Water Maser Evidence for UV/X-ray Emission During High-Mass Protostellar Accretion Bursts

J.M. Vorster[1,2,*], J.O. Chibueze[2,3,4], T. Hirota[5,6], G.C. MacLeod[7,8], D.J. van der Walt[2], E.I. Vorobyov[9,10], A.M. Sobolev[9,11], and M. Juvela[1]

***Corresponding Author:** jakobus.vorster@helsinki.fi

[1]University of Helsinki, Finland, [2]North-West University, South Africa, [3]University of South Africa, South Africa, [4]University of Nigeria, Nigeria, [5]National Astronomical Observatory of Japan, Japan, [6]The Graduate University for Advanced Studies, Japan, [7]The Open University of Tanzania, Tanzania, [8]Hartebeesthoek Radio Astronomical Observatory, South Africa, [9]Ural Federal University, Russia, [10]Southern Federal University, Russia, [11]Chinese Academy of Sciences, People's Republic of China.

High mass protostars gain upto half of their mass in short intense bursts of accretion

Protostars of all masses gain a substantial fraction (~50 %) of their mass during episodes of enhanced accretion [1]. Various disk instability mechanisms (e.g. thermal instability, magneto-rotational instability, or gravitational fragmentation) can cause these bursts. The bursts from high-mass protostars ($M_* > 8\ M_{sol}$) release a lot of energy (~$10^4\ L_{sol}$ over t_{burst}) into their environments, but it is unknown whether the burst energy is only reprocessed infrared radiation, or whether there is a substantial UV or X-ray component. The **radiation spectra** for accretion bursts is connected both to the **details of the accretion** close to the protostar, and the effects of the bursts on the **environment.** Masers are a quirky tool that might help to answer this question.

We aimed to measure the 22 GHz water maser variation during the burst. Multi-wavelength data was qualitatively compared to theory of 22 GHz water maser variability. Our hope was to improve water masers as an tracer in variable radiation environments.

NGC6334I-MM1: A hot multi-core with three jets and a wide angle outflow

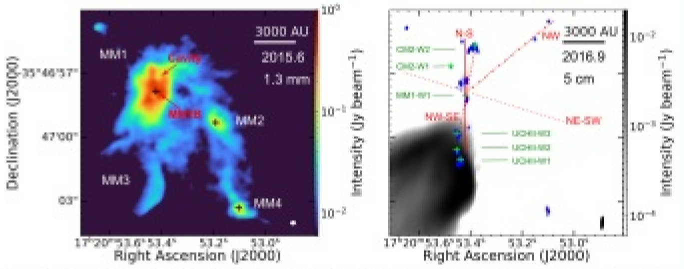


Figure 1: Left panel - ALMA 1.3 mm continuum [2]. The bursting source MM1B, and a jet cavity is marked in red. Right panel - JVLA 5 cm continuum, with jets marked in red, and maser associations in green. Blue spots are individual maser detections [2].

We combined seven VLBI epochs with ALMA maser observations and single dish monitoring

The accretion burst in MM1B started in 2015.1 (Fig. 2) [3]. **To understand the effect of the burst on the water maser variability**, we used:

1. Seven epochs at 22 GHz with VLBI Exploration for Radio Astrometry (VERA) (About VERA, see [4]).

2. HartRAO 22 GHz single dish monitoring.

3. Epoch 2019.1 imaging of 321 GHz water masers with Atacama Large (sub) Millimeter Array (ALMA).

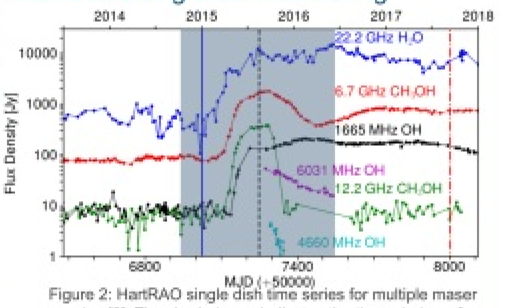


Figure 2: HartRAO single dish time series for multiple maser species [3]. The shaded area indicates the time window of our seven VLBI epochs.

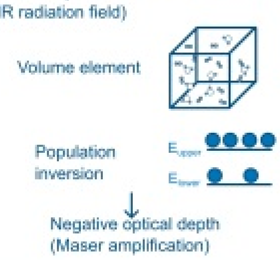
Maser variability primer

Flux density variability of 22 GHz water masers is *really* hard to interpret. Here is a simple introduction to:

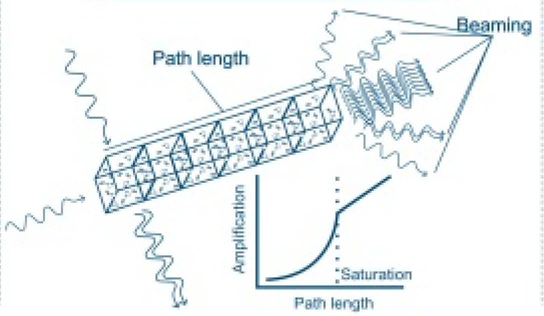
1. Physical quantities that affect maser brightness *per volume*.
2. Effect of masering geometry on observed flux densities.
3. Examples systems in star-forming regions where we observe these masers.

1. Pumping affected by

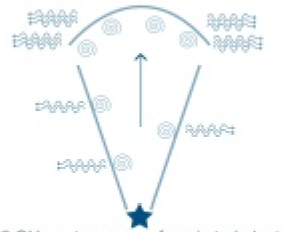
- H_2 density
- H_2O abundance
- Dust temperature (IR radiation field)
- H_2 temperature
- FUV/X-ray radiation



2. Geometric and saturation effects



3. Water Masers in SFRs



22 GHz water masers form in turbulent shocked regions (e.g protostellar jets). They are brighest perpendicular to the jet axis.

Unexpected flaring in the bow-shock CM2-W2

All maser associations except CM2-W2 dropped in intensity 1 yr after the burst (Fig. 3). The masers in CM2-W2, associated with a bow shock at the edge of a NW-SE jet, brightened (Fig. 4). This was unexpected, as water masers are dampened by strong mid-IR radiation fields. We considered explanations such as variable background continuum, radiatively pumped water masers, or radiative heating by UV/X-rays through a low-optical depth cavity (left panel of Fig. 1).

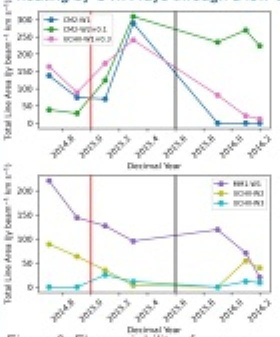


Figure 3: Flux variability of maser associations with VERA.

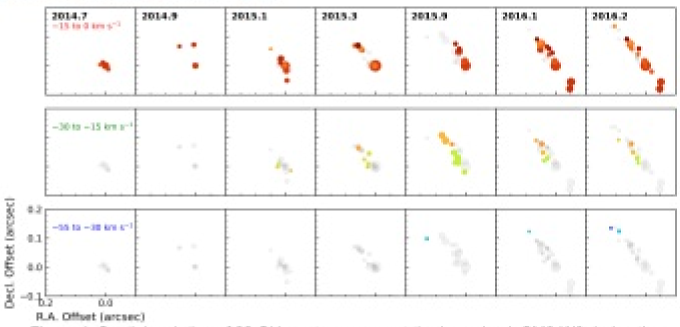


Figure 4: Spatial variation of 22 GHz water masers at the bow shock CM2-W2 during the accretion burst (2015.1) with VERA. Spotsize $\propto F^{0.5}$.

A Single 321 GHz maser spot was detected with ALMA. The 321/22 flux density ratio implies excitation in C-shocks

Multi-transition maser observations can distinguish masers from Jump and Continuous shocks [5,6]. Masers in C-shocks flare more than those in J-shocks when irradiated [7].

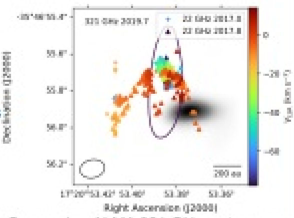


Figure 5: Greyscale - ALMA 321 GHz water maser. Markers - JVLA 22 GHz water masers [2].

Why Water Masers Matter for Star Formation

Water masers at 22 GHz occurs in about 10 000 galactic star forming regions. The only explanation we could find for water maser flares from this accretion burst is radiative heating of the collisional partner H_2 due to UV/X-rays generated in the accretion column close to the protostar.

UV Irradiation can be tested with Boltzmann diagrams of H_2 lines in the near infrared with ground telescopes (e.g. VLT), or near-to-mid infrared with JWST.

If you see 22 GHz water masers co-flaring with 6.7 GHz methanol masers, point an IR spectrometer at it!

Pre-burst vs post-burst ratios of variance in 22 GHz SD time series *may* be a way to decouple random geometric variability (see primer #2) from systematic pump variability (primer #1).

Higher pumping efficiency should also amplify random path length variations. We used variance before and after the burst to identify pump amplification or dampening for different features. If this method is robust, variance analysis can be used on other SFRs to characterise sources of maser variability.

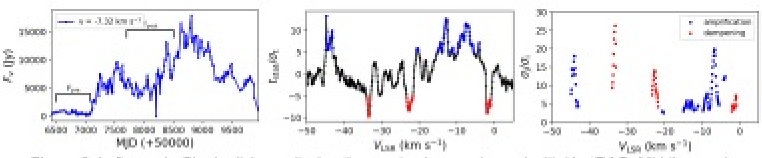


Figure 6: Left panel - Single dish monitoring time series in one channel with HartRAO. Middle panel - Channels with statistically significant variance changes. Right panel - Identification of channels with pump amplification or dampening from variance ratio.

References

[1] Meyer, D. M. A., et al., 2021, *MNRAS*, 500.4, p4448
[2] Brogan, C. L., et al., 2018, *ApJ*, 866.2, p87
[3] MacLeod, G. C., et al., 2018, *MNRAS*, 478.1, p1077
[4] Collaboration, V. E. R. A., 2020, PASJ, 72, p50
[5] Hollenbach, D. et al., 2013, *ApJ*, 773.1, p70
[6] Kaufman, M. J., and Neufeld, D. A., 1996, *ApJ*, 456, p250
[7] Gray, M. D., et al., 2024, *MNRAS*, 530.3, p3342

There is a lot of follow-up we could do with this project:

- This source is still in burst phase, so we would like to point VLT or JWST to it.
- We could test the variance ratio on a large sample of archival single dish maser monitoring sources (e.g. 6.7 GHz methanol and 22 GHz water).
- Apply what we have learned to water masers in other accretion bursting sources (in progress).

See the details in our paper