The Extraordinary Outburst in the Massive Protostellar System NGC 6334 I-MM1: Spatiokinematics of Water Masers during a Contemporaneous Flare Event

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Abstract

Following an eruptive accretion event in NGC 6334I-MM1, flares in the various maser species, including water masers, were triggered. We report the observed relative proper motion of the highly variable water masers associated with the massive star-forming region, NGC 6334I. High velocity H2O maser proper motions were detected in five maser clusters, CM2-W2 (bow-shock structure), MM1-W1, MM1-W3, UCHII-W1, and UCHII-W3. The overall average of the derived proper motion is 85 km s\(^{-1}\). This mean proper motion is in agreement with the previous results from VLA multiepoch observations. Our position as well as the velocity variance and covariance matrix analyses of the maser proper motions show its major axis to have a position angle of \(-79^\circ\), cutting through the dust cavity around MM1B and being aligned in the northwest–southeast direction. We interpret this as the axis of the jet driving the CM2 shock and the maser motion. The complicated proper motions in MM1-W1 can be explained by the combined influence of the MM1 northeast–southwest bipolar outflow, the CS(6–5) north–south collimated bipolar outflow, and the radio jet. The relative proper motions of the H2O masers in UCHII-W1 are likely not driven by the jets of the MM1B protostar but by MM3-UCHII. Overall, the post-accretion burst relative proper motions of the H2O masers trace shocks of jet motion.

Unified Astronomy Thesaurus concepts: Stellar jets (1607); Star forming regions (1565); Astrophysical masers (103); Long baseline interferometry (932); Shocks (2086)

Supporting material: machine-readable table

1. Introduction

Accretion in young massive protostars is a complex phenomenon. Irregular and fragmented accretion disks lead to episodic accretion with long periods of relatively slow accretion rate and short periods of high mass gain (Meyer et al. 2017). High accretion rates (also called accretion bursts) have been directly observed in massive protostars of S255IR (Caratti o Garatti et al. 2017), NGC 6334I-MM1 (Hunter et al. 2017), and G358.93-0.03-MM1 (Burns et al. 2020). The high accretion rate heats up the protostellar disk, which in turn can dramatically increase thermal radiation by the surrounding dust. Among the consequences of accretion events are the enhancement of existing spectral line emission (Brogan et al. 2018; Hunter et al. 2018; Burns et al. 2020) and the excitation of new maser lines (Brogan et al. 2019; MacLeod et al. 2019; Chen et al. 2020a, 2020b; Volvach et al. 2020). Accretion bursts can also significantly alter the chemical makeup of the protostellar disk for a short time, as observed in low mass protostars (Visser et al. 2015).

In general, astrophysical masers provide clues to the physical conditions and the kinematics of protostellar systems. Maser flares have been found to accompany accretion bursts initially identified in many observations: in 6.7 GHz CH3OH masers near S255IR (Moscadelli et al. 2017; Szymczak et al. 2018) and many maser species from NGC 6334I (MacLeod et al. 2018). Long-term single-dish monitoring observations of variable masers can provide an excellent mechanism to identify the onset of an accretion burst. The early identification of an accretion burst via maser monitoring was detected in G358.93-0.03 by Sugiyama et al. (2019). This exciting result led to the detection of a wide range of methanol maser transitions including several that were not even predicted to exist (Breen et al. 2019; Brogan et al. 2019; MacLeod et al. 2019). Monitoring of 19.967 GHz CH3OH masers toward G358.93-0.03 are presented in Volvach et al. (2020) and for other transitions, in MacLeod G. C. et al. (2021, in preparation) and Yonekura Y. et al. (2021, in preparation).

High-resolution multiepoch Very Long Baseline Interferometry (VLBI) studies of maser proper motion measurements provide useful insights into the gas spatiokinematics of protostellar disks, outflows, and shocks (Moscadelli et al. 2011; Chibueze et al. 2012; Torrelles et al. 2014). NGC 6334I, located at a parallax distance of 1.30 ± 0.09 kpc (Chibueze et al. 2014; Reid et al. 2014; Wu et al. 2014), is a massive star-forming region containing a massive protostar that has recently undergone an accretion burst. Millimeter and submillimeter observations using the Submillimeter Array (SMA) first identified four compact sources in NGC 6334I (MM1-MM4). MM1 and MM2 were the brightest dust sources while MM3 coincided with the ultra-compact H II region NGC 6334 F (Hunter et al. 2006). Five more continuum sources (MM5-MM9) were later identified using the Atacama Large...
Millimeter/submillimeter Array (ALMA) and MM1 was also resolved into six continuum components (A–F) at 1.3 mm (Brogan et al. 2016). Properties of the individual components were modeled, with several having high dust and brightness temperatures $T_{\text{dust}} > 300 \, \text{K}$, $T_{\text{brightness}} > 200 \, \text{K}$. Continuum emission associated with MM1, MM3-UCHII, and CM2 (located north of MM1) was detected in the 5 cm observations of NGC 6334I made using the Karl G. Jansky Very Large Array (VLA; Brogan et al. 2016). Comparison of the ALMA images with earlier SMA images revealed that the luminosity of MM1 increased by a factor of $l_{\text{inc}} = 70 \pm 20$ (Hunter et al. 2017) between 2008 and 2015, with the centroid of the increase aligned with protostar MM1B. In a parallel discovery, MM1F, MM1G, MM1C, and MM3-UCHII underwent their first observed activation of 6.7 GHz masers (Hunter et al. 2018), contemporaneous with flaring of nine other maser transitions beginning in 2015 January (MacLeod et al. 2018). Follow-up 22 GHz $H_2O$ maser emission measurements using VLA identified flaring of water masers in a bow-shock shape in CM2 (Brogan et al. 2018). In contrast, the $H_2O$ masers previously seen surrounding MM1B were also damped significantly, likely due to increased dust temperatures.

Single-dish observations in various CO and CS transitions have consistently shown a northeast–southwest outflow at large scales ($\sim 0.5$ pc) whose origin is centered on MM1 or MM2 (Bachiller & Cernicharo 1990; McCutcheon et al. 2000; Leurini et al. 2006; Qiu et al. 2011). Later interferometric imaging with ALMA of CS(6–5) resolved the central part of the outflow, confirming MM1 as the primary origin, and revealing a north–south outflow centered on MM1B and a blueshifted northwest lobe (Brogan et al. 2018). Subsequent imaging of CS(18–17) and HDO in ALMA Band 10 (McGuire et al. 2018) demonstrated excellent spatial alignment between the warm thermal gas tracing the compact outflow and the 22 GHz $H_2O$ masers embedded in it.

In this paper, we present multi-epoch VLBI measurements of the 22 GHz $H_2O$ maser emission using a combination of Korean VLBI Network (KVN) and VLBI Exploration of Radio Astronomy (VERA) during the first year of the accretion burst event. We derive the relative proper motion measurements for these $H_2O$ masers in order to probe the kinematics of the gas surrounding MM1 and MM3-UCHII in this region of active star formation.

2. Observations and Data Reduction

2.1. Single-dish Monitoring Observations

The ongoing 22.2 GHz (1.3 cm) water maser observations reported here were made using the 26 m telescope of Hartebeesthoek Radio Astronomy Observatory (HartRAO). The single-dish results reported in this paper cover observations taken between 2013 May 7 and 2020 December 2. The coordinates that the telescope pointed to were $(\alpha, \delta) = (17^h20^m53^s4, -35^\circ 47'01''5)$. The beamwidth for this receiver is 2.2'. Pointing observations were made for each epoch. These observations were also corrected for atmospheric absorption. Because of the large velocity extent position switching was employed. The rest frequency of the receiver was set to 22.235120 GHz. The receiver system consisted of left (LCP) and right circularly polarized (RCP) feeds. Dual polarization spectra were obtained using a 1024-channel (per polarization) spectrometer. The receiver is cryogenically cooled. Each polarization is calibrated independently relative to Hydra A, 3C 123, and Jupiter, assuming the flux scale of Ott et al. (1994). The bandwidth was 8 MHz providing a velocity resolution of 0.105 km s$^{-1}$ and a total velocity extent of 107.9 km s$^{-1}$. Typical sensitivities achieved per observation were 2.3–2.9 Jy. Typically, observations were made every 10–15 days. However, the cadence of observations varied depending on the availability of the telescope and the weather conditions. At times observations were done daily, but there are also observations separated by weeks.

2.2. KaVA Observations

$H_2O$ masers in NGC 6334I were observed with the KVN and VERA Array (KaVA) in three epochs taken on 2015 November 21 (2015.89), 2015 December 15 (2015.95), and 2016 January 4 (2016.01), respectively. The position of the phase tracking center of NGC 6334I was $(\alpha, \delta) = (17^h20^m53^s377, -35^\circ 46' 55.08'')$ in the J2000.0 epoch. NRAO530 was used as the bandpass calibrator.

The total bandwidth was 256 MHz (16 MHz × 16 IFs) and data were recorded for the left-hand circular polarization at a 1 Gbps sampling rate. We analyzed only the one 16 MHz IF channel that contained the $H_2O$ 6–5$_{0,1}$–5$_{-3}$ transition. The spectral resolution is 15.625 kHz (0.21 km s$^{-1}$) for the $H_2O$ maser line. The correlation process was carried out at the Korean-Japan Correlation Center, Daejeon, Korea (KJCC: Lee et al. 2015).

The data calibration was carried out using the Astronomical Image Processing System (AIPS) developed by the National Radio Astronomy Observatory (NRAO; van Moorsel et al. 1996). First, the amplitude was calibrated by using AIPS task APCAL using system temperature and measured antenna gains. Next, delays and phase offsets were removed by running AIPS task FRING using NRAO530. Bandpass response was also calibrated using NRAO530. The 3.9 km s$^{-1}$ velocity component of the masers was used as a reference maser component in NGC 6334I. Imaging and CLEAN (deconvolution) were performed using the AIPS task IMAGR. The SAD task was employed for the Gaussian fitting for extraction of the peak intensities and offset positions of the maser spots. A maser “spot” refers to an individual maser emission peak in a spectral channel while a maser feature denotes a group of maser spots considered to exist within the same maser cloudlet and located physically close to each other. The synthesized beams for the first, second, and third epochs was 2.48 mas × 0.97 mas (position angle, PA = $-0^\circ 38'$), 2.66 mas × 1.01 mas (PA = $2^\circ 82'$), and 2.76 mas × 1.06 mas (PA = $10^\circ 64'$), respectively.

Masers features, defined as clusters of masers spots having a position defined by the position of the brightest peak, were carefully identified in each epoch. Maser distributions in MM1-W1 and UCHII-W1 varied significantly from epoch to epoch, and this complexity may have affected, in small measures, the derived proper motions. Our single-dish results support the complex structures of these masers (see Section 3.1). The proper motions $\mu_\alpha$ in R.A., and $\mu_\delta$ in decl. were calculated using the displacement $(\Delta \alpha \cos \delta, \Delta \delta)$ of the maser feature over adjacent epochs. For features detected in all three epochs, the average of the proper motion between epochs 1 and 2, and epochs 2 and 3 were taken.

Fringe-rate mapping was used to derive the absolute position of the reference maser spot and then compared to the closest epoch of the VLA $H_2O$ maser map to obtain the absolute positions of the maser spots/features. The positional accuracy of the masers are within 1.0 mas in R.A. and 3.5 mas in decl.
To register the relative positions of the maser features in the three epochs, we use the position of a bright maser spot in UCHII-W1 region as a reference. The derived relative proper motions are marginally affected by the intrinsic motion of the reference maser spot. The overall uncertainty in our derived relative proper motions due to the motion of the reference maser spot is <10%. This is obtained from the group motion of all maser features around the reference maser spot. It should be noted that all proper motions reported in this work are relative proper motions.

3. Results

3.1. Structures in the H$_2$O Maser Dynamic Spectra

The dynamic spectra of the long-term monitoring of H$_2$O masers is shown in Figures 1(A) and (B). The image provides an interesting metric demonstrating the longevity of emission in a given velocity extent. We note that a subset of this data was presented in MacLeod et al. (2018). The water emission in $-14 \leq V_{LSR} \leq -4$ km s$^{-1}$ suffers significant line blending making it impossible to disentangle maser features and structure in this single-dish data. In panels (a)–(d) more independent masers are visible. In these, and during the MJD extent between the first and last epoch of VLBI observations, little velocity drift appears present in most. Possible velocity drifts may be present in this MJD extent for emission in $-45 \leq V_{LSR} \leq -35$ km s$^{-1}$. This may be the result of multiple masers varying independently. Still the continuity of maser emission during this MJD extent lends comfort to the study of proper motion below.

Between the onset of the 6.7 GHz CH$_3$OH maser burst and the first maximum of the burst (white and black lines in Figure 1(A), respectively), H$_2$O masers in the region are mostly destroyed or heavily suppressed. However, Figure 1(B) shows that most of the maser features, though varied in the flux densities, survived through the epochs of our VLBI observations.

Figure 2 shows the single-dish (HartRAO 26 m) spectra of the highly variable H$_2$O masers in NGC 6334I taken nearest the respective VLBI observations. Significant variations can be seen between 2015 November 18 and 2016 January 1. The most prominent feature of the spectra, $-7$ km s$^{-1}$, and a second, $-15$ km s$^{-1}$, feature are brightening, the rest of the maser features are weakening.

3.2. Proper Motions of the H$_2$O Masers

We obtained the absolute position of the reference maser spot (used for the self-calibration) in the first epoch. This position, with full consideration of the proper motion of the reference maser spot, was used for the registration of the maps in the three epochs. We traced 186 maser proper motions, divided into groups according to the nomenclature used by Brogan et al. (2018).

Figures 3–6 show the traced H$_2$O maser proper motions overlaid on the ALMA 1.3 mm dust continuum from a comparable epoch (2016.6, grayscale from Hunter et al. 2017) and the VLA 5 cm image (white contours from Hunter et al. 2018). The colored vectors (arrows) represent the H$_2$O proper motions traced in the region. The length of each arrow indicates the magnitude of the proper motion and the direction of the arrow indicates the proper motion direction. Proper motions are measured with respect to the reference maser spot in UCHII-W1 located at $(\alpha, \delta) = (\alpha, \delta) = (17^h20^m52^s, -35^\circ46'50")$. The gray circles are water maser detection from Brogan et al. (2018) for comparison. Figures 4–6 show zoomed-in images of the proper motions of different maser groups with colors of the $V_{LSR}$ of the masers (as in Figure 3).

We detected water maser proper motions in the regions CM2-W2, MM1-W1, MM1-W3, UCHII-W1, and UCHII-W3. The positions, proper motions, $V_{LSR}$, and epochs of detection are shown in Table 1. A “+” indicates a detection in a specific epoch of a specific maser feature, while “−” signifies a nondetection. The majority of all the proper motions (56.5%) were traced using all three epochs, while the remaining 43.5% were traced in two epochs. The overall mean of the 3D velocities of the masers is 85 km s$^{-1}$. For the rest of this section, average velocity refers to the magnitude of the average three-dimensional velocity. In the following paragraphs, we describe the properties of each of the groups.
The northernmost region, CM2-W2, is ∼2750 au from MM1B with 87 proper motions. Figure 4 shows the spatial distribution, and proper motions of the H$_2$O masers in the region. There were 39 maser features detected in all three epochs. The proper motions have a spatial distribution comparable to a bow-shock shaped structure. Most of the proper motions point north, with an average velocity of 112 km s$^{-1}$. The region also shows a drastic $V_{\text{LSR}}$ gradient throughout the structure with $-46.98 < V_{\text{LSR}} < 0.63$ km s$^{-1}$. The proper motions detected spanned a linear size of ∼219 au from east to west.

MM1-W1 is found just below MM1B (∼510 au) and is a more complicated region, with proper motions pointing in various directions. The maser spots showing a linear structure with a length of ∼18 au. Figure 5 shows high-resolution images of the spatial distribution and proper motions of water masers in MM1-W1 and MM1-W3. We detected 25 proper motions, 14 traced in three epochs. The average velocity of the region is 43 km s$^{-1}$ and $-0.21 < V_{\text{LSR}} < -3.8$ km s$^{-1}$. The region shows great variation in proper motion direction and magnitude over a relatively small region although there is not a large $V_{\text{LSR}}$ gradient. The region contains a number of high velocity proper motions pointing northward with an average velocity of 54 km s$^{-1}$. The complexity of the observed proper motions can be attributed to the combined influence of the MM1 northeast–southwest, CS(6–5) north-source bipolar outflows, and the radio jet. The relative error in proper motion of this region is only ∼20% for most of the constituent proper motions, indicating that the proper motions do reflect multiple influences on the motion of the maser cloudlets in the region.

MM1-W3 is the maser group just north of MM1B (∼510 au). We detected 13 proper motions with an average velocity of 106 km s$^{-1}$. The region has two distinct associations. The northeastern association consists of eight proper motions, five

Figure 2. Single-dish H$_2$O maser spectra of NGC 6334I taken with HartRAO 26 m closest (within ±4 days) to each of the three epochs of our KaVA observations. Panel (a) shows the full spectra and panel (b) shows the zoomed-in image of the weaker maser features.

Figure 3. H$_2$O maser proper motions derived from our KaVA observations overlaid on 2016.6 ALMA 1.3 mm continuum (brown scale; Hunter et al. 2017). Gray contours are 2016.9 VLA 5 cm continuum observations with levels $0.022 \times [4, 9, 260, 600]$ mJy beam$^{-1}$ (Hunter et al. 2018). H$_2$O maser regions are named according to the corresponding maser groups of Brogan et al. (2018) from north to south (black labels). The blue dashed line shows the axes of the MM1B northwest jet. The red dotted line shows the NE–SW wide angle outflow from MM1 and the black dashed line shows the outflow traced in CS(6–5). The black circles trace water masers measured by VLA in the 2017.8 epoch of Brogan et al. (2018). The gray dotted line shows the main velocity axes derived from the VVCM analysis (see Section 4.1). The linear scale and the transverse velocity scale is shown in the top left corner. The radial velocity of the proper motions is indicated by the color scale. The synthesized beams are shown in the top left corner, where the white and gray ellipses are VLA and ALMA’s beams, respectively. The offsets (visible in zoomed-in images) in the positions of the VLA 2017.8 maser features (black circles) could be due to an error in the absolute position of our KaVA reference maser spot and/or the relative position uncertainty (19 mas in R.A and 66 mas in decl.) of the VLA observations.

are traced in all three epochs. The proper motions point northward with an average of 126 km s$^{-1}$ and a radial velocity $V_{\text{LSR}} \approx -62$ km s$^{-1}$. The second association points northward,
with four of the five proper motions only being traced in two epochs. The average velocity of the association is 72 km s\(^{-1}\) and \(V_{\text{LSR}} \approx 14 \text{ km s}^{-1}\). The linear separation between the two associations is \(\sim 55 \text{ au}\).

UCHII-W1 is about 4300 au south of MM1B. We detected 48 proper motions, with 37 traced in three epochs. The region has an average velocity of 64 km s\(^{-1}\). There is a small radial velocity gradient with \(-16.0 < V_{\text{LSR}} < -8.2 \text{ km s}^{-1}\). It should be noted that the maser spot distribution in this region was very complicated and the tracing of proper motions was difficult. Figure 6 shows the spacial distribution and proper motions of masers in the MM3-UCHII region and a high-resolution image of proper motions in UCHII-W1. Our results show a bulk motion to the north.

UCHII-W3 is well south of MM1 (~2600 au), corresponding to the edge of a jet traced by a CS (6–5) map from Brogan et al. (2018). We detected four proper motions with an average velocity of 89 km s\(^{-1}\) pointing to the southeast. Two maser associations are resolved \(\sim 43\) au apart, the eastern association has an average velocity of 96 km s\(^{-1}\) and \(V_{\text{LSR}} \approx -48 \text{ km s}^{-1}\). The western region has an average velocity of 81 km s\(^{-1}\) and \(V_{\text{LSR}} \approx -36 \text{ km s}^{-1}\).

4. Discussion

4.1. VVCM Analysis

In order to characterize the proper motions of the outflow, we used the position variance–covariance matrix and velocity variance–covariance matrix (PVCM and VVCM) as described by Bloemhof (1993, 2000) and Chibueze et al. (2012). These matrices provide a robust and objective means of extracting the position and kinematic essentials from maser proper motions. The PVCM and VVCM, \(\sigma\), are constructed using:

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

with \(i, j\) iterating over the spatial axes (\(\alpha, \delta\) for the position variance–covariance matrix) and (\(v_\alpha, v_\delta, V_{\text{LSR}}\) for the velocity variance–covariance matrix), \(n\) the \(n\)th of \(N\) maser spots/proper
motions \((N = 186)\). The bar indicates the average overall proper motions. The diagonal entries of the matrix \(\sigma\) is the variance of the variable while the off-diagonal entries are the covariance of two variables.

The PVCM gives a \(2 \times 2\) matrix and using all the regions except UCHII-W1, the PVCM (in units of \(10^{-6}\) arcsec\(^2\)) and its diagonalization were obtained to be:

\[
\begin{pmatrix}
0.034 & -0.163 \\
-0.163 & 0.867
\end{pmatrix}
\Rightarrow
\begin{pmatrix}
0.003 & 0 \\
0 & 0.897
\end{pmatrix}.
\]  
(2)

The corresponding \(3 \times 3\) VVCM matrix and its diagonalization (in units of km\(^2\) s\(^{-1}\)) are given by:

\[
\begin{pmatrix}
454.48 & -476.45 & 132.01 \\
-476.45 & 3431.65 & -108.46 \\
132.01 & -108.46 & 279.21
\end{pmatrix}
\Rightarrow
\begin{pmatrix}
3511.08 & 0 & 0 \\
0 & 452.48 & 0 \\
0 & 0 & 201.79
\end{pmatrix}.
\]  
(3)

Table 2 shows the results of PVCM and VVCM analyses. In Table 2, \(\psi_{\text{max}}\) indicates the largest eigenvalue of the PVCM/VVCM matrix, \(\psi_{\text{min}}\) the smallest eigenvalue and \(\psi_{\text{mid}}\) the middle-valued eigenvalue for the VVCM matrix. The large difference in the magnitudes of the eigenvalues of both position and velocity variance matrices demonstrates the presence of a distinct spatial and kinematic axis in the data. The major axis is defined by the eigenvector corresponding to the largest eigenvalue. The position angle is calculated by projecting the major axis onto the celestial sphere. The axis from the VVCM is plotted in Figure 3 (and its zoomed-in images) with a P.A. of \(-79.4^\circ\) and passing through the position of MM1B from Brogan et al. (2016). The error in the position angle was calculated using a Monte Carlo error of the velocity vectors. UCHII-W1 was not included as the direction of its motion does not seem to be influenced by the jet from MM1B. It should also be noted that including UCHII-W1 in the calculation makes only a marginal difference in the results \((\Delta PA_{\text{max}} \sim -2.25^\circ, \Delta \phi_{\text{max}} \sim 5.88^\circ)\). The axis derived aligns very well with a bipolar outflow terminating at CM2-W2 and UCHII-W3. Assuming the bow-shock in CM2 is symmetric, the inferred inclination angle for this outflow from matrix 2 is \(\phi_{\text{max}} = -6.0^\circ \pm 0.6^\circ\).

4.2. Jet, Cavity, and Shock Structures in MM1

High proper motions of H\(_2\)O near the path of the radio jet of Cepheus A-HW2 is attributed to the influence of the fast moving jet (Torrelles et al. 2011). Typical proper motions of low velocity outflows and expanding ring/bubble structures are \(~10\) km s\(^{-1}\) (Torrelles et al. 2011; Chibueze et al. 2012, 2014). With the mean H\(_2\)O maser proper motion of \(86\) km s\(^{-1}\), the masing cloudlets in NGC 6334I are driven by the jet in MM1. Our VVCM analysis indicates the northwest–southeast axis of the jet driving the maser proper motions (at least of CM2-W2, MM1-W3, MM1-W1, and UCHII-W3) as shown with dotted gray lines in Figure 3. Interestingly, this axis cut through dips in ALMA dust continuum, one in the northwest and the other in the southeast. We interpret these dips as cavities plowed by the jets and this agrees with the suggested excavated outflow cavity by Brogan et al. (2018).

To test the possibility of precession in the jet motion, we compare the position angle of the VVCM results derived with all maser regions with those of the inner regions. About 10\(^\circ\) difference is observed between the two position angles. This could be an indication of jet precession. MM1-W1 and MM1-W3 masers are closer to MM1 (driving source of the jet) and
assuming a jet velocity of 150 km s$^{-1}$, it will take 95 yr for a jet launched by MM1 to reach the location of CM2.

The synchrotron continuum point source CM2 (Brogan et al. 2018), located northwest of the radio jet of MM1B, hosts the bright masers in the region and its nature has been discussed in Brogan et al. (2018). The observed proper motions of H$_2$O masers in CM2 are similar to those reported in Burns et al. (2016). In a study of S255IR-SMA1 they reported a bow-shock shape traced in H$_2$O masers with a velocity of $\sim$20 km s$^{-1}$, and a $V_{\text{LSR}}$ gradient throughout the shock. They also reported three

![Figure 6. Left: zoomed-in image of the UCHII region. Right: high-resolution image of the proper motions of the UCHII-W1 region. The $V_{\text{LSR}}$ scale for both images is shown on the colorbar of the left image. Contour lines, black circles, and the gray dotted line are the same as in Figure 3 for both images. Linear distance and velocity scale are shown in the top left of both images.](image)

**Table 1**

| ID | Region | Offset | Proper Motion | Radial Motion | Detections |
|----|--------|--------|---------------|---------------|------------|
|    |        | $\alpha$ | $\delta$ | $\mu_x$ | $\sigma_{\mu_x}$ | $\mu_y$ | $\sigma_{\mu_y}$ | $V_{\text{LSR}}$ | 1 | 2 | 3 |
| 1  | CM2-W2 | 2.394  | 0.168 | 21.709 | 0.168 | -27.594 | + | + | - |
| 2  | CM2-W2 | 3.711  | 0.168 | 24.368 | 0.168 | -28.226 | + | + | - |
| 3  | CM2-W2 | 0.980  | 2.200 | 12.964 | 0.413 | -5.477 | + | + | - |
| 4  | CM2-W2 | 0.000  | 0.213 | 17.487 | 0.213 | -14.535 | + | + | - |
| 5  | CM2-W2 | 1.400  | 0.231 | 35.020 | 0.213 | -14.533 | + | + | - |
| 6  | CM2-W2 | 1.284  | 0.373 | 17.487 | 0.413 | -14.533 | + | + | - |
| 7  | CM2-W2 | 1.658  | 0.213 | 17.487 | 0.413 | -14.533 | + | + | - |
| 8  | CM2-W2 | 1.960  | 0.213 | 21.105 | 0.213 | -2.316 | + | + | - |
| 9  | CM2-W2 | 0.238  | 1.643 | 30.351 | 3.193 | -0.206 | + | + | - |
| 10 | CM2-W2| 4.179  | 0.168 | 17.412 | 0.168 | -14.112 | + | + | - |

**Notes.**

a Maser feature ID.
b Offsets are with respect to the reference maser at ($\alpha$, $\delta$) = (17h20m52s600, $-$35°46'50"508).

(This table is available in its entirety in machine-readable form.)
distinct ejections, with the most recent ejection being the shock traced in H$_2$O masers with a dynamical timescale $t_{\text{dyn}} \lesssim 130$ yr. Ogbodo et al. (2017) also reported a bow-shock structure for IRAS 20231+3440 traced with H$_2$O masers, with an average maser velocity of 14.26 km s$^{-1}$. These studies report bow-shock maser velocities significantly lower than we found in NGC 6334I. Further studies into the driving mechanisms of the jets and outflows of NGC 6334I and other sources are necessary to explain the bow-shock velocity discrepancies. This and the above mentioned studies (among others) indicate that a high velocity ($V_{\text{ave}} > 10$ km s$^{-1}$) H$_2$O maser proper motions in a bow-shock shape might be a common tracer for jets in massive protostars.

### 4.3. Impact of MM3-UCHII on UCHII-W1 Maser Spatiokinematics

Brogan et al. (2018) reported a bulk motion of 112 ± 12 km s$^{-1}$ for the UCHII-W1 maser group using multiepoch VLA observations between 2011 (pre-burst) and 2017 (post-burst). They suggested that the H$_2$O masers of the two 2017 epochs are possibly pumped by the beamed radiation from MM1B. The proper motions of UCHII-W1 point northward against the direction of the jet. This suggests that spatiokinematics of the masering gas in this subregion is not driven by the jet but by the MM3-UCHII.

We investigated the possibility that the magnetic field reversal reported by Caswell et al. (2011) and Hunter et al. (2018) are responsible for the northward proper motion of UCHII-W1 H$_2$O masers. A reversal in magnetic field is reported in OH masers in UCHII-OH6 (located 0°35 southwest of UCHII-W1) and UCHII-OH7 (located 0°7 south of UCHII-W3) (see Figure 5 and Table 8 of Hunter et al. 2018). The reversed Zeeman splitted OH masers are >500 au from UCHII-W1 and rather closer to UCHII-W3 and W2 (see Brogan et al. 2018), and therefore may not be responsible for the observed northward proper motions of UCHII-W1 masers. The UCHII-W1 proper motion is likely driven by MM3-UCHII or by the outflow of TPR-9 (with X-ray counterpart, CXOU 172053.21-354726.4) infrared star (Tapia et al. 1996) as suggested by Brogan et al. (2018).

### 5. Conclusion and Summary

We reported for the first time the spatiokinematics of H$_2$O masers in a massive star-forming region (NGC 6334I) just after an accretion event. The proper motions of the H$_2$O masers in CM2-W2, MM1-W3, MM1-W1, and UCHII-W3 are mostly driven by the radio jet of MM1-B. However, some influence from the outflowing gas in MM1 northwest–southeast bipolar outflow and MM1B northwest outflow cannot be completely excluded.

Our results suggested that the motion of the UCHII-W1 H$_2$O maser group is largely driven by the expansion of MM3-UCHII. The significance of impact of the accretion event on the proper motions of the H$_2$O maser, with special consideration of the destruction and reexcitation of the H$_2$O masers in the region, will be presented in Vorster J. et al. (2021, in preparation), which will compare the pre-burst and post-burst H$_2$O maser proper motions. The impact of a heat wave, such as the one reported in Burns et al. (2020), will be explored with the pre-accretion burst VLBI H$_2$O maser data.

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**Table 2**

Position and Velocity Variance/Covariance Matrix Analysis for the NGC 6334I Proper Motions

| Matrix No. | $\psi_{\text{max}}$ (10$^{-6}$ arcsec$^2$) | $\psi_{\text{mid}}$ (10$^{-6}$ arcsec$^2$) | $\psi_{\text{min}}$ (10$^{-6}$ arcsec$^2$) | $\psi_{\text{max}}$ | $\psi_{\text{mid}}$ | $\psi_{\text{min}}$ |
|-----------|--------------------------------|--------------------------------|--------------------------------|-----------------|-----------------|-----------------|
| 1         | 0.897                          | 0.003                          | 79.3                           | 0.0003          | 0.0001          | -84.4           |
| 2         | 0.545                          | 0.002                          | 79.0                           | 0.0001          | -1.5            | 8.8             |
| 3         | 0.152                          | 0.0001                         | -32.4                          | -2.9 ± 0.3      | 35.1 ± 6.3      |

Notes:

1. CM2-W2, MM1-W1, MM1-W3, and UCHII-W3. All the maser regions associated with the jet. (2) CM2-W2 and UCHII-W3. The maser regions furthest from MM1B. (3) MM1-W1 and MM1-W3. The maser regions closest to MM1B.

2. Position angle of the axis with the largest eigenvalue $\psi_{\text{max}}$.

3. Position angle of the axis with the second largest eigenvalue $\psi_{\text{mid}}$.

4. Inclination angle of the axis corresponding to $\psi_{\text{max}}$ with respect to the sky plane.

5. Inclination angle of the axis corresponding to $\psi_{\text{mid}}$ with respect to the sky plane.
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