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A ONE-SIDED KNOT EJECTION AT THE CORE OF THE HH 111 OUTFLOW

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RESUMEN

Presentamos un estudio astrométrico de la radiofuente VLA 1 de la cual se origina el flujo HH 111 usando nuevos datos (2007) así como también observaciones de archivo (1992–1996). Todos los datos fueron tomados en 3.6 cm con el Very Large Array en su configuración más extendida (A). La fuente VLA 1 ha tenido un cambio dramático, mostrando una eyección monopolar en la época de 2007. También reportamos la detección de una fuente de continuo compacta (VLA 3) localizada a $(-10\farcs6, 98\farcs7)$ de VLA 1. No se encontraron movimientos propios significativos en VLA 1 ni en VLA 3 y los límites superiores son consistentes con los encontrados para radiofuentes (embebidas) en la Nebulosa de Orión. Favorecemos la interpretación de que en 3.6 cm estamos observando dos chorros casi perpendiculares. HH 111 representa un nuevo caso de eyecciones monopolares en un objeto joven estelar. No se pudo establecer si VLA 3 es galáctica (o extragaláctica).

ABSTRACT

We present an astrometry study of the radio source VLA 1 at the core of the HH 111 outflow using new data (2007) as well as archival observations (1992–1996). All data were taken at 3.6 cm with the Very Large Array in its most extended (A) configuration. The source VLA 1 has undergone a dramatic morphological change, showing a one-sided knot ejection in the 2007 epoch. We also report the detection of a 3.6 cm compact continuum source (VLA 3) located at $(-10\farcs6, 98\farcs7)$ from VLA 1. No significant absolute proper motions were found for VLA 1 and VLA 3 and the upper limits are consistent with those found for (embedded) radio sources in the Orion Nebula. We favor the interpretation that in the continuum at 3.6 cm we are observing two nearly perpendicular jets. HH 111 presents a new case of one-sided jet ejection in a young stellar object. The galactic (or extragalactic) nature of VLA 3 remains unclear.

Key Words: astrometry — ISM: individual objects (HH 111) — ISM: jets and outflows — radio continuum: ISM

1. INTRODUCTION

Many observations have increasingly shown that stars are rarely born alone (e.g., Lada & Lada 2003). Binary and multiple systems may be surrounded by circumstellar and/or circumbinary disks, and often drive episodic jets and powerful outflows. For instance, Pech et al. (2010) presented Very Large Array (VLA) multi-epoch observations of the very young hierarchical multiple system IRAS 16293−2422. These authors found a bipolar ejection and suggested it was a consequence of an episode of enhanced mass loss possibly produced by an increase in accretion onto the protostar.

An interesting binary system is found at the core of the giant Herbig-Haro object HH 111, originally discovered by Reipurth (1989). This flow in Orion has been extensively studied since its discovery (see Noriega-Crespo et al. 2011, and references therein). It is highly collimated approximately in the east-west direction and displays a large number of individual knots moving in the plane of the sky with veloci-

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TABLE 1

VERY LARGE ARRAY OBSERVATIONS AT 3.6 CM

Epoch	Project	Phase calibrator	Bootstrapped flux density (Jy)	Synthesized beam[a]	σ (mJy beam^{-1})
1992 Nov 2 (1992.84)	AR278	0541−056	0.8691 ± 0.0002	$0''.26 \times 0''.23; +42°$	0.02
1992 Dec 18 (1992.96)	AR278	0541−056	1.0253 ± 0.0002	$0''.25 \times 0''.24; +37°$	0.02
1992 Dec 19 (1992.97)	AR278	0541−056	1.0229 ± 0.0002	$0''.28 \times 0''.25; +8°$	0.02
1994 Apr 30 (1994.33)	AR277	0552+032	0.7663 ± 0.0003	$0''.21 \times 0''.20; -57°$	0.02
1996 Nov 11 (1996.86)	AR367	0552+032[b]	0.8085 ± 0.0001	$0''.25 \times 0''.22; -12°$	0.01
1996 Dec 28 (1996.99)	AR277	0552+032	0.6997 ± 0.0001	$0''.25 \times 0''.22; -5°$	0.02
1996 Dec 29 (1997.00)	AR277	0552+032	0.7088 ± 0.0001	$0''.30 \times 0''.25; +3°$	0.02
2007 Aug 12 (2007.61)	AG747	0552+032	0.6780 ± 0.0003	$0''.26 \times 0''.23; -11°$	0.01

[a]Major axis × minor axis; position angle of major axis.

[b]For this epoch, the source 0541−056 was also observed.

ties of several hundred km s^{-1} (Reipurth, Raga, & Heathcote 1992). We will refer to this east-west jet as the HH 111 optical jet. Near-infrared observations by Gredel & Reipurth (1993) revealed the presence of a second outflow (HH 121) nearly perpendicular to HH 111, making the system a quadrupolar outflow. We will refer to this second jet, approximately in the north-south direction, as the infrared jet.

The driving sources of the HH 111 jets are believed to be the components of the suspected binary, class I source IRAS 05491+0247, which was associated to the radio source VLA 1 reported by Reipurth et al. (1999) at 3.6 cm. These authors also detected an additional faint, unresolved, radio source (VLA 2) to the north-west of VLA 1. Recently, Lee (2011) imaged the HH 111 protostellar system at 1.3 mm. A faint (4σ) source appeared at the same position of VLA 2 possibly tracing its putative dusty disk.

Rodríguez et al. (2008) presented observations of the system at 7 mm and discussed three possible interpretations for VLA 1, since the emission revealed a structure that can be described as two overlapping, almost perpendicular, elongated sources. They favor two interpretations in which the quadrupolar structure was either a disk elongated in the north-south direction with a perpendicular jet or two orthogonal disks. In the third interpretation, the emission comes from two jets. Nevertheless, the free-free contribution is only about 30%, hence the emission is dominated by dust. However, it is possible that the core is dominated by dust and the extended emission by free-free emission (see Rodríguez et al. 2008). The emission at 1.3 mm that showed a structure elongated in the north-south direction and perpendicular to the HH 111 optical jet (Reipurth et al. 1999) was attributed to thermal emission from a disk (Lee 2011).

In this paper we present sensitive, high angular-resolution 3.6 cm continuum observations at the core of the HH 111 outflow to search for absolute proper motions and to study the evolution of the HH 111 jet in VLA 1. In § 2, we describe our observations carried out with the Very Large Array as well as the data reduction. In § 3, we present the results together with the analysis. The discussion is presented in § 4 in the context of one-sided knot ejections versus bipolar ejections and a summary is given in § 5.

2. OBSERVATIONS AND DATA REDUCTION

The 3.6 cm (ν = 8.4 GHz) continuum observations of the core of the HH 111 outflow were made with the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO[6]) in the A configuration on 2007 August 12. The phase center of the observations was at α(J2000) = $5^h51^m46^s.25$, δ(J2000) = $2°48'29''.6$. The phase calibrator 0541−056 was observed for the first three 1992 epochs while the source 0552+032 was used as phase calibrator for the rest of the epochs (see Table 1). The absolute amplitude calibrator was the source 1331+305. We used a model image for 1331+305 provided by NRAO in order to improve flux accuracy.

In addition, we used seven epochs taken from the VLA archive. The eight analyzed data sets span about 15 years and are listed in Table 1. The data were analyzed in the standard manner using the Astronomical Image Processing System (AIPS) software package; the calibrated visibilities were imaged using weights intermediate between natural and uniform (with the ROBUST parameter set to 0) and

[6]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

CLEANed in an iterative fashion. To obtain accurate absolute astrometry, we precessed the data taken in B1950.0 to J2000.0 using the task UVFIX and used the most recent position of the phase calibrator for all epochs. We expect that the residual systematic error affecting the data to be around 10 milliarcseconds (mas). These residual errors were added in quadrature to the positional uncertainty delivered by a Gaussian fitting program (task JMFIT of AIPS).

3. RESULTS AND ANALYSIS

We detected the source VLA 1 at epoch 2007.61 and show the image in the upper panel of Figure 1. The morphology of VLA 1 changed drastically between the early epochs (Rodríguez & Reipurth 1994; Reipurth et al. 1999) and the 2007.61 epoch. In the last epoch there is a knot ejection to the east which was not present in previous observations. Parameters of the ejecta and discussion of the one-sided ejection are presented in §§ 3.3 and 4.1, respectively. Weak emission (at 3σ level) to the north and south of VLA 1 is also detected. We believe this weak emission is associated with the base of the infrared jet.

In the 2007 observations, due to potential problems with several antennas that were in transition to the K. Jansky Very Large Array (VLA) system, the rms noise level was not sufficient to detect the VLA 2 source, as previously reported in Reipurth et al. (1999).

On the other hand, we report the detection of a radio source (hereafter VLA 3) located at ($-10''.6$, $98''.7$) from VLA 1. Inspection of the maps at other epochs confirms the presence of this source. After correcting the image for the primary beam response, VLA 3 has a flux density of $S = 0.22 \pm 0.03$ mJy in the 2007 image. The flux density at all four epochs is consistent with a value of $S = 0.3 \pm 0.1$ mJy. There is a suggestion of time variability, but the data of 1992 and 1994 do not have a sufficient signal-to-noise ratio to reach a firm conclusion. The elongation of the source in the north-south direction seen in the bottom panel of Figure 1 is caused by bandwidth smearing and is not intrinsic to the source.

3.1. *Proper motions*

In order to search for absolute proper motions of VLA 1 and VLA 3, we concatenated the epochs 1992.84, 1992.96, and 1992.97 into epoch 1992.92; and the epochs 1996.86, 1996.99, and 1997.00 into epoch 1996.95. Figure 2 shows the radio positions of VLA 1 and VLA 3 as a function of time. We performed a least squares fit to four epochs (1992.92, 1994.33, 1996.95, and 2007.61) and the results are listed in Table 2. We found that VLA 1 and VLA 3 do not show significant absolute proper motions and they are consistent within 2σ with those found for (embedded) radio sources in the Orion Nebula (Gómez et al. 2005).

Further observations will be necessary to detect VLA 2, so that we are able to obtain relative proper motions with respect to VLA 1 and test the hypoth-

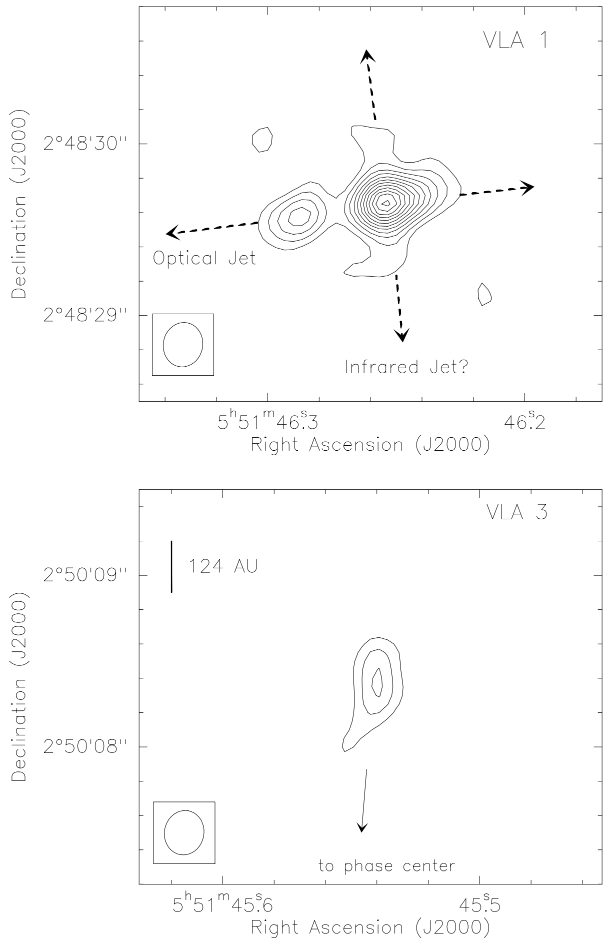

Fig. 1. Contour images of the 3.6 cm continuum emission of VLA 1 (top) and VLA 3 (bottom) at epoch 2007.61. The synthesized beam ($0''.26 \times 0''.23$; PA $= -11°$) is shown in the bottom left corner. Top: First contour and contour spacing for VLA 1 are 31.5 μJy beam^{-1} (3σ). The arrows in the east-west direction indicate the P.A. of the HH 111 jet (97.5°; Noriega-Crespo et al. 2011). The arrows in the north-south direction indicate the orientation of the HH 121 infrared jet. Bottom: First contour and contour spacing for VLA 3 are 42.0 μJy beam^{-1} (3σ). The bar indicates the linear scale. The arrow points in the direction to the phase center. The map has been corrected for the primary beam response.

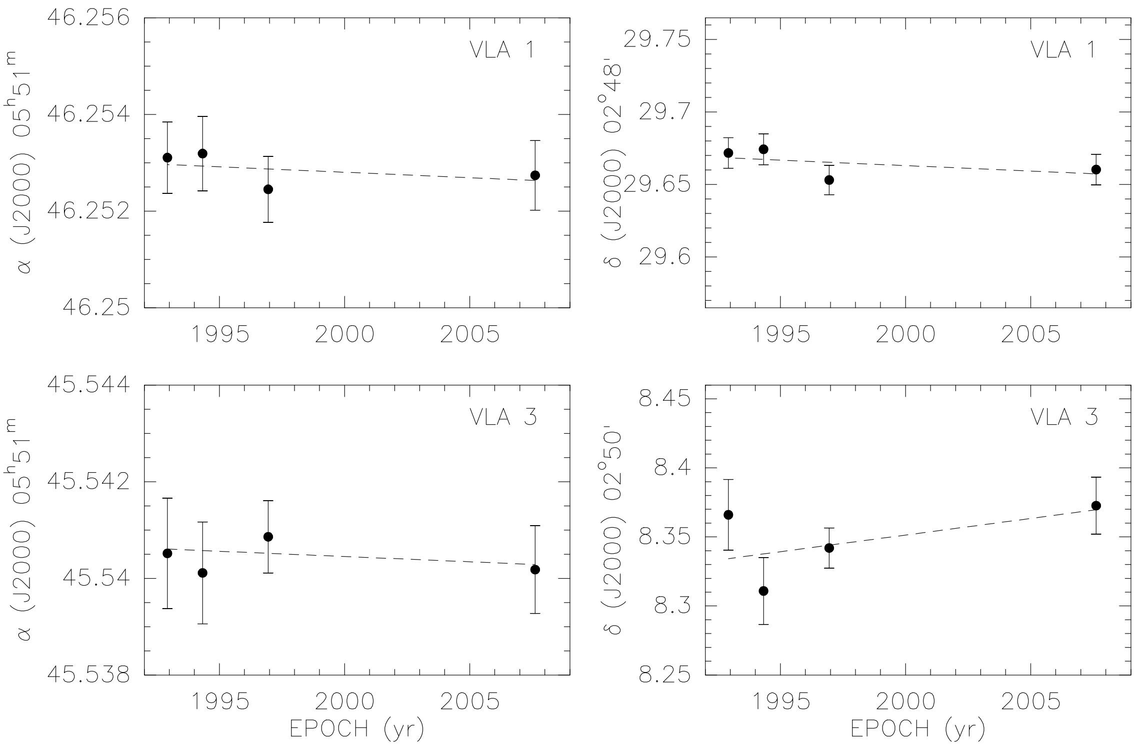

Fig. 2. Absolute proper motions in right ascension (α) and in declination (δ) for VLA 1 (upper panels) and the newly reported radio source VLA 3 (bottom panels) as a function of time. The dashed line in each panel represents the least squares fit to the data. The right ascension axis is given in seconds, while the declination axis is given in arcseconds.

TABLE 2

ABSOLUTE PROPER MOTIONS

Source	$\mu_\alpha \cos\delta$ (mas yr^{-1})	μ_δ (mas yr^{-1})
VLA 1	-0.34 ± 0.50	-0.75 ± 0.93
VLA 3	-0.33 ± 0.57	2.41 ± 2.23

esis that these sources form a non-hierarchical triple system in disintegration (Reipurth et al. 1999).

3.2. *On the nature of VLA 3*

In order to obtain the expected number of extragalactic sources, N, in the field of study with a flux density comparable or larger than that of VLA 3, we follow Windhorst et al. (1993)

$$N = 2.4 \times 10^{-3} \left(\frac{S}{\mathrm{mJy}}\right)^{-1.3} \mathrm{arcmin}^{-2}, \quad (1)$$

where S is the flux density in mJy. For $S \simeq 0.3$ mJy and a field of $\sim 3.4 \times 3.4$ arcmin^2, N corresponds to 0.13 sources. Thus, VLA 3 only has a 13% probability of being extragalactic.

VLA 3 does not show significant proper motions, as expected for an extragalactic source, but is also consistent with Orion sources. Therefore, the measurement of proper motions, in this case, is not useful to determine its nature. Very recently, the AMI Consortium et al. (2012) detected a radio source whose emission peaks at the position of VLA 3 at 1.9 cm (16 GHz) with a beam size of $69'' \times 27''$. They obtained a spectral index, α_{AMI}, of -0.23 ± 1.10, a value consistent with those found for extragalactic sources, but whose large error makes it consistent with several different emission mechanisms.

We searched for possible counterparts in three point source catalogs, namely, the AKARI (Murakami et al. 2007), 2MASS (Skrutskie et al. 2006), and WISE (Wright et al. 2010) catalogs. We found no association with sources from the AKARI and 2MASS catalogs. A WISE point source was found as possible counterpart of VLA 3 at a distance of $\sim 1''$. The source is detected in the 3.4 μm and 4.6 μm bands. There are marginal signals in the 12 μm and 22 μm bands that are considered as spurious or affected by other artifacts in the catalog.

Although VLA 3 is more likely to be an extragalactic source, in the remaining of this contribution we restrain ourselves from further interpretation of VLA 3.

3.3. *VLA 1: ejecta parameters*

The parameters of the ejecta are estimated from observables at epoch 2007.61. Using the model by Mezger & Henderson (1967), and assuming optically thin free-free emission, the mass of ionized gas, M_i, and the electron density, n_e, of a homogeneous sphere can be calculated as

$$M_i = 3.39\times10^{-5}\left(\frac{T_e}{10^4\ \mathrm{K}}\right)^{0.175}\left(\frac{\nu}{1\ \mathrm{GHz}}\right)^{0.05}\left(\frac{S_\nu}{1\ \mathrm{mJy}}\right)^{0.5} \times\left(\frac{D}{1\mathrm{kpc}}\right)^{2.5}\left(\frac{\theta}{1''}\right)^{1.5} M_\odot\,, \quad (2)$$

$$n_e = 7.2\times10^{3}\left(\frac{T_e}{10^4\ \mathrm{K}}\right)^{0.175}\left(\frac{\nu}{1\ \mathrm{GHz}}\right)^{0.05}\left(\frac{S_\nu}{1\ \mathrm{mJy}}\right)^{0.5} \times\left(\frac{D}{1\mathrm{kpc}}\right)^{-0.5}\left(\frac{\theta}{1''}\right)^{-1.5} \mathrm{cm}^{-3}\,, \quad (3)$$

where T_e is the electron temperature, ν is the frequency, S_ν is the observed integrated flux density, D is the distance, and θ is the angular size. We assume a T_e of 10^4 K at 8.4 GHz, and use a distance of 414 pc (Menten et al. 2007). The flux density was obtained by fitting a Gaussian to the ejecta. The emission was resolved in only one direction with a deconvolved angular size of $0\farcs28$, while in the other direction the emission comes from a region smaller than $0\farcs23$. Using the fitting parameters of $S = 0.18$ mJy and the geometric mean of the deconvolved angular size of $\lesssim 0\farcs25$, we obtain $M_i \lesssim 2.2\times10^{-7}\ M_\odot$ and $n_e \gtrsim 4.2\times10^{4}\ \mathrm{cm}^{-3}$.

4. DISCUSSION

4.1. *A one-sided knot ejection*

Figure 3 compares the images for VLA 1 of four epochs, including the 2007 observations. We show images of concatenated data for epochs 1992 and 1996 (see § 3.1). For the 1992 epoch, Rodríguez & Reipurth (1994) note that the emission of VLA 1 consists of a single component elongated to the west, possibly tracing a faint ejection. The elongation is seen to the east in the 1994 epoch, and to the east-west for the structure in the 1996 epoch, whereas in the new 2007 observations we additionally see a second component to the east, which we interpret as a one-sided knot ejection (see also Figure 1). Moreover, weak emission is detected in the north-south direction, and according to Rodríguez et al. (2008), it probably is due to the presence of the second (infrared) HH 121 jet. In the 3.6 cm map presented by Reipurth et al. (1999), VLA 1 shows clear elongations in the north-south direction after using a maximum entropy reconstruction (see their Figure 3).

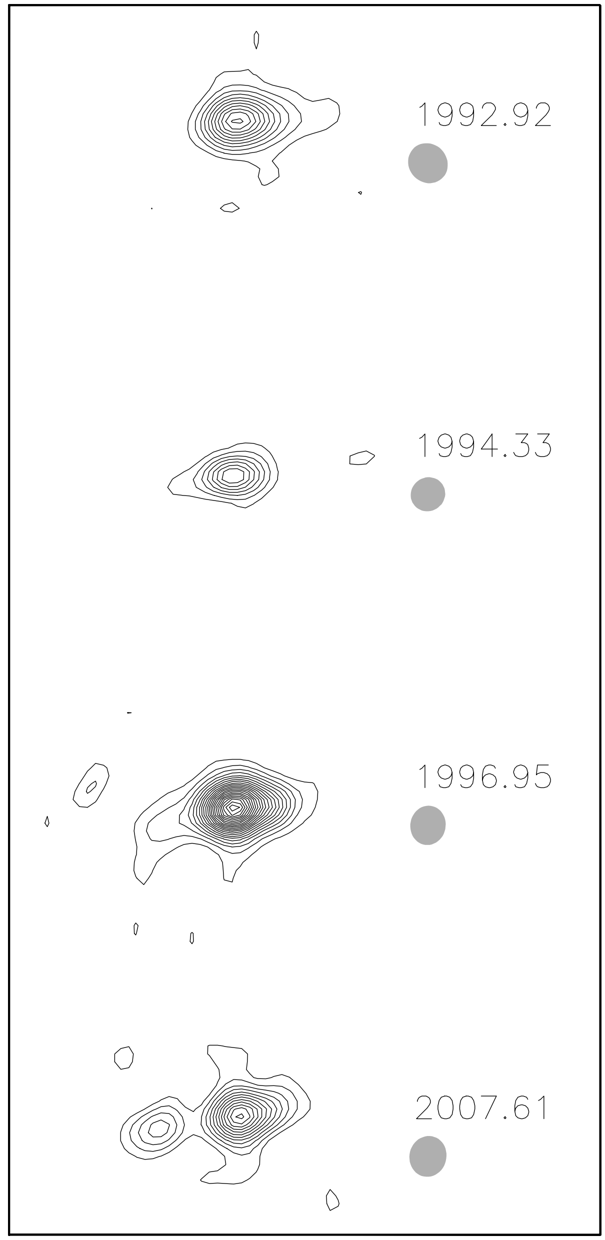

Fig. 3. Contour images of the 3.6 cm continuum emission of VLA 1 at different epochs. Details for epoch 2007.61 are the same as in Figure 1. First contour and contour spacing for VLA 1 are, from top to bottom, 36.0 μJy beam^{-1} (3σ), 54.3 μJy beam^{-1} (3σ), and 21.0 μJy beam^{-1} (3σ), for epoch 1992.92, 1994.33, and 1996.95, respectively. The synthesized beams are shown as filled ellipses for each epoch [($0\farcs26\times0\farcs24$; PA = 34°), ($0\farcs22\times0\farcs21$; PA = −41°), ($0\farcs25\times0\farcs22$; PA = −8°)].

It is important to point out that the map corresponding to the 1996 epoch, which has a better rms compared to the 2007 epoch, presents an elongation to the east but the ejection cannot be resolved. It is also interesting that, in the optical, the (eastern) redshifted lobe is completely obscured (see Reipurth et al. 1992), contrary to what we see at radio wavelengths in the 2007 epoch where the ejection is clearly seen to the east.

Dust extinction affects observations at optical and infrared wavelengths, while the radio regime suffers the least. One may think that asymmetries often seen in jets at the former wavelengths (Hirth et al. 1994) are mainly due to the material in the parental cloud, where the protostars are embedded, while observations in the radio would show symmetric jets. In reality, this is not always the case. For instance, for the (high-mass) young stellar object Cepheus A HW2, Curiel et al. (2006) see an asymmetry in the radio lobes and explain it in terms of proper motions of the exciting source and of temporal variations in the velocity of the ejections. As we mentioned in § 3.1, VLA 1 does not show significant absolute proper motions; hence, the scenario in which the driving source has proper motions can be ruled out. New and more sensitive VLA observations will be necessary to also measure proper motions of the ejecta. Another possibility is that the ejection is due to episodic mass loss rate increments (e.g., Pech et al. 2010). Other examples of asymmetry in the radio were presented by Rodríguez et al. (2012a,b) for the (low-mass) stars DG Tau and DG Tau B, where similar one-sided knot ejections were noticeable in the 3.6 cm maps.

There are two models for describing the launching region of jets: the disk-winds (Königl & Pudritz 2000) when they originate from the accretion disk and the X-winds (Shu et al. 2000) when they originate in the disk-star interface. Although much progress has been made in star-disk simulations (see, e.g., Pudritz et al. 2007), questions of whether these winds co-exist or one is at work while the other is not still remain unanswered. Possible causes for jet asymmetries may be traced back to asymmetries in the disk, e.g., a warped disk. Obviously, further theoretical work on the mechanisms at work in episodic, one-sided jets is urgently needed.

Observations of VLA 1 in HH 111 together with those of DG Tau, DG Tau B, and Cepheus A HW2 suggest one-sided knot ejection events do occur in young stellar objects.

5. SUMMARY

We have performed 3.6 cm continuum observations with the VLA together with the analysis of additional archival data toward the core of the HH 111 outflow. Our main results can be summarized as follows:

- The source VLA 1 has undergone a dramatic morphological change, showing a one-sided knot ejection at epoch 2007.
- We have confirmed that the base of the infrared jet HH 121 is detectable at centimeter wavelengths, although it is weaker than the emission from the base of the optical HH 111 jet.
- We have reported the detection of the radio source VLA 3 located to the north of VLA 1. However, its galactic or extragalactic nature remains unclear.
- We have found that VLA 1 and VLA 3 do not show significant absolute proper motions and the upper limits determined by us are consistent with the proper motions found for (embedded) radio sources in the Orion Nebula.

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