Riding the heatwave: account of the G358.93-0.03 maser flare.

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High-mass stars are thought to accumulate much of their mass via short, infrequent bursts of disk-aided accretion [1; 2]. Such accretion events are rare and difficult to observe directly but are known to drive enhanced maser emission [3; 4]. In this Letter we report high-resolution, multi-epoch methanol maser observations toward G358.93-0.03 which reveal a new phenomenon; the sub-luminal propagation of a thermal radiation "heat-wave" emanating from an accreting high-mass proto-star. The extreme transformation of the maser emission implies a sudden intensification of thermal infrared radiation from within the inner (40 mas, 270 au) region. Subsequently, methanol masers trace the radial passage of thermal radiation through the environment at 4-8% the speed of light. Such a high translocation rate contrasts with the $\leq$ 10 km s^{-1} physical gas motions typically observed with VLBI arrays. This scenario can readily be attributed to an accretion event in the high-mass proto-star G358.93-0.03-MM1. While being the third case in its class, G358.93-0.03-MM1 exhibits unique attributes hinting at a possible 'zoo' of accretion burst types. These results promote the advantages of maser observations in understanding high-mass star formation, both through single-dish maser monitoring campaigns and via their international cooperation as VLBI arrays.

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Masers provide a novel approach to investigating accretion bursts [3; 4]. **The $5_1 \rightarrow 6_0$ A^+ methanol transition at 6.7 GHz being of particular suitability as it arises in the presence of far-infrared radiation from warm (>100 K) dust and high gas densities (10^{5-8} cm^{-3}) [5], making it a sign-post of high-mass star formation [6]. It has been seen to trace rotating disks and tori [7; 8; 9], and actively responds to changes in its local environment [10].**

G358.93-0.03 was discovered by its 6.7 GHz methanol maser in the Methanol Multibeam survey [11], conducted in 2006. The early 6.7 GHz spectrum showed several < 10 Jy peaks in the velocity range of -22.0 to -14.5 km s^{-1}. In January 2019 a flare of the 6.7 GHz methanol maser at -15.9 km s $^{-1}$ was identified [12] using the Hitachi 32m telescope [13], prompting intensive monitoring and follow-up observations across a wide range of facilities. These observations, coordinated by the Maser Monitoring Organisation (M2O[1]) constitute the first observational campaign conducted *during* an accretion burst in a high-mass star.

Early results from target of oportunity observations with the SMA, ALMA [14] the ATCA [15], the VLA [16; 17] **and SOFIA** [18] have already been established. These contemporary works have revealed striking temporal behavior [19; 14], rich and dynamic hot core chemistry [15; 14], complex maser emission [14; 17; 16] **and a kinematic signature indicating possible expansion** [14]. The (sub)mm dust continuum uncovered a cluster environment, with the most luminous source ($L_{bol} = 5700 - 22000$ L_o), G358.93-0.03-MM1 (hereafter "G358-MM1"), being the counterpart to the aforementioned flare activity [14]. **An enhancement in the far infrared continuum of this source confirms that an accretion burst has occurred [18]**.

Using hot core thermal tracers [14] adopt a line of sight velocity in the Local Standard of Rest of $v_{LSR} = -16.5 \pm 0.3$ km s^{-1}, and estimate a kinematic distance of $D = 6.75^{+0.37}_{-0.68}$ kpc using a Bayesian statistics Galactic distance estimation tool [20]. Gaia parallaxes of visible stars within a 0.25 arcminute field around G358 had distance estimates within 5 kpc [21]. Assuming that such stars are foreground to the G358 high-mass star forming region imposes a lower distance limit which is consistent with the kinematic distance.

As part of the M2O-lead campaign we initiated VLBI (very long baseline interferometry) observations to contribute the highest angular resolution view of masers during the G358-MM1 maser flare. Two VLBI observations of the 6.7 GHz methanol maser were conducted with the Australian long baseline array (LBA) shortly following the discovery of the maser burst (see Methods). Spectral profiles delineating both auto- and cross-correlations for each epoch are presented in Figure 1, in which emission is appears in the velocity range of -14.3 to -20.5 km s^{-1}; centered near the source systemic velocity [14].

Auto-correlation spectra are sensitive to all emission within the arcminute scale primary beams of the VLBI array elements. Contrarily, cross-correlation spectra are exclusively sensitive to compact gas, on scales similar to the VLBI array synthesised beam (a few milliarcseconds). The similarity of the auto- and cross-correlation spectral profiles implies a common origin and similar spatio-kinematics of the maser gas at both extended and compact scales. Comparison of the auto-correlation and cross-correlation flux densities indicate that at least 90% of the maser emission in G358-MM1 originates from gas at angular scales larger than the synthesised beam of the LBA (see Table 1). Generally, maser emission in G358-MM1 rapidly evolves toward a more complex spectral profile with most features increasing in flux density by several times their initial values.

Phase referenced, astrometric positions of the masers around G358-MM1 are shown in Figure 2, in which the white cross indicates the peak of the millimeter core detected by ALMA at (RA, DEC) = (17:43:10.1014, -29:51:45.693; [14]). Despite significant changes across the two

[1]The M2O is a global co-operative of maser monitoring programs. https://MaserMonitoring.org

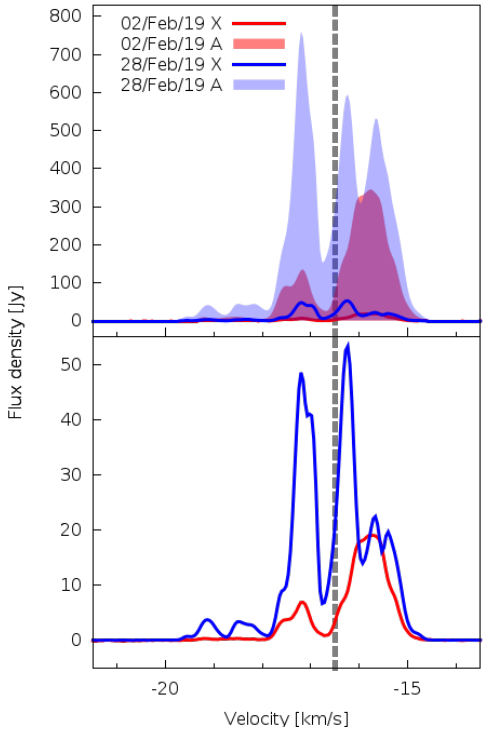

Figure 1: Spectral profiles of the 6.7 GHz methanol maser emission in G358-MM1. *Above* depicts a comparison of the auto- and cross-correlation profiles with the cross-correlation data shown *below*. The dashed line indicates the source systemic velocity.

epochs, the 6.7 GHz methanol maser emission in G358-MM1 is generally arranged in a ring-like structure roughly centered on the position of the millimeter core. By the very nature of maser emission detections are biased toward regions of longest velocity-coherent path length along the line of sight. As such, the ring-like structures likely represent 2D projections of a 3D shell centered on G358-MM1.

The most striking aspect of the VLBI data is the rapid transformation of the methanol maser distribution. Circles fit to the spot maps (Figure 3 *right*) delineate radii of 40 mas and 77 mas (260 and 520 au) in the first and second epochs respectively, corresponding to a translocation of 1 mas/day in the NW direction, 2 mas/day in the SE direction and an average radial expansion of 1.5 mas/day generally progressing outward from a position near the MM1 continuum peak [14].

Considering the short period between observations (26 days), spatial evolution of the maser emission must be dominated by local phenomena ($\sim$ mas/day) with no significant contribution expected from Galactic systemic apparent proper motions ($\sim$ mas/yr).

Translocation rates of 1-2 mas/day, correspond to $11,700$ to $23,400$ km s^{-1} at the source's kinematic distance of 6.75 kpc, equivalent to 0.04 to 0.08c. Methanol does not achieve high gas phase abundance in the presence of shocks faster than 10 km s^{-1} [22], therefore such a fast morphological transformation can not be attributed to physical motions of methanol gas clouds. Instead, it is suitably explained by the sequential creation and quenching of maser emitting regions at ever increasing radii, as the conditions favorable to maser production [5] propagate outward from an origin at G358-MM1.

A sudden production and subsequent propagation of thermal heating, **emanating from** the inner 270 au region in G358-MM1, can readily be explained under the hypothesis of an accretion event **in which enhanced far infrared radiation drives the production of** $5_1 \rightarrow 6_0$ A^+ **methanol masers.**. The propagation progresses as a random-walk of the energy transfer by dust absorption and re-emission. The mean free path of photons becomes small at high optical depths, and energy absorption in the melting of ice mantles can further slow radiative transfer, leading to subluminal propagation (see [23]).

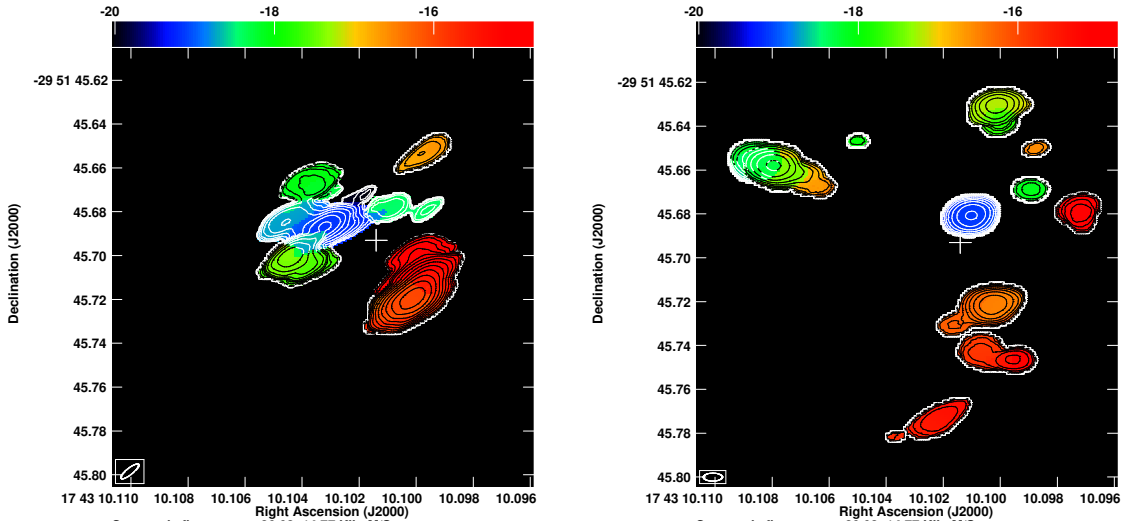

Figure 2: Zero'th (contours) and first (colours) moment maps of the 6.7 GHz methanol maser emission in G358-MM1. *Left* shows the distribution of emission during the VX026A epoch while *right* shows that of VX026C, taken 26 days later. Contours increase by factors of 2 multiples of the first contour at 2 Jy beam^{-1} km s^{-1}. The white cross indicates the position of the brightest millimeter continuum peak of the G358-MM1 region from [14].

Alternative explanations for the phenomena seen in G358-MM1, including super-/nova and changes in the geometry and/or radiation of a high-mass protostellar system, fail to explain the global flux increase in all velocity components of the maser emission, its temporal behavior and rapid morphological changes, and the accompanying FIR enhancement. All of which are consistent with the accretion burst hypothesis.

High-mass protostars may be facilitated in achieving their necessarily high accretion rates by disk-aided inward transport of material and a reduction of the stellar UV radiation. The latter may be induced via non-continuous accretion mechanisms [24] which cause a bloating of the stellar radius and a subsequent reduction in its effective temperature [25]. Such 'episodic accretion' is exemplified by the FUori and EXori class of low-mass protostars (reviewed in [24]) and, **despite differences in the initial conditions, timescales, environments and protostellar radiation fields present in low- and high-mass protostars [26], episodic accretion** is quickly becoming considered a necessary component of high-mass star formation [1; 2]. Accretion bursts were identified retrospectively in high-mass protostars S255NIRS3 [27] and NGC6334I-MM1 [28] and the behavior has been inferred indirectly via outflow ejection histories[29].

The G358-MM1 accretion burst contrasts to the those of S255NIRS3 [27] and NGC6334I-MM1 [28] in that no clear enhancements in the near- and mid-infrared, were confirmed [14; 18]. The former can be explained by a high opacity in the immediate surroundings of the high-mass protostar, and the latter implying a subsequent failure to sufficiently heat the dust in the disk mid-plane. This may be due to a less substantial mass transfer, leading to less intense accretion luminosity. Indeed, S255NIRS3 exhibited a bolometric luminosity increase of a factor of 4 while that of NGC6334I increased by a of 10, despite a common underlying mechanism. The G358-MM1 event may therefore represent a new discovery amongst a 'zoo' of high-mass protostar accretion burst varieties. It is likely that this class of events will diversify as more follow-up investigations of accretion bursts are reported.

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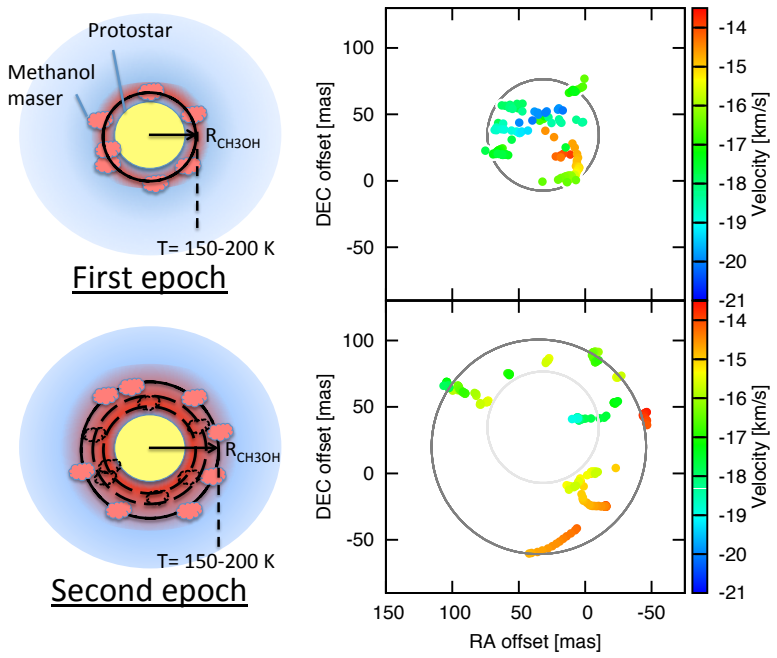

Figure 3: (*Left*) A schematic model of the maser distribution and evolution in an accreting star-disk system. *Right* Spot maps detailing the evolution of methanol maser emission in G358-MM1 where the upper and lower panels illustrate the data of VX026A (2nd Feb 2019) and VX026C (28th Feb 2019), respectively. Directional offsets are stated with respect to the coordinate (RA, DEC) = (17:43:10.1014, -29:51:45.693). The dark rings delineate the fits to each epoch, while the grey ring indicates the extent of the VX026A masers at the epoch of VX026C.

Methods

Target of opportunity observations were requested to the Australian long baseline array (LBA)[2] on January the 28th 2019 in response to reports from the M2O of the 6.7 GHz burst event [12]. Two VLBI epochs were granted. The array parameters for which are described in Table 1

Observations consisted of phase reference cycles between G358-MM1 and two phase reference sources, J1744-3116 and J1743-3058, interchangeably, with a 4.5 min cycle time. Each hour, scans were made of bright calibration sources 3C273, PKS B1934-638, NRAO530, which were also used to phase-up the ATCA. Two 16 MHz channels of dual circular polarisation data were recorded with 2 bit, Nyquist sampling, corresponding to a data rate of 128 Mbps. Data were correlated with a 2 second accumulation period at the Pawsey correlator center using DiFX [30]. Two passes were performed, one comprising the full bandwidth correlated at 32 spectral points per channel, and one single 'zoom band' of 4 MHz, centered on the maser peak, with 4096 spectral points corresponding to frequency and velocity spacings of 0.977 kHz, and 0.045 km s^{-1}. Full Stokes correlation products were computed.

Data were calibrated using the AIPS software package[3]. Individual station gains were calibrated by scaling the auto-correlation spectrum of the maser to match contemporaneous monitoring data provided by the M2O. Absolute flux density calibration is considered accurate to 20%. Bandpass subtracted auto- and cross-correlated spectra for both epochs are shown in Figure 1.

Delay calibration was performed using 3C273, PKS B1934-638 and NRAO530 and solutions applied to all sources. Phase calibration was established using the maser data and refined by self calibration to remove the effects of source structure. The solutions were then applied to J1744-3116 and J1743-3058, thereby establishing the coordinates of the maser source with respect

[2]The Long Baseline Array is part of the Australia Telescope National Facility which is funded by the Australian Government for operation as a National Facility managed by CSIRO.

[3]Astronomical Image Processing System, http://www.aips.nrao.edu/index.shtml

to the International Celestial Reference Frame to within ±3 milli-arcseconds (mas). During imaging the data were weighted to produce a comparable synthesised beam shape across the two epochs. Zero'th and first moment maps (Figure 2) were produced for both epochs in which a channel dependent noise cutoff was applied to remove any side-lobe emission. Finally, two dimensional Gaussian functions were fit to each maser emitting region to produce the spot maps shown in Figure 3.

Table 1: Summary of the observations

Obs. code	Obs. date	Duration [hrs]	Stations	Synth. beam [mas]
VX026A	2 Feb 2019	11	ATCA, Ceduna, Hartebeesthoek Hobart, Mopra, Warkworth	10.17×2.96
VX026C	28 Feb 2019	13	ATCA, Ceduna, Parkes Hobart, Mopra, Warkworth	8.56×3.64

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