Sánchez Contreras et al. 2004; Nakashima et al. 2007; Lee et al. 2009, 2013; Tafoya et al. 2013). We attribute the fast molecular outflow closer to the center to a more vigorous recent binary interaction. Namely, the same companion returned again in its eccentric orbit, but after losing angular momentum and energy. It hence dived deeper into the primary AGB star.

An ILOT event was recently simulated by Akashi & Soker (2013), who launched a wide massive outflow into a dense AGB wind close to the center. The jets–shell interaction is within a distance of $r_I \sim 10$ AU. The mass in each jet was $\sim 0.01 \, M_\odot$ and its initial velocity was set to 1000 km s^{-1}. In this regime the radiative cooling of the gas is set by photon diffusion time, and that flow was found to be cooling slowly and be unstable. The bullets proposed for CRL618, on the other hand, seem to cool rapidly.

Within months of a periastron passage, the companion launched two opposite twin-jets (twin bullets), each with a velocity of $v_b \simeq 500$ km s^{-1}. Each bullet reached a distance of ~ 10 AU within the interaction time. We take the typical interaction of jets with their dense AGB wind to be at a distance of $r_I = 3$ AU. The ratio of the photon diffusion time out of the interaction region of a bullet to the flow time r_I/v_f does not depend on the opening angle of the jet and is given by (Akashi & Soker 2013)

$$\frac{\tau_{diff}}{t_f} = \frac{M_b \kappa}{4 r_I^2} \frac{v_b}{c}$$
$$\simeq 0.007 \left(\frac{M_b}{5 \times 10^{-5} \, M_\odot} \right) \left(\frac{v_b}{500 \text{ km s}^{-1}} \right) \left(\frac{r_I}{3 \text{ AU}} \right)^{-2}, \quad (1)$$

where $\kappa = 0.34$ is the opacity. This ratio implies that the bullets rapidly cool and maintain the narrow flow, unlike the wide jets simulated by Akashi & Soker (2013). The few bullets that can be formed along each of the four lobes can result from the stochastic nature of the launching process, or from interaction with the surrounding gas.

3. A TWIN-JET STRUCTURE IN NGC 1333 IRAS 4A2

The jets of the YSO IRAS 4A2 are presented in Figure 1. Although the properties of the jets are not exactly the same as those of CRL618, we here find similarities in the twin-jet structure.

Choi et al. (2011a) used the Very Large Array to observe the bipolar jets of IRAS 4A2 in the SiO $v = 0$ $J = 1 \rightarrow 0$

Table 1
The Angles of Each Component

Sub-jet	Component	θ	ϕ
I	Ia	12°.8	0°
I	Ib	11°.2	5°.0
II	IIc	4°.6	6°.5
II	IId	7°.1	7°.7

line. They investigated the kinematics of the two opposite SiO jets by placing slits perpendicular to the jets' axis; these were called cuts. The jets and the positions of the cuts (marked by numbers) are shown in Figure 1. Choi et al. (2011a) produced P–V diagrams for each cut, where they positioned the zero displacement of each cut at the emission peak according to Choi (2005). The P–V diagrams of the perpendicular slits are presented in Figure 2 here, taken from Figure 2 of Choi et al. (2011a), where the colored crosses are our addition which we discuss below.

The P–V diagram of each cut shows a multi-peak, three to four, structure, like the clear separated structures in cuts 10 and 11. The central peak of cut 8 is the brightest, and might be the overlap of two peaks.

We try to fit the peaks with twin-jets, where each twin-jet is composed of two "components." Here a twin-jet refers to both northern and southern parts. Namely, a twin-jet has two opposite parts relative to the central star. The same holds for a "component." We model each of the four components as a straight line of gas on the two opposite sides of the star, as drawn in Figure 1. The axis of each component is parameterized by two angles: the inclination relative to the plane of the sky, θ, and the angle on the plane of the sky relative to component Ia, ϕ. For $\theta > 0$, the northern part points away from us, i.e., redshifted. The values of θ and ϕ are given in Table 1. Based on Choi et al. (2006), we take all components to have the same radial expansion velocity of $v_j = 71$ km s^{-1}. We compute the P–V diagram of the four components and draw them as colored crosses on Figure 2, where the velocity and position are at the center of the cross. The crosses themselves represent our crude estimations of the errors in the derived values of θ and ϕ. From our trials of different fittings, we crudely estimate the errors to be of few degrees.

The four components (Ia, Ib, IIc, and IId) do not perfectly fit the observed P–V diagram as can be seen in Figure 2. First, there is a substantial interaction of the jets with the ambient gas. This is clearly evident from the sharp bend of the northern jet which occurs farther out (Choi et al. 2006; not seen here). Other regions also show some interaction with the surroundings, as is evident from the wiggling boundaries of the jets. Second, this interaction or jittering of the jets' source might cause random change in the expansion directions of the different components.

We note that we can substantially improve the fitting by displacing components Ia and Ib together in cut 8, and components IIc and IId in cut 9. The displacement is $\Delta\theta = -3°.7$, namely, redward in the southern jet, for components Ia and Ib in cut 8, and $\Delta\theta = 2°.0$, namely, blueward in the southern jet, for components Ic and Id in cut 9. The P–V diagram with these displacements is presented in Figure 3. The displacement in cut 8 explains why the peak there is as twice as high as in the other cuts. As the simultaneous displacement of components Ia and Ib accounts quite well for the P–V diagram in cut 8, we identify them as a single twin-jet I. We identify components IIc+IId as twin-jet II as well. The displacement in cuts 8 and 9 we apply here seems
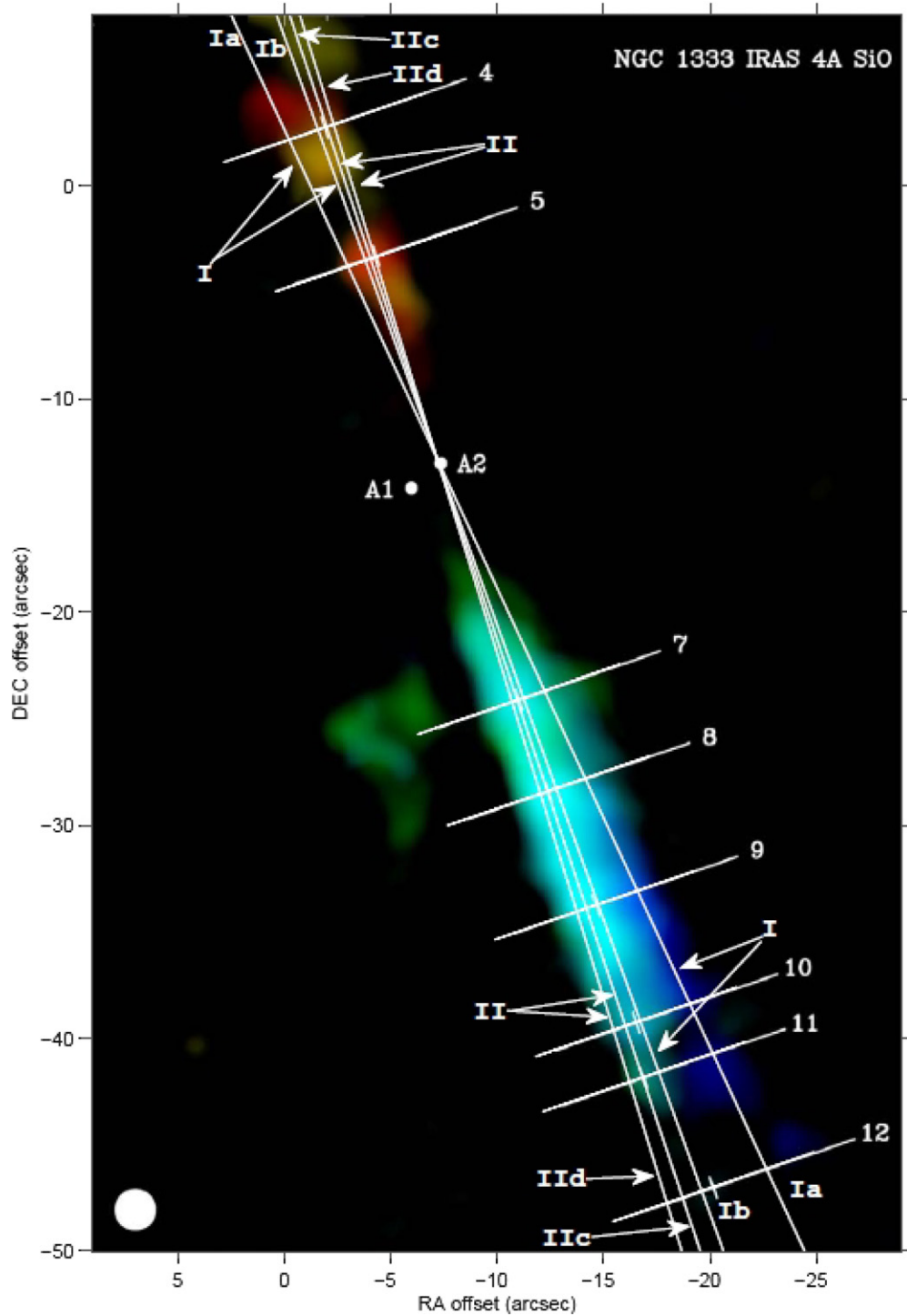
Figure 1. Color composite image of the NGC 1333 IRAS 4A2 bipolar jet in the SiO $v = 0$ $J = 1 \rightarrow 0$ line from Choi et al. (2011a). The white lines across the jets that are labeled by numbers, the "cuts" are from the original figure of Choi et al. (2011a), while the four lines along the two opposite jets are our addition. These four lines mark the two opposite twin-jets (I and II), each twin composed of two components (marked by letters).

(A color version of this figure is available in the online journal.)

ad hoc and speculative. But, noting that the angles between the east and west twin-jets of the PN CRL618 are different, this turns out to be a very plausible explanation.

Our main conclusions from the simple fitting, although not perfect, of the $P-V$ diagram of IRAS 4A2 are as follows.

1. The two opposite jets of IRAS 4A2 are actually composed of two bipolar twin-jets, reminding us of the narrow lobes in

CRL618. Each of the bipolar twin-jets, I and II, is composed of two components, Ia and Ib, and IIa and IIb, respectively.

2. We can make the fitting with two twin-jets that have the same radial velocity, and with a very small angle between them. These suggest a common launching site.

3. There is no sign of precession. The twin-jets and the two components composing each of them maintain an average constant direction. We note that Balick et al. (2013)
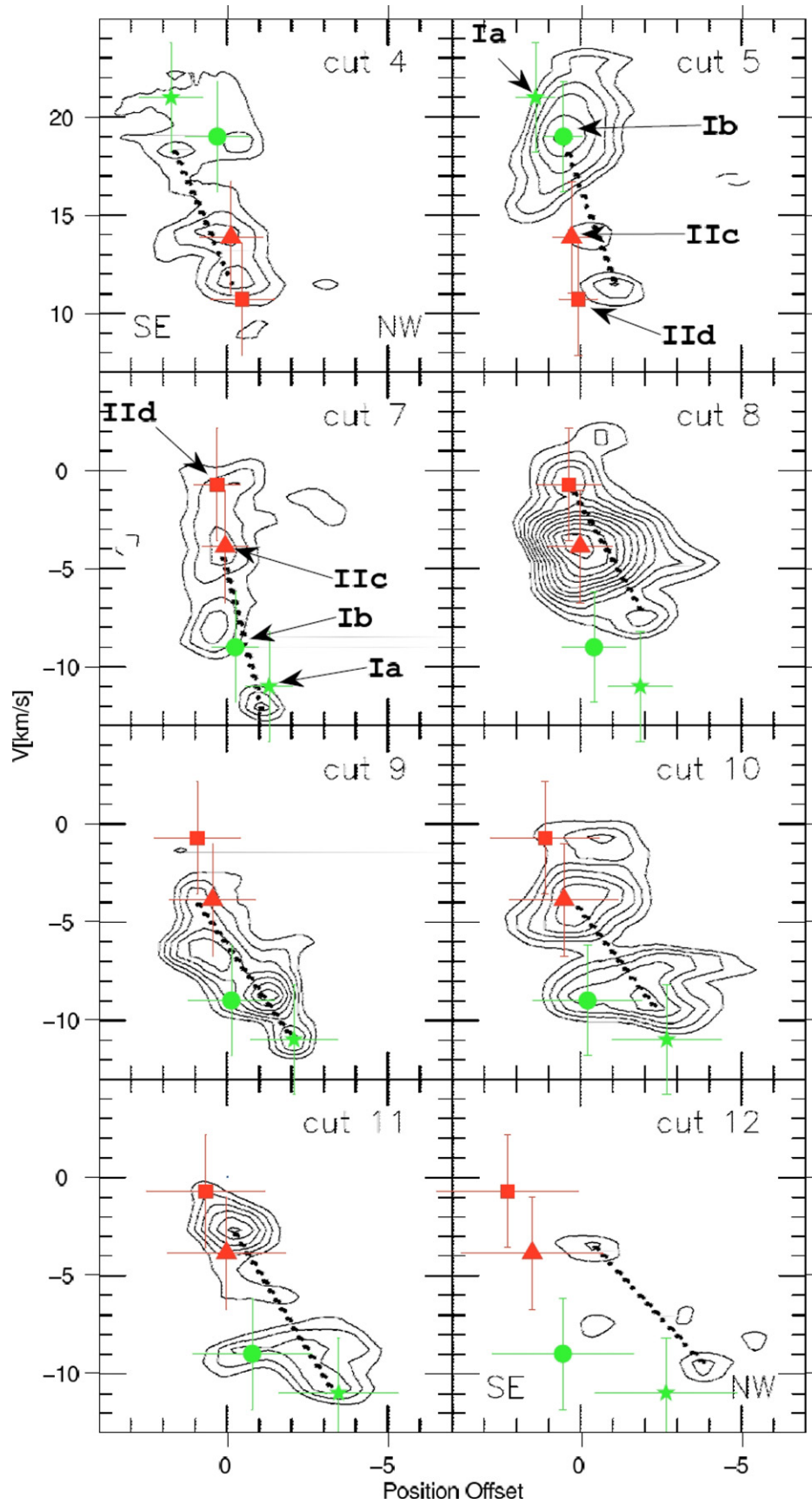
Figure 2. Position–velocity (P–V) diagrams from Choi et al. (2011a). The colored crosses are our addition. The center of each cross represents the Doppler shift and position of a twin-jet's component along the appropriate cut. Each of the four symbols of the crosses represents one component, as marked on two of the panels.

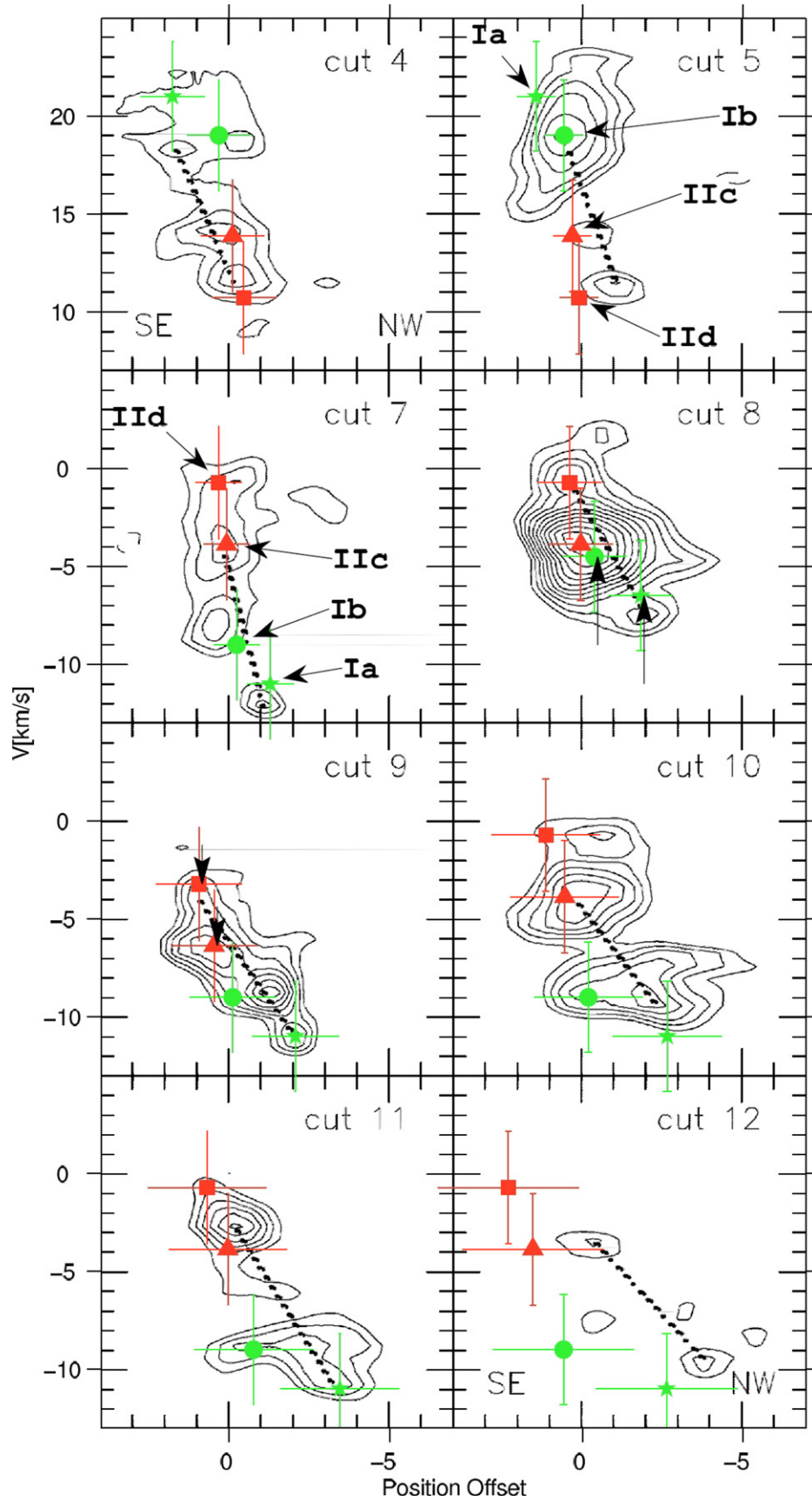(A color version of this figure is available in the online journal.)

Figure 3. Same as Figure 2, but with a displacement of twin-jet I in cut 8 and of twin-jet II in cut 9, as marked by the vertical black arrows.
(A color version of this figure is available in the online journal.)

conclude that "The fingers of CRL618 are straight and show no sign of a precessing or varying jet launcher."

4. The structure of the four components and two twin-jets exists on both sides of the star (north and south jets). This shows that the twin-jet structure does not result from a random collision and stochastic interaction with the surrounding gas.

5. The relatively large displacement of one twin-jet we identify in cuts 8 and 9, according to our interpretation, can result from either a change in the launching direction, as is suggested by the structure of the twin-jets in CRL618, or by interaction with the surrounding gas.

6. No extra component of jet rotation is required in our interpretation.

4. DISCUSSION AND SUMMARY

Our interpretation of the P–V diagram of IRAS 4A2 of two twin-jet structure requires that the launching process has a preferred direction that does not change with time, at least not for the time period span by the jets, of $\sim$500 yr for IRAS 4A2. This excludes the possibility that the preferred direction is the direction toward a companion in a circular orbit. For a slowly varying direction toward the companion, the orbital period must be thousands of years or more. Such a companion will be at a distance too large to influence the launching process of the jets.

However, if the orbit is eccentric, the semimajor axis of the orbit defines a preferred direction that can maintain a constant direction for a very long time. We proposed, therefore, that the launching process of the jets in IRAS 4A2 is substantially influenced by the presence of a companion on a highly eccentric orbit.

Ardila et al. (2005) present the interaction of a disk with a close binary star on a parabolic orbit. This passage creates two large-scale spiral arms in the disk ($m = 2$ mode). The spiral arms extend inward to a distance of $\sim$0.1r_p, where r_p is the periastron distance, and preserve a more or less constant direction for most of the time. The dense spiral arms' structure in the gas component of the disk lasts for a time of $\sim$0.5P_p, where P_p is the orbital period of a circular orbit of radius r_p. The two spiral arms can lead to the formation of the two sub-jets, i.e., twin-jets, which we identify in the outflow from IRAS 4A2. Spiral arms in the inner part of a Keplerian disk, but in the $m = 1$ mode and with no fix orientation, are also discussed for some models of supergiant Be binary star systems (e.g., Okazaki 1997).

We can estimate plausible parameters for the orbit in IRAS 4A2. Taking the IRAS 4A2 jets' velocity of 70 km s^{-1} to be the escape speed from their launching radius r_L, we find $r_L \simeq 6\,R_\odot$, where the mass of the primary star is $M_* = 0.08\,M_\odot$ (Choi et al. 2011b). Let the companion periastron be then at $r_p \simeq 3$–$10 r_L \simeq 20$–$60\,R_\odot$, and the apastron be at $\xi \gg 1$ times this distance. The orbital time of the binary system (assuming the companion to have a mass of $M_2 \ll M_1 = 0.08\,M_\odot$) is

$$P_{\rm orb} = 1.1 \left(\frac{M_*}{0.08\,M_\odot} \right)^{-1/2} \left(\frac{r_p}{50\,R_\odot} \right)^{3/2} \left(\frac{1+\xi}{4} \right)^{3/2} {\rm yr.} \quad (2)$$

Each jet's launching episode lasts for a few months. Over the jets' lifetimes of hundreds of years, the many launching episodes will be smeared to continuous jets. While the system is near apastron, the disk near the primary star can rebuild itself.

One prediction of the model we proposed is that a careful monitoring of IRAS 4A2 will reveal a periodic activity with a period time between few months and several years. Observations should be "lucky" enough to catch the system near a periastron passage when massive launching takes place. The companion is a brown dwarf or a massive planet.

We cannot elaborate on how the two spiral arms in the disk lead to the formation of two sub-jets. Simply, there is no agreed-upon model for the launching of jets that we can use to derive the process. As for the two components of each twin-jet (sub-jet; e.g., Ia and Ib of twin-jet I), numerical simulations of the gravitational interaction of the companion with the disk around the primary star should be carried out, probably in three dimensions. Such simulations can reveal the presence of higher harmonics in the accretion disk in addition to the spiral arms, as well as the development of instabilities. But again, the way the structure in the disk influences the jets' formation is a more complicated process.

Based on this interpretation, we also speculate that the central star of CRL618 has a main-sequence binary companion on an eccentric orbit. Lee et al. (2003) commented that the multipolar ejections at different directions in CRL618 are probably due to the presence of a binary companion. We go further and attribute the interaction to an eccentric orbit. The periastron distance is about the radius of an AGB star, such that high-rate mass transfer process could have taken place during the several weeks of the periastron passage. This event could have been classified as an ILOT event about a century ago. The orbital period can be from few years to tens of years (if the orbit is highly eccentric, as in η Carinae). In CRL618 it is the companion that launched the twin-jets after accreting the mass. In our scenario, the AGB star induced the double-arm spiral structure in the accretion disk that led to the formation of the twin-jets. A companion on an eccentric orbit can account also for the departure from axisymmetry of CRL618 (i.e., the two twin-jets are not exactly opposite to each other).

Balick et al. (2013) proposed that the several bullets on each side of CRL618 result from a spray of bullets formed from instabilities in a rapid mass ejection, such as in the process proposed by Blackman et al. (2001) and Matt et al. (2006). We note, however, that a model based only on instabilities will not explain a constant direction for each twin-jet over a long time, as is the case with IRAS 4A2 that has long-lasting jets. This is the reason we propose that the preferred direction determined by the two twin-jets is a result of a binary eccentric orbit.

REFERENCES

Acker, A., Boffin, H. M. J., Outters, N., et al. 2012, RMxAA, 48, 223
Akashi, M., & Soker, N. 2013, arXiv:1305.6264
Ardila, D. R., Lubow, S. H., Golimowski, D. A., et al. 2005, ApJ, 627, 986
Balick, B., & Frank, A. 2002, ARA&A, 40, 439
Balick, B., Huarte-Espinosa, M., Frank, A., et al. 2013, ApJ, 772, 20
Blackman, E. G., Frank, A., Markiel, J. A., Thomas, J. H., & Van Horn, H. M. 2001, Natur, 409, 485
Blackman, E. G., Frank, A., & Welch, C. 2001, ApJ, 546, 288
Boumis, P., & Meaburn, J. 2013, MNRAS, 430, 3397
Choi, M. 2005, ApJ, 630, 976
Choi, M., Hodapp, K. W., Hayashi, M., et al. 2006, ApJ, 646, 1050
Choi, M., Kang, M., & Tatematsu, K. 2011a, ApJL, 728, L34
Choi, M., Kang, M., Tatematsu, K., Lee, J.-E., & Park, G. 2011b, PASJ, 63, 1281
Cox, P., Huggins, P. J., Maillard, J.-P., et al. 2003, ApJL, 586, L87

Kastner, J. H., Weintraub, D. A., Gatley, I., & Henn, L. 2001, ApJ, 546, 279

Lee, C.-F., Hsu, M.-C., & Sahai, R. 2009, ApJ, 696, 1630

Lee, C.-F., & Sahai, R. 2003, ApJ, 586, 319

Lee, C.-F., & Sahai, R. 2004, in ASP Conf. Ser. 313, Asymmetrical Planetary Nebulae III: Winds, Structure and the Thunderbird, ed. M. Meixner, J. H. Kastner, B. Balick, & N. Soker (San Francisco, CA: ASP), 438

Lee, C.-F., Sahai, R., & Mundy, L. G. 2003, Rev. Mex. Astron. Astrofis. Ser. Conf., 15, 139

Lee, C.-F., Yang, C.-H., Sahai, R., & Sanchez Contreras, C. 2013, ApJ, 770, 153

Matt, S., Frank, A., & Blackman, E. G. 2006, ApJL, 647, L45

Nakashima, J.-i., Fong, D., Hasegawa, T., et al. 2007, AJ, 134, 2035

Okazaki, A. T. 1997, A&A, 318, 548

Sahai, R., & Nyman, L.-Å. 2000, ApJL, 538, L145

Sahai, R., & Trauger, J. T. 1998, AJ, 116, 1357

Sánchez Contreras, C., Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Sargent, A. 2004, ApJ, 617, 1142

Soker, N. 1990, AJ, 99, 1869

Soker, N., & Kashi, A. 2012, ApJ, 746, 100

Soker, N., & Livio, M. 1994, ApJ, 421, 219

Soker, N., & Rappaport, S. 2000, ApJ, 538, 241

Tafoya, D., Loinard, L., Fonfría, J. P., et al. 2013, arXiv:1306.2630

Trammell, S. R., & Goodrich, R. W. 2002, ApJ, 579, 688