Spatio-kinematics of the massive star forming region NGC6334I during an episodic accretion event

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Abstract. Episodic accretion in massive protostars is an exciting and upcoming field of study. In this paper we report multi-epoch very long baseline interferometry (VLBI) observations of 22 GHz water masers before and during the recent accretion burst in NGC6334I. We traced proper motions before and during the accretion burst, showing significant variability in the water maser flux densities and number of detections due to the variable radiation field from the bursting high mass young stellar object. We calculated an average proper motion of 82 ± 38 km s^{-1} before and 85 ± 36 km s^{-1} during the accretion burst. The average proper motions were not expected to change as the dynamical timescale of the system is of the order of decades. On the other hand, we did see significant variability in the number and position of proper motions in CM2, MM1-W1, UCHII-W1, UCHII-W2 and UCHII-W3. In CM2, the water masers flared, as seen in previous studies, and new maser features were excited. In MM1-W1 and UCHII-W1, pre-burst maser features dropped below detection limits during the burst and new features were re-excited ~ 10 AU from previous detections. The simultaneous flaring and dampening of water masers due to an increase in infrared flux has not been adequately discussed in maser modelling, and we discuss possible explanations for this phenomenon. The VERA observations continue the campaign to understand this important accretion bursting source.

1. Introduction

Massive ($M > 8M_{\odot}$) stars play an important role in galactic evolution. They are an important source of heavy elements and feedback due to the type II supernovae they cause at the end of their lifetimes [1]. They have also contributed greatly to the ionization in galaxies on different scales [2] and cosmic times [3]. Yet, their early stages are difficult to observe due to their short lifetimes and their formation in embedded clusters with high dust extinction [4]. Radio interferometric arrays, combined with Very Long Baseline Interferometry (VLBI) and long term single dish monitoring have played a pivotal role in studying star forming regions at different angular scales, wavelengths and time scales [5]. The study of NGC6334I is a prime example of this multi-instrument approach. At a distance of 1.3 kpc [6], the region harbours multiple possible protostars in the millimetre peaks MM1-MM9 detected by the Atacama Large

Millimetre/Submillimetre Array (ALMA) [7]. NGC6334I-MM1 harbours multiple outflows, a ~ 0.5 pc NE-SW jet [8], a N-S jet and the blueshifted half of a NW outflow has been detected [5]. These jets indicated at least three previous ejection events. An important discovery was the observation and confirmation of an accretion burst in this region [9]. Simulations have shown that high mass young stellar objects (HMYSOs) gain significant portions of their mass in episodic periods of high accretion due to the infalling of fragments from the protostellar disc [10]. As the HMYSO absorbs the fragment, its natal region heats up significantly. Observationally, an accretion burst is most clearly shown by the significant increase in the region's dust temperature. Due to the dust temperature increase, various maser species and chemical line emission may flare significantly [11]. It was found that NGC6334I-MM1 had a luminosity increase of a factor of 16.3 ± 4.4 [12]. Significant flaring in the 6.7 GHz methanol masers, and the 22 GHz water masers was also found co-temporal with the dust temperature increase [10]. Interferometric observations with the Karl Jansky Very Large Array (JVLA) of 22 GHz water masers showed interesting behaviour, close to the accreting HMYSO (MM1B) the water masers were dampened close to the HMYSO, but had an order of magnitude flare in a region ~ 3000 AU from the source, CM2 [5]. High resolution multi-epoch VLBI observations using KaVA, a collaboration between the Korean VLBI network (KVN) and the Japanese VLBI Exploration of Radio Astrometry (VERA) of 22 GHz water masers relative proper motions measured an average proper motion of 86 km s^{-1}, tracing a major outflow with a position angle of -79.4° [13]. This measurement of another NW-SE jet, separate from the N-S jet, shows that the HMYSO/HMYSOs driving the jets in MM1 have had multiple previous accretion bursts leading to ejection events. As there have only been few observations of accretion bursts, the effects of the burst on the natal environment on the HMYSO is still poorly understood. In this paper we present preliminary results of multi-epoch 22 GHz water maser observations with VERA, as a continuation of a multi-epoch and multi-instrument campaign to probe the region. This data set is unique in that it traces water maser proper motions before and during the burst.

2. Observations and data reduction

We used the 4-antenna VERA array to undertake 7 epochs of observation of the 22 GHz water masers associated with NGC6334I. The pointing centre was $(\alpha,\ \delta)=(17^h20^m53.377^s,\ -35^\circ46'55.808'')$ in the J2000.0 epoch. The data reduction procedure and proper motion calculations were similar to the procedure described in [13]. To be able to compare the proper motions before and during the burst, we split the seven epochs into pre-burst epochs (4 epochs 2014.72-2015.28) and burst epochs (3 epochs 2015.88-2016.19). We then traced the proper motions for the pre-burst and burst epochs respectively. Individual maser detections (2D Gaussian fits in an individual channel), which we call "maser spots", were averaged into "maser features". Maser features are regions assumed to be moving together due to similar motion and to be in the same channel with equal V_{LSR}. The positions in $(\alpha,\ \delta)$ of the maser features over time were fit linearly to time to calculate the proper motion $(\mu_{\mathrm{x}},\ \mu_{\mathrm{y}}) = (\Delta\alpha\cos\delta,\ \Delta\delta)$ mas yr^{-1}. We performed self-calibration on the maser maps by choosing the brightest feature in UCHII-W1 as a reference maser. We did not perform phase referencing to obtain absolute position information on this feature, so our water maser positions are relative to the position of the reference maser. The same reference maser was used in all epochs. As the proper motions are relative in the reference maser's velocity frame, they can, therefore be shifted by adding a constant vector $\vec{\mu}_{\mathrm{R}}$, the proper motion of the reference maser. To be able to compare the proper motions with previous KaVA results, we shifted the VERA proper motions by a constant velocity vector $\vec{\mu}_{\mathrm{R}} = (-1.94 \pm 0.3,\ 17.3 \pm 0.4)$ mas yr^{-1} and position $\vec{P}_{\mathrm{R}} = (-0.68921,\ 5.28800)$ arcsec. This shift was calculated by calculating the vector so that the proper motion and position of the VERA reference maser corresponds to the proper motion and position of the same maser region in the KaVA observation (ID: 70-73 of Table 1 of [13]). The uncertainty in the proper motion of

Table 1: General characteristics of water maser proper motions detected by VERA before and during the burst. Columns 2, 3 and 4 are the number of detections, average transverse velocity (in km s^{-1}) and the error of the velocity (in km s^{-1}) before the burst (4 epochs, 2014.72-2015.28). Columns 5, 6 and 7 are the same quantities for the water maser proper motions during the burst (3 epochs, 2015.88-2016.19).

Region	#Detections	$\bar{v}$	$\delta\bar{v}$	#Detections	$\bar{v}$	$\delta\bar{v}$
All	125	82	38	102	85	36
CM2	49	112	26	55	111	23
MM1-W1	14	95	24	7	81	22
UCHII-W1	44	48	24	20	48	20
UCHII-W2	10	52	9	13	39	6
UCHII-W3	4	97	29	7	74	4

the VERA reference maser is known as it was previously derived in the KaVA observations and was taken into account. The error on the KaVA reference maser induces an error $< 10\%$ in our VERA proper motions in the KaVA velocity/position frame. This shift gives us good ground to compare the proper motions measured using the two instruments, noting that VERA has worse angular resolution and sensitivity.

3. Results

Table 1 shows the most general results for the water maser proper motions. The average proper motions stayed the same before and during the burst although the number of detections dropped by 19.4%. Figure 1 shows the proper motion positions, orientations and magnitudes. CM2 showed little variation in the number of detections and average proper motions but new maser features were excited in CM2 during the burst on both edges of the bow shape. MM1-W1 had northerly point proper motions both before and during the burst. The number of detections halved, and the average proper motion dropped by 10%. Notably, all the water masers detected pre-burst dropped below detection limits in the burst epochs and new masers were detected in a region 12 AU to the north-east. UCHII-W1 had almost half of the detections, although the average proper motion was completely unchanged. The region has a group of maser detections which also dropped below detection limits before the burst and new detections were made 12 AU to the north-east, similar to MM1-W1. UCHII-W2 had 3 more detections (from 10) and had a reduced average proper motion, although the orientatitions and magnitudes of the proper motions stayed relatively constant before and during the burst. UCHII-W3 had 3 more detections (from 4), and a reduction of 24% in average proper motion, with a notable decrease in the error on the mean from $\delta\bar{v} = 29 \rightarrow 4$ km s^{-1}. The maser features detected before the burst in UCHII-W3 were not detected during the burst, and two new features were excited during the burst ~ 100 AU to the east.

4. Discussion

4.1. VERA and KaVA proper motions

The water maser proper motions traced with VERA can be compared with water maser proper motions observed with KaVA [13]. The VERA observations, although less sensitive and with lower angular resolution, covers a longer time. We also detected some proper motions not detected by KaVA. UCHII-W2 and some features in UCHII-W1 were not detected by KaVA. The VERA results further confirm the KaVA results. The proper motions calculated in CM2 align very well. The following discrepancies should be noted: With the VERA observations, we detected quite clear upward motion with $\bar{v} \sim 90$ km s^{-1} in MM1-W1, while in the KaVA observations we detected complicated motions with $\bar{v} \sim 43$ km s^{-1}. In UCHII-W1 the average

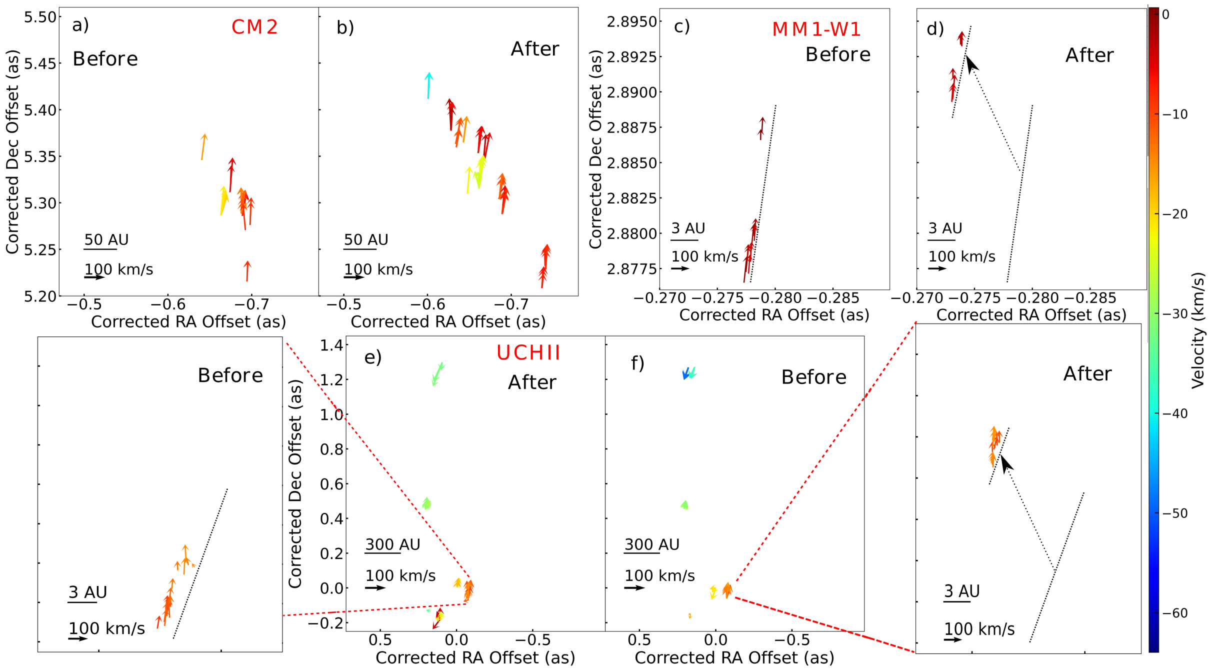

Figure 1. The panels on the left (a,c,e) are the pre-burst proper motions and the panels on the right (b,d,f) are the proper motions during the burst. The name of each region is written in red using the same naming convention of [13]. Panels e and f also contain zoom-ins of a region in UCHII-W1, note the different distance scales of the different regions. For clarity, the panels before and after the peak of the accretion burst were labelled "before" and "after". The positions and orientation of the arrows indicate the positions and orientations of the proper motions. The colour scale indicate the radial velocity. On the bottom left of each plot is the linear distance scale, and the linear velocity scale for the arrows.

proper motion differs by 16 km s^{-1} during the burst between VERA and KaVA. In both regions the water maser spatial distribution was very complicated, and errors in the calculation in the maser features might be the cause of the discrepancy. Note that due to the three additional short baselines in KaVA, it has significant improvements in sensitivity over VERA. VERA detected significantly less proper motions during the burst in both regions than KaVA, and the high velocity northward motions in MM1-W1 is visible in Figure 5 of [13], although proper motions derived from fainter spots point in other directions, changing the average. In UCHII-W1 the same can be noted. In summary: The differences are due to selection effects due to the sensitivity and angular resolution differences in the instruments.

4.2. Insights into water maser variability

22 GHz water masers are famously variable [14], and this causes a lot of difficulty in the interpretation of their proper motions. Observationally, there is no difference between a newly excited maser spot with the disappearance of another spot, and a real proper motion. If water masers in a region are variable in a timescale of multi-epoch observations, discerning real proper motions from re-excitations is a difficult task. It is therefore imperative to constrain water maser variability to reduce false detections in water maser proper motions. In the case of NGC6334I, we have an excellent testing ground to refine water maser interpretations. The accretion burst did not cause changes in gas kinematics of most of the water maser regions (for a fast jet of 400 km s^{-1}, it would take decades for the material from the burst to reach most regions we observe).

Therefore, the abrupt differences in the spatial distribution of the water masers must be due to *radiative* changes in the maser environment. In NGC6334I, both *dampening* and *amplification* of water masers has been seen [15]. Dampening of water masers due to increases in the external radiation has been seen by [5], and we see the anti-correlation with radiation in the destruction of the water maser regions MM1-W1 and UCHII-W1. This can be explained by a heat wave that caused unfavourable masing conditions as was already seen in this region by [5]. On the other hand, *amplification* of water masers due to an increase in external radiation has not been adequately explained. 22 GHz water masers are seen as collisionally pumped, as they typically form in environments with high kinetic temperatures such as shock fronts or turbulent regions. This is contrary to 6.7 GHz methanol masers, which are radiatively pumped. Co-spatial water and methanol masers have been found to be anti-correlated [16]. In NGC6334I it is not clear if this was the case. CM2 brightened significantly [5] due to an increase in external radiation associated to the accretion burst. This observation stands contrary to the "collisionally pumped" paradigm. Two realistic alternatives to explain this phenomenon have recently come to the fore. One explanation is an unpublished possible "radiatively pumped" 22 GHz water maser that occurs at high densities and low kinetic temperature (Gray M., 2021, private communication). This can be tested by seeing if there are co-spatial correlated 6.7 GHz methanol and 22 GHz water masers. There are 6.7 GHz methanol masers in CM2 [9]. Figure 9 of [15] shows a time series of 22 GHz water, 6.7 GHz methanol and other maser species close to the systemic velocity of the source (-7.6 km s^{-1}). They found a clear correlation between the 6.7 GHz methanol and water maser fluxes. From VLA K band observations of [5] it is known that CM2 is by far the brightest source of 22 GHz water masers at that velocity. [17] imaged the 6.7 GHz methanol masers with VLA, and showed that the brightest methanol masers at that velocity are not in CM2, but about 1200 AU north from the probable source of the accretion burst MM1B. There are faint 6.7 GHz methanol masers in CM2. VLA K and C band observations from 2019 (Project ID: 19A-256) can be used to test the radiatively pumped water maser hypothesis by comparing the water and methanol maser maps to 2017 observations. This data is publicly available at the time of writing. The 2019 6.7 GHz CH_3OH results are planned to be presented early in 2022 (Hunter T., private communication), while the 2019 K band data is still being processed. The second hypothesis is that the water masers stay "collisionally pumped", but that the simple correlation/anti-correlation to radiation for 22 GHz water masers is a simplification. Modelling of formaldehyde masers show a complex relationship between maser gain and the radiation field, where the maser gain in a certain part of parameter space (density and kinetic temperature) is dampened by external radiation, while other parts of parameter space seems to be undergoing a flare. This means that an observer might observe a flare of one maser spot and a dampening of another in the same radiation field if the spots are in regions of different kinetic temperatures and densities (van der Walt J., 2021, private communication). This hypothesis can be tested by more detailed modelling of water masers using variable background radiation. A consequence of this hypothesis is that the temporal variation in water masers might be used to constrain the time dependence of densities, kinetic temperatures and radiation fields.

5. Conclusion

We have reported high-resolution water maser proper motions in the accretion bursting source NGC6334I before and during the burst. We detected proper motions in CM2, MM1-W1 and the southern UCHII region. We found proper motions consistent with previous studies, and have found destruction and re-excitation of two water maser regions: MM1-W1 and UCHII-W1. We have also discussed possible ways to test new insights into water maser pumping models. Future studies with JVLA water maser maps could test these models. Accretion bursts in massive protostars are showing to be interesting phenomena in themselves, and also helpful test beds for other physical phenomena.

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References

[1] Tsujimoto T, Nomoto K, Yoshii Y, Hashimoto M, Yanagida S and Thielemann FK 1995 Relative frequencies of type Ia and type II supernovae in the chemical evolution of the galaxy, LMC and SMC, *MNRAS* **277** 945−58

[2] Dale JE, Ercolano B and Bonnell IA 2012 Ionizing feedback from massive stars in massive clusters - II. Disruption of bound clusters by photoionization, *MNRAS* **424** 377−92

[3] Haehnelt MG, Madau P, Kudritzki R and Haardt F 2001 An Ionizing ultraviolet background dominated by massive stars, *ApJ* **549** L151−4

[4] Zinnecker H and Yorke HW 2007 Toward understanding massive star formation, *ARAA* **45** 481−563

[5] Brogan CL, Hunter TR, Cyganowski CJ, Chibueze JO, Friesen RK, Hirota T, MacLeod GC, McGuire BA and Sobolev AM 2018 The extraordinary outburst in the massive protostellar system NGC 6334I-MM1: flaring of the water masers in a north-south bipolar outflow driven by MM1B, *ApJ* **866** 87-102

[6] Chibueze JO, Omodaka T, Handa T, Imai H, Kurayama T, Nagayama T, Sunada K, Nakano M, Hirota T and Honma M 2014 Astrometry and spatio-kinematics of H2O masers in the massive star-forming region NGC 6334I(North) with VERA, *ApJ* **784** 114−22

[7] Brogan CL, Hunter TR, Cyganowski CJ, Chandler CJ, Friesen R and Indebetouw R 2016 The massive protostellar cluster NGC 6334I at 220 au resolution: discovery of further multiplicity, diversity, and a hot multi-core, *ApJ* **832** 187−205

[8] Qiu K, Wyrowski F, Menten KM, Gusten R, Leurini and, Leinz C 2011 APEX CO (9-8) Mapping of an extremely high velocity and jet-like Outflow in a high-mass star-forming region, *ApJ* **743** L25−30

[9] Hunter TR, Brogan CL, MacLeod G, Cyganowski CJ, Chandler CJ, Chibueze JO, Friesen R, Indebetouw R, Thesner C and Young KH 2017 An extraordinary outburst in the massive protostellar system NGC6334I-MM1: quadrupling of the millimeter continuum, *ApJ* **837** L29−35

[10] Meyer DMA, Vorobyov EI, Kuiper R and Kley W 2017 On the existence of accretion-driven bursts in massive star formation, *MNRAS* **464** L90−4

[11] Caratti o Garatti A, Stecklum B, Garcia Lopez R, Eisloffel J, Ray TP, Sanna A, Cesaroni R, Walmsley CM, Oudmaijer RD, de Wit WJ, Moscadelli L, Greiner J, Krabbe A, Fischer C, Klein A and Ibãnez JM 2017 Disk-mediated accretion burst in a high-mass young stellar object, *Nature Physics* **13** 276−9

[12] Hunter TR, Brogan CL, De Buizer JM, Towner APM, Dowell CD, MacLeod GC, Stecklum B, Cyganowski CJ, El-Abd SJ and McGuire BA 2021 The extraordinary outburst in the massive protostellar system NGC 6334 I-MM1: strong increase in mid-infrared continuum emission, *ApJ* **912** L17−25

[13] Chibueze JO, MacLeod GC, Vorster JM, Hirota T, Brogan CL, Hunter TR and van Rooyen R 2021 The extraordinary outburst in the massive protostellar system NGC 6334 I-MM1: spatiokinematics of water masers during a contemporaneous flare event, *ApJ* **908** 175−84

[14] Felli M, Brand J, Cesaroni R, Codella C, Comoretto G, Di Franco S, Massi F, Moscadelli L, Nesti R, Olmi L, Palagi F, Panella D and Valdettaro R 2007 Water maser variability over 20 years in a large sample of star-forming regions: the complete database, *A&A* **476** 373−664

[15] MacLeod GC, Smits DP, Goedhart S, Hunter TR, Brogan CL, Chibueze JO, van den Heever SP, Banda PJ and Paulsen JD 2018 A masing event in NGC6334I: contemporaneous flaring of hydroxyl, methanol, and water masers, *MNRAS* **478** 1077−92

[16] Szymczak M, Olech M, Wolak P, Bartkiewicz A and Gawronski M 2016 Discovery of periodic and alternating flares of the methanol and water masers in G107.298+5.639, *MNRAS* **459** L56−60

[17] Hunter TR, Brogan CL, MacLeod GC, Cyganowski CJ, Chibueze JO, Friesen R, Hirota T, Smits DP, Chandler CJ and Indebetouw R 2018 The extraordinary outburst in the massive protostellar system NGC 6334I-MM1: emergence of strong 6.7 GHz methanol masers, *ApJ* **854** 170−86