A HIGHLY COLLIMATED WATER MASER BIPOLAR OUTFLOW IN THE CEPHEUS A HW3d MASSIVE YOUNG STELLAR OBJECT

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ABSTRACT

We present the results of multi-epoch very long baseline interferometry (VLBI) water (H2O) maser observations carried out with the VLBI Exploration of Radio Astrometry toward the Cepheus A HW3d object. We measured for the first time relative proper motions of the H2O maser features, whose spatio-kinematics traces a compact bipolar outflow. This outflow looks highly collimated and expanding through \( \sim 280 \) AU (400 mas) at a mean velocity of \( \sim 21 \) km s\(^{-1}\) (\( \sim 6 \) mas yr\(^{-1}\)) without taking into account the turbulent central maser cluster. The opening angle of the outflow is estimated to be \( \sim 30^\circ \). The dynamical timescale of the outflow is estimated to be \( \sim 100 \) years. Our results provide strong support that HW3d harbors an internal massive young star, and the observed outflow could be tracing a very early phase of star formation. We also have analyzed Very Large Array archive data of 1.3 cm continuum emission obtained in 1995 and 2006 toward Cepheus A. The comparative result of the HW3d continuum emission suggests the possibility of the existence of distinct young stellar objects in HW3d and/or strong variability in one of their radio continuum emission components.

Key words: ISM: individual objects (Cepheus A) – ISM: jets and outflows – masers – stars: formation

1. INTRODUCTION

The last decade has seen a lot of efforts toward understanding how massive stars form and evolve. The fact that massive stars have a very significant impact on the evolution of the interstellar medium of galaxies, with strong influences in their environments (through strong winds, expanding H II regions, UV radiation, supernova explosions), and sometimes activating other star formation events, underscores the importance of this research. However, it is still among the most poorly understood topics in the field of astronomy. This is mainly because massive stars form in highly obscured mediums, thus making it very difficult to observe them in their early phases. In addition, they evolve quickly (formation timescales of \( \sim 10^4 \) yr), and form in distant clusters and associations, and therefore it is hard to isolate single high-mass stars for their study (see reviews by, e.g., Hoare & Franco 2007; McKee & Ostriker 2007; Zinnecker & Yorke 2007). Based mostly on theoretical simulations, different attempts have been made in proposing the formation scenarios of massive stars. There are mainly three proposed scenarios: massive star formation through the merging of less massive stars (Bonnell et al. 1998), competitive accretion in a protocluster environment (Bonnell & Bate 2006), and gravitational collapse involving high-rate, disk-assisted accretion into the core which helps to overcome radiation pressure (Yorke & Sonnhalter 2002; McKee & Tan 2003; Krumholz et al. 2005, 2009).

With high brightness temperatures exceeding \( 10^{10} \) K and compact nature, H2O masers have proven to be very useful in astrophysical studies using very long baseline interferometry (VLBI) with milliarcsecond (mas) angular resolution, particularly in identifying present sites of high-mass star formation in molecular clouds for studying the very vicinity of massive young stellar object (YSO) candidates (e.g., Genzel et al. 1981; Torrelles et al. 2001a, 2003; Imai et al. 2002; Goddi et al. 2005, 2006; Moscadelli et al. 2005; Vlemmings et al. 2006; Surcis et al. 2011).

In this paper, we report the results of nine epochs of H2O maser observations toward the Cepheus A (Cep A) high-mass star-forming region using the VLBI Exploration of Radio Astrometry (VERA). We adopt the distance to Cep A to be \( \sim 700 \) pc (Johnson 1957; Moscadelli et al. 2009; Dzib et al. 2011). We focus mainly on HW3d in Cep A, one of the 16 radio continuum objects discovered by Hughes & Wouterloot (1984), and located \( \sim 3^\circ \) south from the brightest radio continuum source in the region, HW2. HW2 clearly harbors a massive YSO in it, which is indicated by the observations of a jet and a disk, intense magnetic fields, and powerful H2O masers (Rodríguez et al. 1994; Patel et al. 2005; Curiel et al. 2006; Jiménez-Serra et al. 2007; Torrelles et al. 2007, 2011; Vlemmings et al. 2010). On the other hand, the observational properties are not so clear in the case of the other HW objects. In fact, Garay et al. (1996), through multifrequency Very Large Array (VLA) radio continuum observations, argued that some of the HW objects are internally excited by a YSO, while others are externally shock-excited at the interface between winds of other YSOs and molecular clumps in the region. HW3d is one of the objects that was proposed to be excited internally by its own YSO, on the basis that the radio continuum emission presents an elongated structure with positive spectral index, which is suggestive of a thermal jet nature. Hughes et al. (1995) also supported it on the basis of its association with strong hydroxyl (OH) and H2O maser emission (Cohen et al. 1984), although they did not find evidence for outflow activity in this object. The evidence for outflow activity is now presented in this paper through our
VERA H$_2$O maser observations, giving a conclusive support that the HW3d object is internally excited by a massive YSO.

2. OBSERVATIONS

2.1. VERA Observations

The observations of the Cep A H$_2$O masers at 22.235080 GHz with VERA were carried out in nine epochs from 2006 May to 2007 August. Table 1 gives a summary of these observations. At each epoch, the total observation time was about 8 hr, including the scans on the calibrators (J2005+7752, BL Lac, J2015+3710). Using the advantage of the VERA’s dual-beam system, Cep A and J2302+6405 (a position reference source spatially separated by 2$’$19 from Cep A) were simultaneously observed with the aim of determining the annual parallax of Cep A. The result of the measurement of the parallax distance would be published in a separate paper. The received signals were digitized in four quantization levels, and then divided into 16 base-band channels (BBCs) in a digital filter unit, each of which had a bandwidth of 16 MHz, corresponding to a velocity coverage of 216 km s$^{-1}$ centered around 50 km s$^{-1}$ with respect to the local standard of rest (LSR). One of the BBCs was assigned to the frequency of the H$_2$O maser emission in Cep A while the other 15 BBCs were assigned to the continuum emission from J2303+6405 and other sources observed in the B-beam of the VERA system.

The data correlation was made with the Mitaka FX correlator. The accumulation period of the correlation was set to 1 s. The correlation outputs consisted of 512 and 64 spectral channels for the H$_2$O maser and reference continuum emission, respectively. A velocity spacing of 0.21 km s$^{-1}$ was obtained in each spectral channel for the H$_2$O maser emission.

The data reduction was made with the National Radio Astronomy Observatory (NRAO) Astronomical Image Processing System (AIPS) package using standard procedures. The instrumental delay calibration was made with the scans on the calibrators. The fringe fitting and self-calibration procedures were performed for a Doppler velocity channel including a bright maser spot (velocity component) in the HW3d region of Cep A. Their solutions were applied to all the data and then the map of the maser clusters were made. The CLEANed image cubes of the maser source were created using the beam that was synthesized from naturally weighted visibilities. The typical size of the synthesized beam was $\sim$1.3 mas. The H$_2$O maser image cubes were made with a cell size of 0.2 mas.

Because we carried out self-calibration procedure using a bright maser spot in the HW3d region, the maser spot positions in the image cubes were measured with respect to the bright maser spot used for self-calibration mentioned above. For the wide-field mapping and objective maser spot identification, we used an automatic pipeline script which runs on the AIPS POPS environment and mainly consists of AIPS tasks and adverbs: IMAGR, IMSTAT, and SAD. The H$_2$O maser feature identification was done by adopting a signal-to-noise ratio cutoff of $\sim$8. From the Gaussian fitting errors, we estimated the accuracies of the relative positions of the maser spots to be 0.01–0.20 mas in right ascension and 0.02–0.30 mas in declination. The individual maser features were defined as clusters of maser spots or velocity components and each feature position was defined from the brightness peak of the feature (for identification method, see Imai et al. 2002).

We adopted special procedures to measure the absolute coordinates of the detected H$_2$O masers. This enables a comparative study with the 1.3 cm continuum emission map from VLA observations described in Section 2.2. The position-reference source J2303+6405 observed concurrently in the B-beam of the VERA system was not detected by applying the normal fringe fitting. To detect the weak emission of the position-reference source and thus measure the coordinates of the maser features with respect to it, we applied the inverse phase-referencing technique. This procedure involves common calibrating the group delay residuals of the A- and B-beam data using the data of the bright continuum calibrators (BL Lac, J2005+7752) observed in the B-beam. Then we did fringe fitting and self-calibration as described above using a bright maser velocity component. Subsequently, we applied all the phase calibration solutions obtained to the position-reference source (J2303+6405) data. We successfully carried out this procedure in the observation epoch of 2007 February 18, using a bright maser spot at $V_{LSR} = -6.67$ km s$^{-1}$ near HW2 and detected the position-reference source (30 mJy beam$^{-1}$) at a position offset of 15.4 mas in R.A. and 606.5 mas in declination from J2303+6405 map center. This inversely indicates the position offset of the phase-referenced maser spot from the delay-tracking center. We determined the absolute coordinates of the position-reference maser spot (maser spot used for the AIPS self-calibration procedure) to be R.A.($J2000)$ = $22^h56^m17^s97745$, decl.($J2000)$ = +62$^\circ$01$'49"$3784 by computing the negative of the offset of the position-reference source (J2303+6405) from the map origin.

There was no maser feature consistently identified in all the epochs which could be used as a reference position; therefore we adopted the following method to trace individual maser features at as many successive epochs as possible. First, from any two adjacent epochs, we calculated the mean coordinate offset of the maser features at the second epoch with respect to that at the first epoch using only the maser features that were detected at both epochs. Second, these mean offsets were referred with respect to the earliest epoch taken on 2006 May 13. Then, these offsets were subtracted from the coordinates originally used in the individual epochs (see Torrelles et al. 2001b). In so doing we were able to register all maser feature maps and obtain a reference frame whose spatial stability at all epochs depends on that of the maser feature distribution. The map origin of the reference frame is very close to a quasi-stationary maser feature.
in HW3d (Feature 15 in Table 2). We tested the stability of the reference position offset using the Feature 15 (seen at the same position within 1 mas and at the same LSR velocity; see the Appendix) identified at five epochs. The estimated proper motion in the reference frame is $\mu_x \sim 0.001$ (mas yr$^{-1}$) and $\mu_y \sim 0.003$ (mas yr$^{-1}$), and the standard deviation of the offset coordinates of the maser feature is 0.02 mas in right ascension and 0.05 mas in declination. All maser offset positions in this paper are given with respect to the derived reference position offset.

### 2.2. VLA Archive Data

In order to compare the masers imaged from our VERA observations with the radio continuum emission of HW3d, we retrieved data from the VLA archive. We found a 1.3 cm continuum data set around the same epoch of the VERA observations under the project name AC0810, taken on 2006 February 11 in the most extended A configuration of the VLA at an observation frequency of $\sim 22.29$ GHz. The data include the two circular polarizations with an effective bandwidth of 100 MHz. It is important to note that these continuum data do not overlap with the frequency of the H$_2$O masers, and thus they are free of contamination from the line emission. The sources 1331 + 305 and 2230 + 697 were the flux density and phase calibrators, respectively. The calibration was carried out under standard procedures outlined in the chapter 4 of the AIPS cookbook. The assumed flux density for the amplitude calibrator was 2.59 Jy, while the estimated flux density of the phase calibrator was 0.51 Jy. The total time on source was $\sim 4$ hr, which yielded an rms noise in the final image of $\sim 52$ $\mu$Jy beam$^{-1}$ using naturally weighted visibilities.

### 3. RESULTS

#### 3.1. Spatio-kinematics of H$_2$O Masers and the Morphology of the Radio Continuum Emission in HW3d

We detected H$_2$O maser clusters corresponding to all the sub-regions R1–R8 around HW2, previously reported by Torrelles et al. (2011), as well as maser clusters associated with HW3d. In this paper, we will concentrate on the results obtained toward HW3d, presenting for the first time H$_2$O maser proper motion measurements in this object.

The VLA 2006 data turned out to be very useful because they also allowed us to explore the variability of HW3d by comparing these observations with those of VLA 1995 reported in Torrelles et al. (1998). Figure 1 shows the VLA 1.3 cm continuum map obtained from the 2006 data, showing the HW2 radio jet, and the HW3c and the HW3d objects, which are located $\sim 3''$ south...
and the mean value of the proper motions without considering the turbulent central cluster (∼6 mas yr⁻¹ or ∼21 km s⁻¹) indicate that in HW3d there is a collimated bipolar outflow driven by an internal (probably) massive YSO that we propose to be located very close to the central position of cluster C. The fact that this cluster has the highest radial velocity dispersions (∼20 km s⁻¹; Table 2) of all the observed maser clusters in HW3d, also supports this C cluster as the main center of activity containing a driving YSO. The estimated dynamical timescale of this outflow is ∼100 years. The fact that the radio continuum emission of HW3d is elongated along the direction of the outflow masing motions suggests a radio jet nature for this object, supporting the interpretation given by Garay et al. (1996) based on spectral index measurements.

There is in addition a fourth group of masers located at ∼(+135 mas, −39 mas), but their proper motions toward the northwest (see Figure 2 and Table 2) cannot be explained within a single bipolar outflow scenario excited by a single YSO close to the (0,0) position. The possibility of multiplicity of YSOs in this region is considered in Section 4. We estimated the opening angle of the outflow using the deconvolved size of the radio jet of HW3d (∼325 × 99 mas), giving a value of ∼30°.

### 3.2. Position and Velocity Variance/Covariance Matrix Analyses of the HW3d H₂O Maser Spatio-kinematics

We carried out the position and velocity variance/covariance matrix analyses of the H₂O maser spatio-kinematics to test the existence of an outflow in the H₂O maser region. The positional and kinematical essentials were extracted using the position and velocity variance/covariance matrix (PVVCM) diagonalization technique (Bloeenhof 1993, 2000) for the whole maser feature proper motions. We estimated the uncertainties associated with the derived eigenvectors and eigenvalues from their standard deviations calculated from the Monte Carlo simulation for the VVCM diagonalization using velocity vectors randomly distributed around the observed values within their estimated errors (Imai et al. 2006). This technique is not a model fitting approach, having no free parameters. It is a fully objective, analytic tool, generally composed of the following elements:

\[
\sigma_{ij} = \frac{1}{N-1} \sum_{n=1}^{N} (v_{i,n} - \bar{v}_i)(v_{j,n} - \bar{v}_j),
\]

where \( i \) and \( j \) denote the two-dimensional space axes in the case of position, or three orthogonal space axes in the case of velocity. \( n \) is the \( n \)th maser feature in the collection summing up to \( N (=30) \). The bar indicates averaging over the maser features. The diagonalization of the position variance/covariance matrix (PVCM) gives the essentials of the maser position field, while that of the VVCM gives the essentials of the velocity field. Classification of the spherical symmetry of an outflow into spherical outflow from a cometary or a bipolar outflow can be done using the relative magnitudes of the three principal velocity variances. The direction of the major principal axis gives the outflow axis of a bipolar outflow. PVCM and VVCM provide a robust and objective means of extracting the position and kinematic essentials from maser proper motions, and also support some other spherical symmetric or asymmetric model in deriving the vital clues from masers. The position angles and inclinations are derived from the eigenvectors obtained from the diagonalized matrices. As examples, the diagonalized matrices from HW2. In what follows, we will concentrate on the HW3d object. The main properties of the HW2 thermal radio jet and the HW3c object can be found in Rodríguez et al. (1994) and Garay et al. (1996).
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Figure 2. Left: the distribution of the H$_2$O masers detected in our VERA observations superposed to the HW3d 1.3 cm continuum map obtained with the VLA in 2006. Right: the proper motions of these maser features. The position, length, and direction of an arrow indicate the position, speed, and direction of the maser feature motion on the sky, respectively. The continuous lines represent proper motions traced in three or more epochs while the dashed lines represent those traced in two epochs only (see also Figure 4 in the Appendix). The motion speed of 10 km s$^{-1}$ is indicated by a white arrow length in the upper left corner. The color code indicates the LSR velocity of the individual maser features. The absolute coordinates of the (0,0) position (Feature 15, Table 2) are R.A.(J2000) = 22h56m18.1753, decl.(J2000) = +62°01′46″2114.

The larger eigenvalue of position dispersion is 389 times the smaller one. This indicates a very high collimation with respect to the position dispersion of the masers. The position angle, PA, of the eigenvector corresponding to the larger eigenvalue is 108°.

To verify our interpretation, we also made the three-dimensional VVCM diagonalization analysis of the H$_2$O maser proper motions, obtaining the following $3 \times 3$ diagonalized matrix in units of km$^2$ s$^{-2}$:

\[
\begin{pmatrix}
85.49 & -35.62 & -7.62 \\
-35.62 & 59.99 & 5.00 \\
-7.62 & 5.00 & 12.50
\end{pmatrix}
\Rightarrow
\begin{pmatrix}
111.41 & 0 & 0 \\
0 & 34.90 & 0 \\
0 & 0 & 11.66
\end{pmatrix}.
\]

The larger eigenvalue of velocity variance dominates, three times the second largest eigenvalue.

of one PVCM and one VVCM are shown below while the results are presented in Table 3.

We applied Equation (1) in two spatial dimensions using the position offsets of all of the 30 maser features. The $x$- and $y$-axes correspond to the right ascension and declination, respectively. The diagonalized PVCM in the unit of mas$^2$ as a $2 \times 2$ matrix is

\[
\begin{pmatrix}
11421.79 & -3811.39 \\
-3811.39 & 1308.13
\end{pmatrix}
\Rightarrow
\begin{pmatrix}
12697.28 & 0 & 0 \\
0 & 32.64 & 0
\end{pmatrix}.
\]
the largest eigenvalue. The factor of three between the largest eigenvalue
with respect to the second one in the VVCM indicates collimation
of water maser proper motions. The eigenvector corresponds
to the principal or largest eigenvalue. The factor of three between the second-largest
eigenvalue. The eigenvector corresponding to the second-largest eigenvalue.
φ Position angle of the second largest eigenvalue (°)
ν Position angle of the largest eigenvalue (°)
ψ Inclination angle of 1

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3.3. Properties of the Outflow

In order to test the originating point of the outflow exciting
the surrounding H2O maser features, we performed the least-
squares method for the model-fitting analysis as presented by Imai et al. (2000, 2011). This fundamentally involves the minimizing of the squared sum of the difference between the observed and model velocities, $S^2$:

$$S^2 = \frac{1}{3N_m - N_p} \sum_{i}^{N_m} \left\{ \left[ \frac{\mu_{ix} - w_{ix}}{(a_0d)} \right]^2 \sigma_{\mu_{ix}}^2 + \left[ \frac{\mu_{iy} - w_{iy}}{(a_0d)} \right]^2 \sigma_{\mu_{iy}}^2 + \left[ \frac{\mu_{iz} - w_{iz}}{} \right]^2 \sigma_{\mu_{iz}}^2 \right\},$$

where $N_m$ is the number of maser features with measured proper motions, $N_p$ the number of free parameters in the model fitting, $a_0 = 4.74 \text{ km s}^{-1} \text{ mas}^{-1} \text{ yr kpc}^{-1}$ a conversion factor from a proper motion to a linear velocity, and $d$ the distance ($\sim 700 \text{ pc}$) to the maser source from the Sun, respectively. $\mu_{ix}$ and $\mu_{iy}$ are the observed proper motion components in the R.A. and declination directions, respectively, $\sigma_{\mu_{ix}}$ and $\sigma_{\mu_{iy}}$ are their uncertainties, $u_i$ the observed LOS velocity, and $\sigma_{\mu_{iz}}$ is its uncertainty. For simplicity we assume a spherically expanding outflow. The modeled velocity vector, $w_i (w_{ix}, w_{iy}, w_{iz})$, is given as

$$w_i = V_0 + V_{\exp}(i) \frac{r_i}{d},$$

where $V_0 (v_{0x}, v_{0y}, v_{0z})$ is the systemic velocity vector of the outflow,

$$r_i = x_i - x_0$$

(or $r_{ix} = x_i - x_0$, $r_{iy} = y_i - y_0$, $r_{iz} = z_i$),

$$z_i = \frac{(u_{ix} - v_{0z})r_{iz}^2 + r_{iz}^2}{(u_{ix} - v_{0z})r_{ix} + (u_{iy} - v_{0y})r_{iy}},$$

and

$$u_{ix} = \mu_{ix}a_0d, \quad u_{iy} = \mu_{iy}a_0d.$$

Equation (6) satisfies the following constraint; the obtained position minimizes the value of $S^2$,

$$\frac{\partial S^2}{\partial z_i} = 0.$$
The motion vector of the outflow on the sky ($V_{0x}$, $V_{0y}$), $z_0 = 0$ and $V_0 = -12$ km s$^{-1}$ are fixed. Here we consider the possibility of a single driving source of the outflow.

Table 4 gives the parameters of the best-fit model. This fitting, considering the errors (within 2 sigma), is fully consistent with the origin of the bipolar outflow being at the position of the C H$_2$O maser cluster, supporting our interpretation given in Section 3.1 that the C cluster is the main center of activity containing a driving YSO.

Figure 3 shows the distributions of the estimated expansion velocities of the individual maser features $V_{\text{exp}}(i)$, in which the originating point of the outflow is considered to be at or very close to the position of Feature 15 (0,0) (see Imai et al. 2000, 2011). If a single expanding flow exists, the data points should be concentrated on the range of positive expansion velocities. The maser kinematics in Cluster C seems to be significantly contaminated by random motion. It should be noted that this analysis has large uncertainties in the estimated sign of $V_{\text{exp}}$ (positive or negative) for the individual maser features close to the estimated position of the originating point because the position estimated from the model fitting using the large-scale maser clusters has a large uncertainty (see Table 4). Nevertheless, we cannot discard the possibility that some of these negative $V_{\text{exp}}$ are due to infalling motions. In fact, to produce these infalling motions of $\sim 10$ km s$^{-1}$ at distances of 0.015 (105 AU), a central binding mass of $\sim 12 M_\odot$ would be necessary, which is not an unlikely value (a B3 star has been proposed to explain the radio continuum emission of HW3d; Garay et al. 1996). Alternatively, we also cannot discard the possibility that these masers, especially those at (+135 mas, $-39$ mas) are excited by a close YSO other than the driving source at the center (see below, Section 4).

### Table 4

| Systemic Proper Motion | Position Offset of the Reference Maser Spot |
|------------------------|--------------------------------------------|
| $V_{0x}$ (km s$^{-1}$)  | $\Delta x_0$ (mas) 20.0 $\pm$ 10.5 |
| $V_{0x}$ (km s$^{-1}$)  | $\Delta y_0$ (mas) $-17.0 \pm 9.0$ |
| $\sqrt{\Delta x^2 + \Delta y^2}$ | 3.3 |

Note. Mean of the rms residual of the model fitting (errors at 1σ).

During the process of the formation of this likely massive YSO, a “YSO-jet” system has been formed, similar to what happens in the formation of low-mass stars. However, not all of the observed properties of HW3d can be explained with just a single YSO. In fact, the VERA observations show a cluster of H$_2$O masers located at $(+135$ mas, $-39$ mas), with proper motion vectors that do not fit within the bipolar expanding motions outward from the center (Sections 3.1, 3.2, and Figure 2). Another YSO might in principle be responsible for the excitation of the masers in that cluster.

In addition, and most importantly, by comparing the HW3d 1.3 continuum emission observed in two epochs (1995 and 2006) with similar angular resolution ($\sim 0.1$), we see that this source is variable in its total flux density ($\sim 9$ mJy [1995], $\sim 6.9$ mJy [2006]), and on the other hand that the position of its peak emission has changed by $\sim 0.2$ between these two epochs. We find that this position shift is highly significant, in particular when considering that the peak emission of the other two nearby objects HW2 and HW3c have not changed in position in these two epochs within $\sim 10$ mas in right ascension and declination (see Figure 1). In the case that there was only a single exciting source, then the shift in the position of the continuum emission could be the result of the proper motion of the YSO. However, this would correspond to a YSO velocity of $\sim 65$ km s$^{-1}$. Such a high velocity for the proper motion of the YSO itself is quite unlikely, thus buttressing the likelihood of the two continuum peaks representing two different YSOs in close proximity and high flux density variability. Alternatively, the change in the peak position could be due to internal proper motions of clumps in the jet with flux density variations. This radio continuum variability of HW3d was also previously reported by Hughes et al. (1995), which also invoked the presence of different variable YSOs to explain the main characteristics of the object.

This scenario can be tested with high-angular sensitive Expanded Very Large Array (EVLA) and Submillimeter Array (SMA) (sub)mm observations to trace the dust continuum emission and molecular gas around the possible different YSOs associated with HW3d, and possible proper motions of the radio jet. These observations would also be very valuable to elucidate the nature of the YSO(s) (mass, dust, and gas contents), and in particular to detect and study the expected circumstellar disk around the driving source of the compact bipolar outflow.
Figure 4. Variation of the positions and the LSR velocities of maser features whose relative proper motions were measured. The proper motions were typically obtained in three or more epochs (continuous lines), those obtained in only two epochs (dashed lines) are very isolated in velocity and/or position. See the text for details.
Figure 4. (Continued)
Figure 4. (Continued)
observed with VERA. The fact that in Cep A (the second-closest high-mass star-forming region after Orion) we have two very close “YSO-jet” systems, HW2 and HW3d (separated in the sky by ∼3′′, ∼2100 AU), gives a unique opportunity to study their possible different properties in terms of the mass and evolution of the massive systems.

5. SUMMARY

We have carried out VERA nine-epoch H₂O maser observations toward the radio continuum object Cep A HW3d. We have measured the relative proper motions of 30 H₂O masers associated with HW3d, showing for the first time outflow activity in this radio continuum object. This result gives strong support that HW3d harbors (at least) an internal massive YSO. The spatio-kinematical distribution of the masers show a main bipolar structure at scales of 0′′.4 (280 AU) along the direction of elongation of the continuum emission and dynamical timescale of ∼100 years, suggesting that a “YSO-jet” system has formed in this massive object.

The H₂O maser proper motions that do not fit within the bipolar expanding motion outward from the originating center, as well as the observed shift in the peak positions of the VLA 1.3 cm continuum emission between different epochs, may be indicating the presence of more than one exciting sources in HW3d. This possible multiplicity can be tested with SMA and EVLA high-angular-resolution observations.

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APPENDIX

We have carried out careful registration and identification of the H₂O maser relative proper motions in HW3d especially for the masers in the C cluster (see Figure 2). Maser features coincident in LSR velocity within 1 km s⁻¹ and position offset within 2 mas between epochs were used in tracing the proper motions. A larger fraction of the proper motions were traced in three or more epochs, while some were traced in just two epochs. The proper motions traced in two epochs are clearly isolated in either LSR velocity, position, or both. This is to avoid any case of proper motion misidentification especially in the complex C maser cluster. Before arriving at the 30 H₂O maser proper motions, we have carefully dropped some maser proper motions with high identification uncertainties. The tracing of the relative proper motions is shown in Figure 4. A gradient is expected for the R.A. and decl. trace of the maser relative motions except for the reference maser feature (Feature 15) which is quasi-stationary, but the LSR velocity is observed to remain constant. It can be observed that the LSR velocity was not actually constant in some of the proper motions. Some of the masers indicate LSR velocity drift, but in this paper we do not consider the possible acceleration of the H₂O masers.

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