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A REASSESSMENT OF THE KINEMATICS OF PV CEPHEI BASED ON ACCURATE PROPER MOTION MEASUREMENTS

L. Loinard,[1] L. F. Rodríguez,[1] L. Gómez,[2] J. Cantó,[3] A. C. Raga,[4] A. A. Goodman,[5] and H. G. Arce[6]

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RESUMEN

Presentamos dos observaciones de la estrella de pre-secuencia principal PV Cephei tomadas con el Very Large Array con una separación de 10.5 años. Estos datos implican que los movimientos propios de esta estrella son $\mu_\alpha \cos\delta = +10.9 \pm 3.0$ mas año^{-1}; $\mu_\delta = +0.2 \pm 1.8$ mas año^{-1}, muy similares a los ya conocidos para HD 200775, la estrella B2Ve que domina la iluminación de la cercana nebulosa de reflexión NGC 7023. Este resultado sugiere que PV Cephei no es una estrella desbocada con movimientos rápidos, como se había sugerido en anteriores estudios. La alta velocidad de PV Cep se había inferido de los desplazamientos sistemáticos hacia el este de los bisectores de pares sucesivos de objetos Herbig Haro a lo largo de su chorro. Estos desplazamientos sistemáticos podrían, en realidad, deberse a una asimetría en los mecanismos de eyección, o en la distribución del material circunestelar.

ABSTRACT

We present two Very Large Array observations of the pre-main-sequence star PV Cephei, taken with a separation of 10.5 years. These data show that the proper motions of this star are $\mu_\alpha \cos\delta = +10.9 \pm 3.0$ mas yr^{-1}; $\mu_\delta = +0.2 \pm 1.8$ mas yr^{-1}, very similar to those –previously known– of HD 200775, the B2Ve star that dominates the illumination of the nearby reflection nebula NGC 7023. This result suggests that PV Cephei is not a rapidly moving runaway star as suggested by previous studies. The large velocity of PV Cephei had been inferred from the systematic eastward displacement of the bisectors of successive pairs of Herbig Haro knots along its flow. These systematic shifts might instead result from an intrinsic asymmetry in the ejection mechanisms, or in the distribution of the circumstellar material.

Key Words: astrometry — ISM: individual (PV Cep) — ISM: jets and outflows — stars: pre-main sequence

1. INTRODUCTION

Compact stellar clusters as well as multiple stellar systems with three or more members can be dynamically unstable (e.g., Valtonen & Mikkola 1991; Poveda, Ruiz, & Allen 1967). Indeed, close few body encounters occurring within them can lead to the acceleration of one or more of the system members, which –if the acceleration is sufficient– can escape their birthplace and become runaway stars. It is important to search for direct observational evidence of these energetic events, because if they occurred with sufficient frequency during the earliest stages of star-formation, they could have a significant impact on the very outcome of the star-forming process (Reipurth 2000). Arguably the most promising case so far, is that of the BN/KL region in Orion where three stars (including BN itself) are moving away

[1]Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Morelia, Mexico.

[2]Max-Planck-Institut für Radioastronomie, Bonn, Germany (Member of the International Max Planck Research School for Astronomy and Astrophysics at the Universities of Bonn and Cologne).

[3]Instituto de Astronomía, Universidad Nacional Autónoma de México, Mexico.

[4]Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico.

[5]Harvard-Smithsonian Center for Astrophysics, Cambridge, USA.

[6]Yale University, New Haven, USA.

TABLE 1

CHARACTERISTICS OF PV CEP

Spectral type	A5
R-band magnitude	$R = 11.1$
Distance	$d = 430^{+155}_{-91}$ pc
Mean position (Equinox J2000,	$\alpha = 20^h45^m53\overset{s}{.}9550 \pm 0\overset{s}{.}0014$
Epoch 2002.26)	$\delta = 67°57'38\overset{''}{.}681 \pm 0\overset{''}{.}008$

at about 30 km s^{-1} from a common point of origin, which happens to be near the center of the massive KL outflow (Rodríguez et al. 2005; Gómez et al. 2005, 2008; Zapata et al. 2009). The dynamical disruption in that case, appears to have occurred a mere 500 years ago.

Goodman & Arce (2004, hereafter GA2004) have suggested that the star PV Cephei (hereafter PV Cep) might be another potential candidate. PV Cep (Table 1) is a Herbig Ae/Be star (Li et al. 1994) that drives a well-studied giant Herbig Haro (HH) flow (Reipurth, Bally, & Devine 1997; Gómez, Whitney, & Kenyon 1997; Arce & Goodman 2002a,b; GA2004). It is located about 1$\overset{\circ}{.}$5 west of the reflection nebula NGC 7023, and the centroid velocity of its CO emission is similar to that of the CO emission from NGC 7023 itself (Cohen et al. 1981). Because of this shared kinematics, it is very likely that PV Cep and NGC 7023 are at the same distance from the Sun. The measured trigonometric parallax of HD 200775 (MWC 361, $V = 7.4$ mag) the B2Ve star that dominates the illumination of NGC 7023 (Herbig 1960) yields a distance for the entire region of 430^{+155}_{-91} pc (Perryman et al. 1997). This value is consistent with the somewhat older estimate of 500 pc used by GA2004. NGC 7023 is associated with a compact cluster of young stars that contains a number of low luminosity pre-main-sequence objects (Lepine & Rieu 1974).

The suggestion by GA2004 that PV Cep might be a runaway star was based on a careful analysis of the kinematics and morphology of the gas surrounding PV Cep. The strongest argument follows from a study of the distribution of successive pairs of HH knots located at nearly equal distances from PV Cep along its jet. The segments joining such successive pairs of knots are expected to pass through the source driving the flow — if the latter is stationary. In the case of PV Cep, however, GA2004 found that the bisectors of the segments were systematically shifted eastward of the source, and increasingly more so, as older HH pairs were considered. This suggests that the source used to be somewhat to the east of its current position, and thus, that it is moving westward relative to its surroundings. Assuming that the HH knots along the flow are fully detached clumps, GA2004 estimated the velocity of the central source to be 22 km s^{-1} (see discussion in § 2). Most remarkably, the velocity vector obtained by GA2004 points almost exactly *away* from NGC 7023, as if PV Cep had been ejected from NGC 7023 about 10^5 yr ago (see their Figure 6). Thus, PV Cep might indeed provide us with an example of a runaway star dynamically ejected from its (still identifiable) parent cluster. Note, however, that the conclusions of GA2004 were based on an analysis of the kinematics and morphology of the gas surrounding PV Cep, and *not* on a direct measurement of the relative proper motion between PV Cep and NGC 7023. In the present paper (§§ 3 and 4), we will provide such a direct measurement, combining published optical proper motions of the brightest star in NGC 7023 and new radio measurements of the proper motion of PV Cep itself.

2. A RE-ANALYSIS OF THE BISECTOR RESULTS

Several theoretical models (both analytic and numerical) have been proposed to explain the curved morphology presented by some HH jets. Cantó & Raga (1995) have developed an analytical model that treats the problem of a *steady* jet interacting with a sidewind. More recently, Masciadri & Raga (2001) presented numerical simulations of a *variable* jet in a sidewind and identified two different regimes. For low-amplitude variability (caused by moderate changes in the jet ejection velocity), small working surfaces (i.e., HH knots) are created along the jet, and they travel following the path predicted by the steady jet model of Cantó & Raga (1995). On the other hand, large working surfaces created by larger changes in the jet ejection velocity eventually become detached "clumps" that travel on somewhat straighter trajectories.

2.1. *Analytic solution for fully detached clumps*

In their analysis of the bisectors of successive HH pairs, GA2004 assumed that the ejecta had become detached clumps, and integrated the equations of motion numerically to obtain the trajectory of the clumps. Recently, however, Cantó et al. (2008) showed that the idealized case of fully detached clumps has a completely analytic solution, which produces trajectories similar to those obtained in numerical simulation. To examine that analytic solution in the case of PV Cep, we assume (following GA2004) that PV Cep is moving relative to the ambient gas in a direction exactly perpendicular to that of its jet. The velocity of the star relative to the surroundings is taken to be v_*, and individual clumps of mass M are ejected at a velocity v_e (see Figure 1a for a schematic description). The trajectory is parametrized by a distance s_0 (Cantó et al. 2008) given by:

$$s_0 \equiv \frac{3}{4}\left(\frac{M v_0^4}{\xi \rho_0 c^4}\right)^{1/3} . \tag{1}$$

Here, ξ is a constant of integration whose numerical value is $\xi = 14$ (Cantó et al. 2008), c is the isothermal sound speed of the clump material, and ρ_0 is the density of the ambient gas. In the present case, where v_* and v_e are perpendicular, v_0 is simply

$$v_0 = \sqrt{v_*^2 + v_e^2} . \tag{2}$$

If one further defines the angle θ as

$$\tan\theta = \frac{v_e}{v_*} , \tag{3}$$

the equation of the trajectory is given analytically by:

$$x = \frac{y}{\tan\theta} - 4 s_0 \left(\frac{v_*}{v_0}\right)\left[1 - \left(1 - \frac{y}{s_0 \sin\theta}\right)^{1/4}\right] . \tag{4}$$

Following GA2004, we adopt $v_e = 350$ km s^{-1} and $\rho_0 = 1.5 \times 10^3$ cm^{-3}. A good fit to the data points (shown in Figure 1a) is obtained for $v_* = 22$ km s^{-1}, provided that $s_0 \approx 6.4 \times 10^{18}$ cm. This, in turn, implies $M \approx 2 \times 10^{-4}\ M_\odot$ if the value for c is taken to be 3.2 km s^{-1} as suggested by GA2004. A comparison between the analytic trajectory obtained using these parameters and the path obtained numerically by GA2004 (see their Figure 2) shows that the analytical and numerical trajectories agree extremely well.

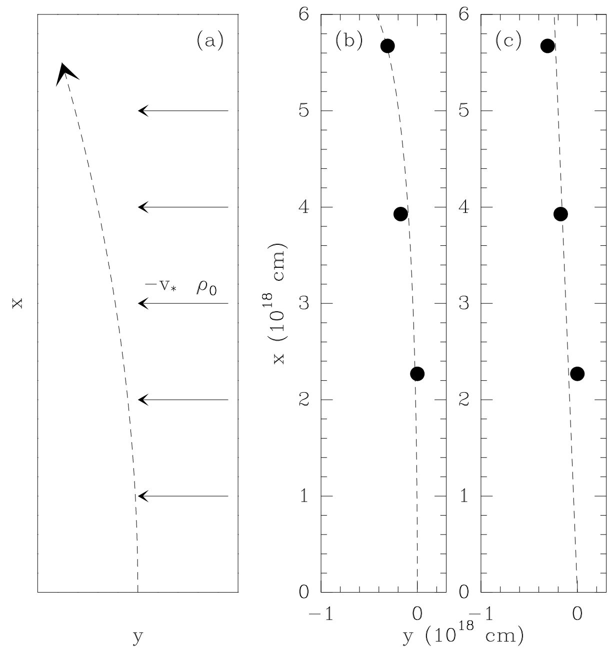

Fig. 1. (a) Schematic diagram of a star which ejects a bipolar outflow along the positive x-axis, in a direction perpendicular to the motion of the star with respect to the surrounding environment. In the frame of reference of the star, the environment moves towards the left along the y-axis, producing a curvature in the bipolar outflow system. (b) and (c) The black filled circles show the positions of the ejecta relative to the source according to the results of GA2004, and the dashed lines represent the best fit for fully detached clumps [Panel (b); see § 2.1] and for a continuous jet [Panel (c); see § 2.2].

It should be mentioned that c in equation (1) is the isothermal sound speed *of the ejecta*. Such ejecta are believed to be ionized, so the appropriate sound speed is $c \approx 10$ km s^{-1}. In their analysis, however, GA2004 used $c = 3.2$ km s^{-1}, the typical velocity dispersion of the *ambient* molecular gas. From equation (1), it is clear that to obtain a similar value of s_0 for $c = 10$ km s^{-1} without resorting to unreasonable assumptions for ρ_0 and v_0, one has to increase the mass of the ejecta by nearly two orders of magnitude, to about $1.5 \times 10^{-2}\ M_\odot$. Even if one allows v_e to increase to 400 km s^{-1} and ρ_0 to decrease to 1000 cm^{-3}, the ejecta must still have masses of order $10^{-2}\ M_\odot$. Moreover, the transverse velocity of the star must then be increased to about 40 km s^{-1} to obtain a good fit. We conclude that if the ejecta from PV Cep are indeed fully detached clumps of ionized gas, they must be very massive[7], and the velocity

[7]As a consequence, in this scenario, PV Cep must have undergone episodes of extremely high accretion/ejection.

of PV Cep might be even larger that the 22 km s^{-1} proposed by GA2004.

2.2. *The HH knots of PV Cep as part of an underlying continuous jet*

The trajectories considered in § 2.1 appropriately describe jets in which large amplitude perturbations leading to fully detached clumps have developed. As mentioned earlier, lower amplitude perturbations create HH knots that travel along different paths: those predicted by the analytical model of Cantó & Raga (1995). Moreover, the analysis of Masciadri & Raga (2001) shows that a smaller sidewind velocity is necessary to create a given jet curvature if the HH knots are such small perturbations along an underlying continuous jet than if they are fully detached clumps. Well-defined HH knots suggestive of detached clumps are certainly present along the jet driven by PV Cep (GA2004, and references therein). There is also evidence, however, for an underlying continuous jet which is always "on". Indeed, the very existence of steady, compact centimeter radio emission associated with PV Cep (which traces free-free emission from the base of an ionized flow; see § 3 below) demonstrates that such a continuous jet exists and that the ejection of matter is not fully episodic. The detection of water masers (Marvel 2005) and of high velocity entrained molecular gas (Arce & Goodman 2002b) in the immediate vicinity of PV Cep confirm the existence of such a steady jet. Let us, therefore, estimate the sidewind velocity that would be required to explain the bisector results of GA2004 in a steady wind scenario. The applicability of this model to the specific case of PV Cep will be discussed in § 5.

As shown by Cantó & Raga (1995), in the vicinity of the source, a bipolar flow in a sidewind approximately follows a parabolical shape[8] (with both the jet and the counterjet on the same parabola) described by

$$y = \frac{x^2}{2\lambda}\,, \tag{5}$$

where x is parallel to the initial outflow direction, and y is the coordinate perpendicular to x and parallel to the motion of the source (Figure 1a). This relation is valid for the case in which the motion of the source is perpendicular to the ejection. The distance λ in equation (5) is given by

$$\lambda \equiv \left(\frac{\dot{M} v_e^3}{\pi c^2 \rho_0 v_*^2}\right)^{1/2} = 7.8 \times 10^{18}\ \mathrm{cm}$$
$$\times \left(\frac{\dot{M}}{10^{-7}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{1/2} \left(\frac{v_e}{100\ \mathrm{km\,s^{-1}}}\right)^{3/2}$$
$$\times \left(\frac{\rho_0}{10^3\ \mathrm{cm}^{-3}}\right)^{-1/2} \left(\frac{v_*}{1\ \mathrm{km\,s^{-1}}}\right)^{-1}, \tag{6}$$

where $\dot{M}$ is the mass-loss rate, and the other parameters have the same meaning as before. The best fit to the observed positions reported by GA2004 using equation (5) yields $\lambda = 4.64 \times 10^{19}$ cm. With this value, we can now use equation (6) to determine the required velocity for the environment:

$$\left(\frac{v_*}{1\,\mathrm{km\,s^{-1}}}\right) = 0.17 \left(\frac{\dot{M}}{10^{-7}\ \mathrm{M_\odot yr^{-1}}}\right)^{1/2}$$
$$\times \left(\frac{v_e}{100\ \mathrm{km\,s^{-1}}}\right)^{3/2} \left(\frac{\rho_0}{10^3\ \mathrm{cm}^{-3}}\right)^{-1/2}. \tag{7}$$

Finally, using the values $v_e = 350$ km s^{-1} and $\rho_0 = 1500$ cm^{-3} determined by GA2004, we obtain $v_* = 0.9$ km s^{-1}, assuming a mass loss rate $\dot{M} = 10^{-7}$ $M_\odot$ yr^{-1}. The corresponding trajectory is shown in Figure 1c.

Thus, a very modest relative motion –of the order of the typical stellar velocity dispersion in newborn stellar clusters– between PV Cep and its surroundings would be required to explain the bisector results of GA2004 in the case of a continuous jet. We will return to this point in § 5.

3. OBSERVATIONS

In this paper, we will make use of 3.6 cm continuum observations obtained on 1997 January 10 and 2007 July 2 with the Very Large Array (VLA) of the NRAO[9] in its most extended (A) configuration. This combination of wavelength and configuration provides an angular resolution of about 0.″3 for images with natural weighting. The absolute amplitude calibrator was 1331+305 (with an adopted flux density of 5.20 Jy at 8.4 GHz) and the phase calibrator was 2022+616, with bootstrapped flux densities of 3.36 ± 0.03 Jy and 3.07 ± 0.02 Jy, for the first and second epochs, respectively. For the first epoch only 14 of the 27 antennas of the VLA were used, with an

[8]Farther out, the jet moves on nearly straight trajectories aligned with the direction of the side wind (Cantó & Raga 1995). Since the knots in PV Cep are clearly not moving perpendicularly to the direction of the jet (GA2004), the portion of the jet considered here can be assumed to be parabolic.

[9]The National Radio Astronomy Observatory is operated by Associated Universities Inc. under cooperative agreement with the National Science Foundation.

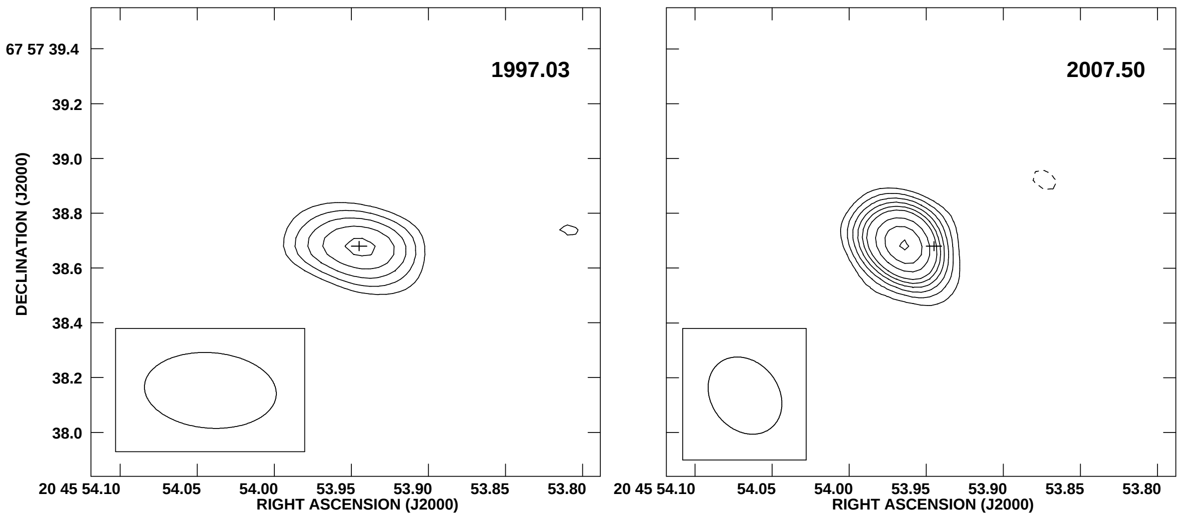

Fig. 2. VLA 3.6 cm images of PV Cep for 1997.03 (left) and 2007.50 (right). The contours are −3, 3, 4, 5, 6, 7, 8, 10, 12 and 14 times 19 and 12 μJy beam^{-1}, the rms noise of the first and second epochs, respectively. The cross marks the position and positional error at the 1997.03 epoch. The half-power synthesized beam for each epoch ($0\farcs48 \times 0\farcs28$; PA = +86° for 1997.03 and $0\farcs30 \times 0\farcs24$; PA = +39° for 2007.50) is shown in the bottom left corner of the images.

on-source integration time of 4.2 hours. For the second epoch we used 23 of the 27 antennas of the VLA, with an on-source integration time of 3.2 hours. The data were edited and calibrated using the Astronomical Image Processing System (AIPS) software package (Greisen 2003).

To ensure accurate astrometry, the position of the calibrator 2022+616 for the 1997 observations was updated to the refined position given in the VLA catalog of calibrators for 2007. The continuum images shown in Figure 2 were used to measure the positions and flux densities of PV Cep for the two epochs (Table 2). The source appears to be unresolved at both epochs, and the emission is most probably free-free radiation from ionized gas at the base of the outflow driven by PV Cep (i.e., Eislöffel et al. 2000). The small variation in flux density between the two epochs is common for this type of sources (e.g., Galván-Madrid, Ávila, & Rodríguez 2004), and most likely reflects moderate variability either of the mass-loss rate or of the velocity of the wind.

As can be seen in Figure 2 and Table 2, the source shows a small displacement ($\sim 0\farcs11$ toward the east. The proper motions of the source measured over the 10.47 year time baseline of the observations are $\mu_\alpha \cos\delta = +10.9 \pm 3.0$ mas yr^{-1}; $\mu_\delta = +0.2 \pm 1.8$ mas yr^{-1}. The base of the jet driven by PV Cep (as traced by the radio emission) is expected to follow closely the motion of the star itself, because the emission is largely dominated by the highest density gas in the wind, which is located very close to the star since the gas density typically falls as $n(r) \propto r^{-2}$. The high accuracy with which VLA observations of free-free emission from young stars can trace the stellar motions themselves can be seen, for instance, from the multi-epoch observations of IRAS 16293-2422 (Loinard et al. 2007; Pech et al. 2010) or of T Tau N (Loinard, Rodríguez, & Rodríguez 2003). Thus, the proper motions measured here can safely be assumed to represent the motion of PV Cep.

4. RESULTS

To test the proposal of GA2004 that PV Cep might be moving at $\sim$ 22 km s^{-1} away from NGC 7023, one must compare the proper motion of PV Cep derived above with the proper motion of stars within NGC 7023. The only star of NGC 7023 (and indeed, the only star within a few degrees of PV Cep) for which we found reliable published proper motions is HD 200775, the bright star responsible for most of the illumination of NGC 7023 (see § 1). Since it is the brightest member of the cluster, HD 200775 is likely to be very near its center of mass, and its proper motion should provide a good estimate of the proper motion of the entire cluster. The most recent reported proper motion for HD 200775 can be found in Ducourant et al. (2005)[10]; they give $\mu_\alpha \cos\delta = +11 \pm 2$ mas yr^{-1};

[10]Indeed, Ducourant et al. (2005) also report proper motions for PV Cep. However, their values of $\mu_\alpha \cos\delta$ =

TABLE 2

POSITIONS AND FLUX DENSITIES FOR PV CEP

Epoch	Position α(J2000)	Position δ(J2000)	3.6 cm Flux Density (mJy)
1997.03	$20^h45^m53\overset{s}{.}9449 \pm 0\overset{s}{.}0051$	$67°57'38\overset{''}{.}680 \pm 0\overset{''}{.}017$	0.14 ± 0.02
2007.50	$20^h45^m53\overset{s}{.}9651 \pm 0\overset{s}{.}0014$	$67°57'38\overset{''}{.}682 \pm 0\overset{''}{.}008$	0.18 ± 0.01

$\mu_\delta = +2 \pm 2$ mas yr^{-1}. HD 200775 is also contained in the Hipparcos catalog, where the reported proper motions are $\mu_\alpha \cos\delta = +6.74 \pm 0.64$ mas yr^{-1}; $\mu_\delta = -1.48 \pm 0.54$ mas yr^{-1}. These two values are consistent with one another at the 1.5σ level.

The relative motion between PV Cep and NGC 7023 (obtained by subtracting the proper motion of PV Cep measured above from that of NGC 7023) is

$$\Delta(\mu_\alpha \cos\delta) = +0.1 \pm 3.6 \text{ mas yr}^{-1}\,,$$
$$\Delta(\mu_\delta) = +1.8 \pm 2.7 \text{ mas yr}^{-1}\,,$$

if the values quoted by Ducourant et al. (2005) are used. Using the Hipparcos figures, we obtain:

$$\Delta(\mu_\alpha \cos\delta) = -4.2 \pm 3.1 \text{ mas yr}^{-1}\,,$$
$$\Delta(\mu_\delta) = -1.7 \pm 1.9 \text{ mas yr}^{-1}\,.$$

Recall that GA2004 predicted a relative velocity of 22 km s^{-1} toward the west, corresponding to a relative proper motion (almost entirely in right ascension) of $\Delta(\mu_\alpha \cos\delta) = +9.3$ mas yr^{-1}. The observed values are inconsistent at the 3σ level with this prediction,[11] and show that PV Cep is in fact very nearly stationary relative to NGC 7023 both in right ascension and declination. If anything, the Hipparcos value suggests a marginal motion of PV Cep *toward* NGC 7023. We conclude that PV Cep is very unlikely to have been ejected from NGC 7023 about 10^5 yr ago.

Strictly speaking, the analysis of GA2004 does not require PV Cep to be moving away from NGC 7023 at 22 km s^{-1}. It only requires PV Cep to be moving at that speed relative to its surrounding gas. The morphology of the jet driven by PV Cep could still be explained by the model proposed by GA2004 if the gas cloud in which PV Cep is embedded were moving at 22 km s^{-1} *toward the east* relative to both PV Cep and NGC 7023. We consider this possibility very unlikely, however, because (i) as mentioned in § 1, the radial velocities of the gas associated with NGC 7023 and with PV Cep are very similar, and (ii) it is not clear what physical mechanism could accelerate an entire molecular cloud to 22 km s^{-1}, particularly without also accelerating the stars that formed within it.

5. DISCUSSION

Given that a relative velocity of 22 km s^{-1} between PV Cep and its surroundings appears to be inconsistent with the present observations, one must seek a different interpretation of the systematic eastward shift of the bisectors of successive HH pairs along the flow driven by PV Cep. One obvious alternative possibility is provided by the continuous jet model presented in § 2.2. In that scenario, a relative velocity between PV Cep and NGC 7023 of a few km s^{-1} would be sufficient to explain the bisector data, and such a small relative velocity would be fully consistent with the astrometry presented in § 3. We note, indeed, that continuous jet models have been used to explain the curved morphologies of other young stellar flows. Of particular relevance is the case of the jet driven by HH 30 (López et al. 1995) whose curved shape was interpreted by Cantó & Raga (1995) in terms of such a continuous flow in a sidewind.

It is important to note, however, that the flow driven by PV Cep does show clear signs of strong variability (GA2004, and references therein). A steady jet is clearly present in the system, but the knots considered by GA2004 in their bisector analysis have likely been created during episodes of significantly increased mass-loss.[12] To completely describe that situation, one should consider a steady, low-level (i.e., moderate mass-loss rate) underlying jet, periodically undergoing episodes of enhanced mass-loss. This is a case intermediate between the two

-3 ± 7 mas yr^{-1}; $\mu_\delta = -14 \pm 7$ mas yr^{-1} have significantly larger errors than our measurements.

[11] They are, of course, even more inconsistent with the relative velocity of 40 km s^{-1} obtained in the detached clump scenario assuming a sound speed of 10 km s^{-1} (see § 2.1).

[12] Note that the flow in HH 30 appears overall more continuous than that in PV Cep, and does lend itself more naturally to a treatment based on the hypothesis of a steady jet.

idealized descriptions provided in § 2, so numerical simulations would in principle be needed to treat it in general. However, since the periodic mass-loss enhancements undergone by PV Cep seem particularly strong, the correct description for that specific source is almost certainly more similar to the case of detached bullets than to that of a continuous jet. In this situation, a relative velocity between PV Cep and its surroundings of at least 20 km s^{-1} would be needed to explain the bisector results of GA2004, and that appears to be inconsistent with our new measurements.

Another alternative interpretation of the bisector results of GA2004 would be to invoke asymmetries. The basic assumption behind the argumentation of GA2004 is that pairs of clumps ejected from a stationary star propagate symmetrically away from it, in such a way that the bisectors of such ejecta pairs intercept the driving source. This assumption would be violated, however, if the ejecta on the two sides of the star moved away at different speeds and/or not exactly in opposite directions, either because of an intrinsic asymmetry in the jet launching mechanism or because of an asymmetry in the density of the circumstellar material. Several jets (e.g., HH 1–2, Cepheus A, or HH 80; Rodríguez et al. 2000; Martí, Rodríguez, & Reipurth 1998; Curiel et al. 2006) are known to exhibit this kind of asymmetries. Arguably the clearest case is that of the very young low-mass protostar IRAS 16293-2422 (Pech et al. 2010). In this object, a bipolar pair of clumps has been ejected just a few years ago, and each clump has now moved (in projection) about 60 AU away from the central source. Multi-epoch radio observations have shown that the projected speed of the southern clump is two to three times larger than that of the northern clump and that –in at least one of the observations– the line joining the ejecta does not pass through the position of the driving source (Pech et al. 2010, particularly their Figure 2). In addition, the large-scale molecular outflow powered by that jet system is known to be highly asymmetric (e.g., Castets et al. 2001; Hirano et al. 2001), the northern lobe being much more conspicuous, massive, and extended that its southern equivalent. Interestingly, the molecular outflow in PV Cep happens to be equally asymmetric (e.g., Arce & Goodman 2002a) with a northern lobe about 2.5 times more massive and 1.5 times more extended than its southern counterpart. Could an asymmetry similar to that in IRAS 16293-2422 be at the origin of the PV Cep bisector results of GA2004?

Three pairs of HH groups have been identified along the jet driven by PV Cep: HH 315 A, B, and C towards the north-west, and HH 315 D, E, and F toward the south-east (e.g., Gómez et al. 1997, see Figure 3). They are believed to have been created during three episodes of enhanced accretion/ejection (Gómez et al. 1997; GA2004; Arce & Goodman 2002a). Moreover, these HH groups are not distributed along a straight line, but along an S-shaped structure, clearly resulting from precession in the underlying jet (Figure 3). A simple precessing jet model that reasonably accounts for that structure has been proposed by Gómez et al. (1997) and is reproduced in Figure 3a. This model (e.g., Hjellming & Johnston 1981) assumes that the jet axis precesses on the surface of a cone of opening angle θ, inclined by an angle i from the line of sight. The jet has constant ejection velocity v_e and precession velocity ω, and the position angle of the precession axis is ϕ. The black line on Figure 3a corresponds to $\theta = 22.5°$, $i = 80°$, $\omega = 1.5$ arcmin yr^{-1}, $v = 180$ km s^{-1}, and $\phi = -36.5°$ (Gómez et al. 1997). As discussed by Gómez et al. (1997), this model shows that successive episodes of enhanced mass-loss occurred in PV Cep roughly every 2000 years.

An asymmetry in the distribution of the HH groups is immediately apparent in Figure 3a. For instance, while the C-F pair is expected to have been created during the same enhanced mass-loss episode, the symmetric model shown in Figure 3a would ascribe to them ages differing by about 1000 yr. A similar situation occurs for the B-E pair. Of course, this age inconsistency is simply a different way of re-expressing the bisector conclusions of GA2004. Because of the asymmetry in the distribution of the HH groups, the segments joining C to F and B to E do not pass through the current position of the driving source. The situation can be significantly improved by relaxing slightly the symmetry of the jet. As an example, we show in Figure 3b a model identical to that of Gómez et al. (1997) for the northern part of the flow, but slightly different for the southern counterpart. Specifically, the velocity of the southern jet is 10% larger than that of the northern jet, and the southern half of the jet precesses around an axis misaligned by 10° relative to the symmetry axis of the northern jet. Such a model represents a somewhat better fit to the positions of the southern HH groups, and ascribes the same age to the B and E groups (4900 yr) and to the C and F groups (6900 yr). Moreover, the bisector of segments joining pairs of same-age positions on either sides of the jet are progressively displaced towards the east as larger ages are considered. In particular, the bisectors at ages 4900 yr and 6900 yr are very nearly coincident

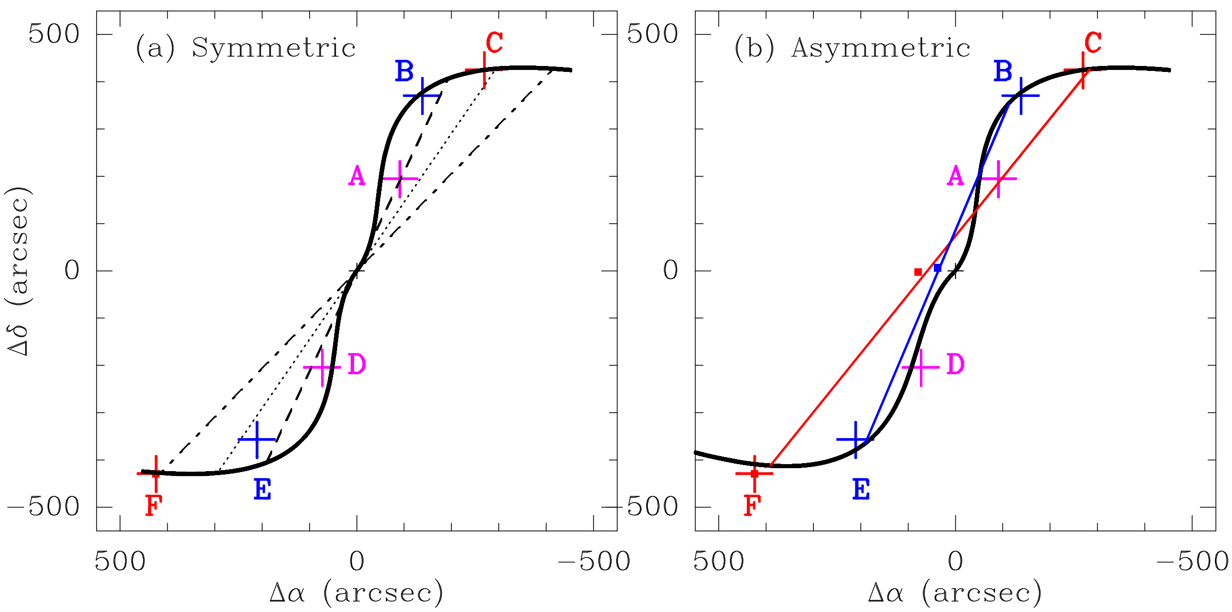

Fig. 3. Distribution of groups of HH knots around PV Cep. The three groups towards the north-west are labelled A, B, and C, and the three groups toward the south-east are D, E, and F. The positions are taken from Gómez et al. (1997). (a) Model based on a symmetric precessing jet following Gómez et al. (1997) with the parameters given in the text (solid black line). Lines joining the expected positions along the jet at times 6000, 7000, and 8000 yr are shown. (b) Model based on an asymmetric precessing jet with the parameters given in the text (solid black line). Lines joining the expected positions along the jet at 4900 and 6900 yr are shown. They intercept the positions of the bisectors of the B-E and C-F pairs (shown as blue and red squares).

with the measured bisectors of the B-E and C-F pairs (Figure 3b).

The model shown in Figure 3b certainly represents an oversimplification of the true structure of the jet in PV Cep, and is clearly not unique. It does demonstrate, however, that a slightly asymmetric jet can provide a better description of the structure of the flow than a symmetric one, and could readily explain the bisector results of GA2004 with no need for a large stellar velocity. It would be interesting to investigate more realistic numerical models of bipolar jets encountering asymmetric surroundings. In particular, it would be useful to know in what domain of the parameter space they can produce bisector results similar to those found in PV Cep by GA2004.

It is worth mentioning that the gas immediately south of PV Cep appears to be significantly denser than the gas immediately north of it (Arce & Goodman 2002a,b). Thus, one might expect the southern lobe to be slower than the northern lobe and not the other way around, as our asymmetric model would suggest. The distribution of the gas surrounding PV Cep, however, is likely to be quite asymmetric. For instance, knot C (to the north) is known to entrain a massive molecular gas shell, whereas no entrained gas is associated with its southern counterpart knot F (Arce & Goodman 2002a,b). This suggests that, on large scales, the density of molecular material north of PV Cep might be higher that south of it. This is reversed compared to the density distribution in the immediate surroundings of PV Cep.

In addition to their bisector results, GA2004 mention two pieces of evidence supporting the idea that PV Cep might be a runaway star. The first one is the existence of a tail of red-shifted gas located to the east of PV Cep. The second is the wiggling of the southern jet seen at small scales. These two effects have not been reported in other outflow systems, and it is unclear if they have a direct relation to the asymmetry of the jet in PV Cep. It certainly would be worthwhile to search for these effects in other outflow systems (symmetric or not) and to investigate numerically in what kind of situation they would tend to develop.

6. CONCLUSIONS

Comparing two VLA observations separated by 10.5 years, we have measured the proper motion of the young star PV Cep. This measurement shows that PV Cep is essentially stationary with respect to its surroundings, and is not a fast-moving runaway star, as suggested by GA2004. The jet morphological characteristics that led GA2004 to conclude that PV Cep might be a runaway star might instead result from an asymmetry in the jet itself. GA2004 had built a case against PV Cep reflected in the title of their paper: "PV Cephei: young star caught speeding?" Given the new evidence presented here, that accusation is now under question.

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Laurent Loinard and Luis F. Rodríguez: Centro de Radiostronomía y Astrofísica, Universidad Nacional Autónoma de México, Apdo. Postal 3-72 (Xangari), 58089 Morelia, Michoacán, Mexico (l.loinard, l.rodriguez@crya.unam.mx).
Laura Gómez: Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany (lgomez@mpifr.de).
Jorge Cantó: Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 70-264, 04510 México, D. F., Mexico.
Alejandro C. Raga: Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Apdo. Postal 70-543, 04510 México, D. F., Mexico (raga@nucleares.unam.mx).
Alyssa A. Goodman: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA (agoodman@cfa.harvard.edu).
Hector G. Arce: Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520, USA (hector.arce@yale.edu).