A Collimated Bipolar Water Maser Outflow in the HW3d Region of Cepheus A

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Chibueze James Okwe
Radio Astronomy Group,
Graduate School of Science & Engineering,
Kagoshima University
Abstract

Results of multi-epoch very long baseline interferometry (VLBI) observations carried out with the VLBI Exploration of Radio Astrometry (VERA) toward the H2O masers in the Cepheus A massive star-forming region.

Obtained the relative proper motions of 30 H2O masers features detected toward the HW3dii region and they seem to be tracing bipolar outflow in the region. The bipolar outflow traced by the water masers is highly collimated, extending over ~400 mas and having a typical proper motion velocity of ~2mas/yr. The dynamical timescale of the outflow was estimated to be 100 years, showing that the outflow is tracing an early formation phase.

Astrometric analysis on one of the observational epoch to determine the absolute coordinates of the masers.

Using very long array (VLA) archive data of 1995 and 2006 at 1.3cm towards Cepheus A, we obtained continuum maps of HW3dii and compared them with the VERA results.

Result thus provides valid evidence of the presence of an exciting source in the HW3d with possibility of the presence of multiple objects in the region.
Goal

- Understanding massive star formation by conducting a statistical study of the maser spatio-kinematics in as many massive star-forming region as possible.
Introduction

• Massive star formation unlike its low-mass counterpart is yet poorly understood
• Complex formation environment caused by closeness of high-mass stars (complicated interactions)
• Short formation timescale & observation sensitivity issues.
Introduction – Recent Results

Main goal
Evolution and nature of the maser structures found in the earlier (1996) VLBA observations

Five observed epochs
2001 Jul 11
2001 Jul 30
2001 Aug 18
2001 Sep 13
2002 Jan 27
Beam = 0.4 mas (0.3 AU)

~ 1800 maser spots detected in each epoch

Torrelles et al. (2011)
Expanding elliptical ring \((r \approx 35 \text{ mas}, 25 \text{ AU})\) rather than a simple bow-shock.

Violent ejection(s) (dynamical time \(\sim 10 \text{ yr}\)) from a massive YSO (still unidentified), predicted to be located at the center of the ring,(-0.03”, -0.18”) from HW2.

To be tested with EVLA/e-MERLIN continuum observations.
Expanding ($\sim 10 \text{ km/s}$) bubble ($\sim 60 \text{ AU}$) currently dissipating in the circumstellar medium, losing its degree of symmetry

Short-lived isotropic ejection event (dynamical time $\sim$ tens of years), excited by a massive YSO of $\sim 10 \, M_\odot$ (already detected)

After R5, other similar examples have been identified in massive YSOs with “isotropic ejections” (e.g., W75N, G24.78; see Surcis et al. 2011), indicating that the very first stages of massive protostars could have these kind of outflows
μ ≈ 13 km/s
$0.5 \text{ AU}$

$\mu \approx 18 \text{ km/s}$
$\mu \approx 70 \text{ km/s}$
\( \mu \approx 70 \text{ km/s} \)

\( \mu \approx 13 \text{ km/s} \)

\( \mu \approx 18 \text{ km/s} \)
## Observations & Data Analysis

### VERA Observation
- K-band, 22GHz
- Target source: Cepheus A
- Phase reference source: J2302+6405
- Number of epochs: 9
- Epoch codes: r06133b, r06208an, r06291a, r06310a, r07004a, r07049a, r07103a, r07135a, and r07243a

### VLA Observations
- 1.3cm continuum, 22GHz
- Target source: Cepheus A
- Observation epochs: 1995 & 2006

### Data Analysis

AIPS normal calibration procedures

Self-calibration

- Proper motion identification technique *(maser features were used, proper motions were identified in 3 or more epochs and in 2 epochs for cases of velocity or position isolation)*
• To obtain the absolute position of the masers, astrometric data reduction was done with the r07049a epoch using the inverse phase referencing technique.

• The phase reference source, though weak, was detected (27 milliJy/beam)

• Thus superposing of masers obtained from VERa and the VLA continuum map was possible.
Results

• **VERA Result**
• Detected masers spots corresponding to the R1, R2, R3, R4, R5, R6, and R8 maser clusters of the HW2 region as well as the maser cluster associated with the HW3d region.
• Masers associated with R7 were not detected.
• Obtained 30 maser proper motions in HW3d
• Tracing a bipolar outflow from a dynamical center.
• The outflow extends over a distance of \( \sim 400 \) mas, having a typical proper motion of \( \sim 2 \) mas yr\(^{-1}\).
• Dynamical timescale of the outflow to be \( \sim 100 \) years, early formation phase.
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• Comparing VLA Maps
• 1.3cm continuum map from VLA archive data of 1995 and 2006

Orange-colored contour map represent the 1995 epoch while the white-colored contour map represents the 2006 epoch
• Estimated proper motion velocity of the peak (for the case of same source) per year shielded $\sim 65$ km/s/yr
• Possibility of a single very fast moving object? Or the presence of multiple sources.
Discussion

• Spatio-kinematics modeling of the maser features.  
  (Non-linear least-square method involving Levenburg-Marquart minimization technique)

• Case 1: Assuming a single exciting source

• Case 2: Assuming two exciting sources are present

• Since the model assumes expanding (outflow) motion, the model fitting result would show positive data points if outflow exists.

\[
\begin{array}{cccc}
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 & HW3dii & HW3dii(east) & HW3dii(west) \\
N_{\text{feature}} & 30 & 13 & 17 \\
\hline
\text{Systemic proper motion:} & & & \\
V_{0x} (\text{km s}^{-1}) & -2.5\pm3.0 & 11.9\pm0.1 & -21.8\pm3.6 \\
V_{0y} (\text{km s}^{-1}) & 5.4\pm2.2 & -1.2\pm0.1 & 12.7\pm2.0 \\
\text{Position offset:} & & & \\
x_0 (\text{arcsec}) & 0.020\pm0.011 & 0.206\pm0.003 & -0.100\pm0.014 \\
y_0 (\text{arcsec}) & -0.017\pm0.009 & -0.060\pm0.004 & 0.058\pm0.009 \\
\sqrt{S^2} & 3.3 & 2.2 & 1.4 \\
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\* Mean of the root-mean-square residual of the model fitting.
Top panel shows the result for the assumption of a single exciting source.

Middle panel shows the result of HW3d east

Bottom panel shows the result of the HW3d west
CONCLUSIONS

• Water maser kinematics can be used to trace the evolutionary phases of massive star formation

• Outflow traced by maser proper motion provides a proof of the presence of an internal exciting source.

• HW3d may be an early phase of the more evolved HW2, with the possibility of multiple sources.