A Multitransition Methanol Maser Study of the Accretion Burst Source G358.93–0.03-MM1

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Abstract

We present the most complete to date interferometric study of the centimeter-wavelength methanol masers detected in G358.93–0.03 at the burst and post-burst epochs. A unique, near-IR/(sub)millimeter-dark and far-IR-loud massive young stellar object accretion burst was recently discovered in G358.93–0.03. The event was accompanied by flares of an unprecedented number of rare methanol maser transitions. The first images of three of the newly discovered methanol masers at 6.18, 12.23, and 20.97 GHz are presented in this work. The spatial structure evolution of the methanol masers at 6.67, 12.18, and 23.12 GHz is studied at two epochs. The maser emission in all detected transitions resides in a region of ~0′2 around the bursting source and shows a clear velocity gradient in the north–south direction, with redshifted features to the north and blueshifted features to the south. A drastic change in the spatial morphology of the masing region is found: a dense and compact “spiral” cluster detected at epoch I evolved into a disperse, “round” structure at epoch II. During the transition from the first epoch to the second, the region traced by masers expanded. The comparison of our results with the complementary Very Large Array, very long baseline interferometry, Submillimeter Array, and Atacama Large Millimeter/submillimeter Array maser data is conducted. The obtained methanol maser data support the hypothesis of the presence of spiral arm structures within the accretion disk, which was suggested in previous studies of the source.

Unified Astronomy Thesaurus concepts: Astrophysical masers (103); Protopstars (1302); Star formation (1569); Star forming regions (1565)

Supporting material: machine-readable tables

1. Introduction

Is there a common mechanism of star formation across the entire stellar mass spectrum? While star formation theory is well established for low-mass stars (e.g., McKee & Ostriker 2007), much less is known about high-mass star formation. Recent studies such as Caratti o Garatti et al. (2017) and Hunter et al. (2017) provide direct evidence that massive young stellar objects (MYSOs), analogously to low-mass stellar objects, form via disk-mediated accretion accompanied by episodic accretion bursts. These bursts may be a result of disk fragmentation (Ahmadi et al. 2019; Meyer et al. 2019). Such a mechanism provides a means to overcome radiation pressure (Hosokawa et al. 2016), and it is thought that up to half of the final stellar mass may be acquired in these accretion events. But the accretion process itself is poorly understood—largely due to scarce observational evidence. Currently, only three cases of accretion bursts in MYSOs have been reported: S255IR (Caratti o Garatti et al. 2017), NGC 6334I (Hunter et al. 2017), and—the topic of this paper—G358.93–0.03 (Stecklum et al. 2021). A potential fourth accretion burst source, G323.46–0.08, may have recently undergone such an event (Proven-Adzri et al. 2019).

A larger sample is clearly needed, but identifying MYSOs undergoing accretion bursts is difficult. It is in this respect that masers have proven to be a powerful probe of the mechanisms of massive star formation. Masing occurs only within certain ranges of physical conditions of the gas and radiation field (see, e.g., the reviews by Ellingsen et al. 2007; Breen et al. 2019). Such, the spatial distribution of masers can reveal the distribution of temperature, density, and radiation enhancements in the region, while the kinematics of maser spots can trace gas motions. All of these properties are essential for understanding the episodic accretion phenomenon.

If the accretion burst augments the local radiation field, the resulting increase in incident photons will cause all masers in the foreground of the continuum emission to increase in flux. Masers, either compact or extended and covering a wide range of velocities, may be involved—as was seen in S255IR (Szymczak et al. 2018), in NGC 6334I (MacLeod et al. 2018), and recently in G358.93–0.03 (Breen et al. 2019; Brogan et al. 2019; MacLeod et al. 2019). Moreover, in all these sources,
multiple maser transitions were seen to flare\textsuperscript{13} and rare maser transitions appeared. The masers then weakened or disappeared in a span of weeks to months for the rarer masers but longer for the more common transitions (MacLeod et al. 2018).

1.1. G358.93$-$0.03

On 2019 January 14, a rapid rise of the 6.67 GHz class II methanol maser flux density, accompanied by the appearance of several new velocity features, was detected in G358.93$-$0.03 (Sugiyama et al. 2019) by the Ibaraki 6.7 GHz Methanol Maser Monitor (iMet) program (Yonekura et al. 2016). The flare of 6.67 GHz maser emission reached a first peak on 2019 February 15, when the flux density of the maser feature at $-15.6$ km s$^{-1}$ reached $\sim 660$ Jy (Figure 1). A second peak occurred on March 12, when the velocity feature at $-17.2$ km s$^{-1}$ reached a flux density of $\sim 900$ Jy. A daily spectrum of the 6.67 GHz methanol maser in G358.93$-$0.03 is published regularly on the iMet project website.\textsuperscript{14}

Intensive follow-up observations were made by the Maser Monitoring Organization\textsuperscript{15} (M2O), a self-organized collaboration of maser monitoring observatories. Monitoring with the 26 m telescope of the Hartebeesthoek Radio Astronomy Observatory (HartRAO, Republic of South Africa; Figure 1) confirmed that the flaring 6.67 GHz methanol maser flux density had been rapidly increasing since 2019 February and in $\sim 1.5$ months reached $\sim 1000$ Jy—about 200$\times$ greater than the stable flux density of $\sim 5$ Jy that had been reported by observations spanning the previous decade (Caswell et al. 2010; Chambers et al. 2014; Hu et al. 2016; Rickert et al. 2019).

In addition to the 6.67 GHz methanol maser flare, the appearance of multiple new maser transitions was observed in G358.93$-$0.03. A rare 23.12 GHz class II methanol maser (only the fourth known occurrence of this transition) was detected. A 12.18 GHz class II methanol maser, previously undetected in this source despite several epochs of observations (Breen et al. 2012), was found to have a higher flux density than the flaring 6.67 GHz maser. The ATCA observations of G358.93$-$0.03, conducted in 2019 March, detected emission from 12 additional methanol transitions, 6 of which were previously undetected class II methanol masers; among these were the first known torsionally excited methanol masers (Breen et al. 2019). In 2019 January–March, Volvach et al. (2020) reported a short-lived (44 days) 19.97 GHz methanol maser emission. More transitions may have been missed owing to insufficient frequency coverage. The latest observations with the Submillimeter Array (SMA; 2019 March) and Atacama Large Millimeter/submillimeter Array (ALMA; 2019 April) yielded an additional 14 methanol maser discoveries in the (sub)millimeter range, primarily from transitions in excited torsional states (Brogan et al. 2019).

G358.93$-$0.03 was a maser-quiet source at the pre-flare epoch, with only two maser transitions detected: the 6.67 GHz methanol maser (Caswell et al. 2010; Chambers et al. 2014; Hu et al. 2016; Rickert et al. 2019) and 22 GHz water maser (Titmarsh et al. 2016). Moreover, G358.93$-$0.03 was not as well studied as S255IR or NGC 6334I. For example, no proper-motion data are available to provide a parallax distance. According to the BeSSeL Revised Kinematic Distance Calculator\textsuperscript{16} (Reid et al. 2014), the near-kinematic distance to the source is 6.75$^{+0.07}_{-0.06}$ kpc.

The SMA and ALMA (sub)millimeter imaging resolved G358.93$-$0.03 into a cluster of eight continuum sources (Brogan et al. 2019). Two of these sources, MM1 and MM3, were found to host hot molecular cores. All of the newly discovered methanol masers were found to be associated with the brightest continuum source, MM1 (e.g., Brogan et al. 2019; Burns et al. 2020).

The flaring class II methanol maser transitions detected in G358.93$-$0.03 require similar physical conditions according to theoretical models, albeit over a wider range of values (Sobolev et al. 1997a, 1997b; Cragg et al. 2004, 2005). Thus, the simultaneous flaring of these masers indicates a sudden change in the local physical conditions—probably related to the radiation field—which could provoke the necessary conditions for maser amplification.

The multiepoch Long Baseline Array (LBA) observations, performed during the 6.67 GHz methanol maser flare, allowed the imaging of the subluminal propagation of a thermal radiation “heat wave” emanating from the accreting high-mass protostar (Burns et al. 2020).

The SMA and ALMA images revealed a partial elliptical ring of the methanol masers, which was interpreted as a coherent physical structure illuminated by a radiative event from the central object (Brogan et al. 2019).

Remarkably, the Very Large Array (VLA) observations of Chen et al. (2020a, 2020b), conducted during the maser flare epoch in 2019 March, revealed that the discovered rare maser transitions of HDO, HNCO, and $^{13}$CH$_3$OH appear to trace a spiral arm structure around the bursting source (Chen et al. 2020b). This finding was the first observational evidence of a link between accretion bursts and disk substructures (Chen et al. 2020b).

The accretion burst in G358.93$-$0.03 was decisively confirmed by multiepoch SOFIA observations (Stecklum et al. 2021). The event is found to be the first near-IR/(sub) millimeter-dark and far-IR-loud MYSO accretion burst, \textsuperscript{13} Hereafter, we use the word “flare” to refer to a sudden increase in the maser flux density (in some cases, caused by an accretion burst) and the word “burst” to refer to the accretion burst itself.

\textsuperscript{14} http://vibi.sci.ibaraki.ac.jp/iMet/G358.9-00-190114/daily.html

\textsuperscript{15} https://www.masermonitoring.org/

\textsuperscript{16} http://bessel.vlbi-astrometry.org/revised_kd_2014
showing an increase in the source flux only in the far-IR, and not in the near-IR or (sub)millimeter bands (Stecklum et al. 2021).

The excellent coordination of the M2O observatories ensured that monitoring of G358.93–0.03 was done in a timely manner. As a result, we had the unique opportunity to observe a stage of the flare that was missed in the cases of S255 and NGC 6334I. In this paper, we present the most complete to date interferometric study of the methanol masers detected in G358.93–0.03 at the burst and post-burst epochs.

2. Observations and Data Reduction

Two observing sessions of G358.93–0.03 were carried out with the Karl G. Jansky VLA on 2019 February 25 (epoch I) and on 2019 June 4 (epoch II) as the Target of Opportunity programs 19A–448 and 19A–476. The first session was a follow-up observation in response to the rapid rise of the 6.67 GHz methanol maser flux density detected in the source in 2019 January (Sugiyama et al. 2019). The second session was made in response to the 22 GHz water maser flare of 2019 April (the M2O monitoring data; Figure 1).

The epoch I observation was made during a C → B reconfiguration that led to an asymmetrical beam, highly elongated in the N–S direction. At the first epoch, the priority was to catch the flaring methanol masers before they faded, so promptness was the driving factor more than resolution. The epoch II observation was made in A-configuration.

In this paper, we present the C-, Ku-, and K-band spectral line and K-band continuum observations. The observing time for each session was 2 hr. The pointing coordinates for G358.93–0.03 were R.A. (J2000) = 17° 43′ 10″ 02 and decl. (J2000) = −29° 51′ 45″ 08, with an LSR velocity of −15.55 km s⁻¹. The same calibration sources were used at both epochs: 3C 286 was used as a flux density, bandpass, and delay calibrator; J1744−3116 was the complex gain calibrator (with an angular separation from the target source of 4° 6).

The maser lines were observed in narrow spectral windows (1, 2, and 4 MHz at C, Ku, and K bands, respectively) with 512 or 1024 channels. Continuum emission was observed in 31 spectral windows with 128 1 MHz channels. Observation parameters, including the synthesized beam size and the rms noise level, for spectral line and continuum data are presented in Tables 1 and 2. Table 1 contains the list of detected maser transitions (detection of maser emission in each band; epoch is marked with “Y,” and nondetection is marked with “N”).

All steps of the post-correlation data reduction were done with the Common Astronomy Software Applications (CASA; McMullin et al. 2007). For basic flagging and data calibration, we used the VLA CASA Calibration Pipeline. Nevertheless, there were two issues that required special, additional treatment. First, during the observations we used the VLA catalog coordinates for the phase calibrator J1744−3116. Post-observation, we learned that the very long baseline interferometry (VLBI) Source Position Catalog lists a more reliable position. The discrepancy from the VLA catalog position is 0″ 313. Prior to calibration and imaging, we

\[ \text{http://astrogeo.org/vlbi/solutions/rfc_2019d/} \]
corrected the calibrator position to the VLBI catalog values with CASA task fixvis. Second, the observations were carried out during a multifrequency maser flare in the source, which led to the detection of a number of methanol maser lines in the wide-band VLA continuum window (for the list of the detected maser lines, see the note to Table 2). The maser lines were not flagged by the pipeline, and their data appeared in the continuum images as a false detection of continuum peaks. Additional manual flagging was done to avoid this contamination.

Calibrated data were imaged with the CASA task clean. Briggs weighting was used for maser data, and natural weighting was used for continuum data. Gaussian fitting of the images was performed with the CASA task imfit. A two-dimensional Gaussian brightness distribution was fit to all maser and continuum emission peaks with a flux density above the 3σ level (see Tables 1 and 2 for 1σ levels) to determine their positions and flux densities. Further in the text, we list and discuss so-called “maser spots”—maser emission detected in a single velocity channel of a data cube.

To estimate the uncertainties in the absolute positions of the masers detected with the VLA, we compared our positions with those obtained by other observations made recently by the M20 collaboration. The 6.7 GHz methanol maser spots detected with the VLA at the first epoch (2019 February 25) were superposed with the 6.7 GHz data obtained with the LBA on 2019 February 28 from Burns et al. (2020). An N–S position difference was noted and estimated to be ∼0′′.07. This value is within the accuracy of the VLBI position measurement and is within 1 pixel of our C-band VLA images. Absolute coordinates measured with VLA can be affected by uncompensated ionospheric propagation delays, and the effect is most notorious for declinations ≤30° (Argon et al. 2000). To estimate the displacements for other types of masers, we (1) measured the median positions of the centers of the maser clusters and (2) estimated shifts between centers of the maser clusters and MM1 (the central source of our maps; Brogan et al. 2019). The estimated offsets are indicated in the notes of Tables 5–9. The offsets were introduced to our data and used in the data analysis and preparation of Figures 3–7, 10–11, and 13–15. Note that the absolute positional uncertainty of MM1, with which we compare positions of the detected masers, is ∼0′′.03 (Brogan et al. 2019). The absolute position shift between the first and second VLA epochs appeared to be of ∼0′′.04.

### 3. Results

#### 3.1. Methanol Maser Emission

Maser emission is detected in all frequency bands; there are not only well-known methanol masers at 6.67 and 12.18 GHz but also rare and recently discovered ones. The four newly discovered methanol maser transitions at 6.18, 12.23, 20.35, and 20.97 GHz, detected in G358.93−0.03 with the 26 m HartRAO telescope (MacLeod et al. 2019) and ATCA (Breen et al. 2019), were observed at epoch II with the VLA. Of the four, only the 20.35 GHz maser was not detected with the VLA, as it had already faded away by the date of the observation.

The position, velocity, and integrated and peak flux density of each maser spot are listed in Tables 4–9. Images of the brightest emission spots detected at a particular frequency, as well as spectra of these maser transitions and their spatial distribution, are presented in Figures 2–7. Each map is centered on the position of the millimeter core MM1 from Brogan et al. (2019; indicated by a star symbol).

Note that the structures seen in the maser spot maps are much smaller than the angular size of the VLA synthesized beam in each band (Table 1). The high signal-to-noise ratio achieved for the bright maser emission allows us to fit the maser spot positions with subbeam size accuracy. Nevertheless, if there is more than one maser spot in a velocity channel, the spatial and velocity structure will be dominated by the brighter component (i.e., we obtain “centroid mapping”; see Section 4.2 for further discussion on the issue). This is especially true for the crowded maser regions detected at the flare epoch.

6.18 GHz.—The 6.18 GHz class II methanol maser is one of the torsionally excited lines discovered with the ATCA during the burst in G358.93−0.03 (Breen et al. 2019). By the time of the VLA epoch II observations, the flux density of the 6.18 GHz maser had dropped significantly and remained at the ∼0.1 Jy level (Figure 2(b)), compared to the flaring flux density of ∼300 Jy. At VLA epoch II, only the −18.6 km s$^{-1}$ feature remained detectable. The ATCA spectrum showed emission from −18.8 to −15.5 km s$^{-1}$, with a peak emission at −16.2 km s$^{-1}$. However, both the ATCA and VLA positions of the 6.18 GHz maser coincide within their positional uncertainties.

6.67 GHz.—The first epoch of the VLA observations was conducted soon after the first 6.67 GHz maser flare in G358.93−0.03. On 2019 February 25 (VLA epoch I), the single-dish flux density of the velocity feature at ∼−16 km s$^{-1}$ decreased from ∼600 to ∼450 Jy, according to iMet data.18 We note that February 25 was also the date when the dominant feature at $V_{{\mathrm{L}\mathrm{S}\mathrm{R}}} \sim −16$ km s$^{-1}$ was overtaken by the feature at $V_{{\mathrm{L}\mathrm{S}\mathrm{R}}} \sim −17$ km s$^{-1}$.

The brightest flare of the 6.67 GHz maser occurred on March 12, when the −17 km s$^{-1}$ velocity feature reached 900 Jy. By the second VLA epoch (2019 June 4), the single-dish flux density of the 6.67 GHz methanol maser had decreased to ∼90 Jy, with both lines—at $V_{{\mathrm{L}\mathrm{S}\mathrm{R}}} \sim −16$ km s$^{-1}$ (dominant in

18 [http://vlbi.sci.hiroshima-u.ac.jp/iMet/G358.9-00-190114/daily.html](http://vlbi.sci.hiroshima-u.ac.jp/iMet/G358.9-00-190114/daily.html)
the first flare) and $\sim -17$ km s$^{-1}$ (dominant in the second flare) — having about the same amplitude (see Figures 1 and 3).

The methanol maser emission at 6.67 GHz is detected at both VLA epochs, coming from an area of $\sim 0''/2$ ($\sim 1$000 au, for an assumed distance of 6.75 kpc) around the MM1 position (Figure 3). Several fainter (<1 Jy) maser spots were detected outside of the main cluster. These “distant” maser spots are located to the west of the main cluster (Figures 3(a), (b)). At the first VLA epoch, the cluster of the 6.67 GHz maser spots was elongated in the NE–SW direction, with most of the blueshifted masers to the NE and the redshifted features to the SW. Here, “blue” and “red” refer to the centroid of the velocity range, of about $\sim -17$ km s$^{-1}$. In contrast, the 6.67 GHz maser spots detected at the second epoch are arranged in a bow-shaped structure, again with the blueshifted velocity features to the north and redshifted features to the south. The overall velocity pattern of the spectrum did not change greatly between epochs, although the weaker velocity features at $V_{\text{LSR}} \sim -18$ to $-19.5$ km s$^{-1}$ detected in the first epoch were not detected at the second epoch.

12.18 GHz.—The methanol maser emission at 12.18 GHz is found in a region of $\sim 0''/2$ around MM1 (Figure 4). This maser transition shows a behavior quite similar to that of the 6.67 GHz maser. At VLA epoch I, the 12.18 GHz maser emission is also elongated in the NE–SW direction with blueshifted velocity features to the northeast and redshifted features to the southwest. At VLA epoch II, there is a wide bow-shaped structure with redshifted masers to the north and a less ordered structure to the south, composed of blueshifted masers.

At the post-flare epoch (VLA epoch II), both maser transitions faded to about the same flux density, with the 6.67 GHz maser slightly stronger: the peak flux densities of the 6.67 and 12.18 GHz emission were $\sim 84$ and $\sim 79$ Jy, respectively.

12.23 GHz.—The 12.23 GHz methanol maser was discovered in observations of G358.93—0.03 with the 26 m HartRAO telescope (MacLeod et al. 2019). The emission in this transition was detected in 2019 March with a flux density of $\sim 1100$ Jy, but only $\sim 0.1$ Jy remained at the VLA observation in 2019 June (Figure 5). The flaring spectral feature at $V_{\text{LSR}} \sim -15.5$ km s$^{-1}$ detected at HartRAO was below our 3$\sigma$ detection limit, and, as for the 6.18 GHz maser, the only emission still detectable at epoch II has a velocity close to the minimum velocity of the flaring spectrum. The brightest 12.23 GHz maser spot detected with the VLA is at $V_{\text{LSR}} \sim -17.1$ km s$^{-1}$. Masers detected with the VLA lie in a region of $\sim 0''/22$ slightly to the NE of MM1.

20.97 GHz.—The 20.97 GHz methanol maser was discovered by the Mopra observations of G358.93—0.03 conducted during the burst (Breen et al. 2019). In the present study, this methanol maser transition was observed only at the second epoch. The maser emission at 20.97 GHz occupies the velocity range of $\sim-18$ to $-15$ km s$^{-1}$, the same as other methanol maser transitions detected in the source. By the time of the VLA observations, the flaring 20.97 GHz spectral feature at
V_{\text{LSR}} \sim -15 \text{ km s}^{-1} \text{ had decayed from } \sim 1000 \text{ Jy (Breen et al. 2019) to } \sim 70 \text{ Jy (Figure 6). The blueshifted feature at } V_{\text{LSR}} \sim -17 \text{ km s}^{-1} \text{ with a flux density of } \sim 100 \text{ Jy had become the dominant one. Spatially, the maser spots trace an almost round structure of size of } \sim 0''22, \text{ pointing eastward from the MM1 position. There is a clear velocity gradient with blueshifted features to the north and redshifted features to the south.}

**23.12 GHz**—During the burst, the 23.12 GHz methanol masers associated with G358.93–0.03 showed the brightest and the most complex spectrum (MacLeod et al. 2019) of this rare maser transition detected to date (see Galván-Madrid et al. 2010 and references therein). The 23.12 GHz emission covers the same velocity range as that of the 6.67 and 12.18 GHz masers, but with about 10× lower flux density. By VLA epoch II, the 23.12 GHz maser had faded to \sim 2 \text{ Jy but continued to have a complex, multicomponent spectrum. Spatially, the 23.12 GHz maser emission is found around MM1 (Figure 7). At the flare epoch, the 23.12 GHz maser

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**Figure 3.** The 6.67 GHz CH$_3$OH maser emission detected in G358.93–0.03 with the VLA. Left panels: VLA images of the brightest 6.67 GHz CH$_3$OH maser emission spots detected at (a) epoch I and (b) epoch II. Yellow plus signs mark the peaks of maser emission (maser spots). (c) Superimposed 6.67 GHz methanol maser spot maps and spectra (the markers on the spectra correspond to the maser spots on the map) from epochs I and II. Plots are color-coded by radial velocity (see color bar for color scale). The error bars indicate the position fitting errors from Table 5.

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**Table 5**

| Epoch | R.A. (J2000) (h m s) | Dec. (J2000) (° m) | Integrated Flux (Jy) | Peak Flux (Jy beam$^{-1}$) | $V_{\text{LSR}}$ (km s$^{-1}$) |
|-------|---------------------|-------------------|---------------------|--------------------------|-----------------------------|
| I     | 17:43:10.0989 ± 0.0001 | -29:51:45.757 ± 0.014 | 15.55 ± 0.15 | 15.80 ± 0.06 | -19.36 |
| I     | 17:43:10.0988 ± 0.0001 | -29:51:45.786 ± 0.010 | 38.08 ± 0.27 | 38.12 ± 0.11 | -19.27 |
| I     | 17:43:10.0989 ± 0.0001 | -29:51:45.768 ± 0.009 | 54.48 ± 0.34 | 54.16 ± 0.13 | -19.19 |

*Note.* (1) Table 5 is published in its entirety in the machine-readable format. A portion is shown here for guidance regarding its form and content. (2) The positional shifts of $\Delta \text{R.A.} = 0.010$, $\Delta \text{decl.} = 0.079$ (epoch I) and $\Delta \text{R.A.} = 0.017$, $\Delta \text{decl.} = 0.017$ (epoch II) were introduced to the data to prepare Figures 3, 10–11, and 13–15 (see Section 2).

(This table is available in its entirety in machine-readable form.)
cluster appeared to be more compact than the 6.67/12.18 GHz masers, with a size of $\sim 0.215$. The flaring 23.12 GHz emission consists of two elongated subclusters, with the northern cluster hosting blueshifted velocity features and the southern cluster with redshifted features. At VLA epoch II, the 23.12 GHz emission is found in an expanded region of $\sim 0.22$ (note that the lower flux densities at epoch II result in higher positional uncertainties, which could affect the apparent size of the region). The structure of the masing region at the post-flare epoch is less ordered but shows the same north–south velocity gradient.

### 3.2. Continuum Emission

The VLA observations toward G358.93−0.03 detected two continuum sources (Table 2). The hot core MM3 showed continuum emission in all three frequency bands at both epochs. Nevertheless, MM3 has no evident association with the bursting source and the detected methanol masers and is not considered further in the present study. The bursting source MM1 was detected in K band at the first epoch of the VLA observations. No K-band emission above the 3$\sigma$ noise level was found at the second epoch.
In our VLA observation, conducted on 2019 February 25 during the burst epoch, MM1 showed an integrated flux density of $\sim 0.2$ mJy at 20 GHz.

Note that the only centimeter observations found in the literature on the pre-burst epoch are those of Hu et al. (2016), who report a null detection at C band, but based on only 20 s of

Table 7
12.23 GHz CH$_3$OH Maser Parameters

| Epoch | R.A. (J2000) (h m s) | Decl.(J2000) (° ′ ″) | Integrated Flux (Jy) | Peak Flux (Jy beam$^{-1}$) | $V_{LSR}$ (km s$^{-1}$) |
|-------|---------------------|----------------------|----------------------|---------------------------|------------------------|
| II    | 17:43:10.1148 ± 0.0012 | −29 51 45.715 ± 0.080 | 0.09 ± 0.02 | 0.07 ± 0.01 | −16.15 |
|       | 17:43:10.1175 ± 0.0008 | −29 51 45.523 ± 0.006 | 0.08 ± 0.02 | 0.08 ± 0.01 | −16.63 |
|       | 17:43:10.1074 ± 0.0013 | −29 51 45.707 ± 0.057 | 0.10 ± 0.02 | 0.08 ± 0.01 | −16.73 |

Note. (1) Table 7 is published in its entirety in the machine-readable format. A portion is shown here for guidance regarding its form and content. (2) The positional shift of $\Delta$R.A. = −0.1, $\Delta$decl. = −0.016 (epoch II) was introduced to the data to prepare Figures 5, 10–11, and 13–15 (see Section 2). (This table is available in its entirety in machine-readable form.)
Table 8

| Epoch | R.A.(J2000)  | Decl.(J2000)  | Integrated Flux | Peak Flux | V$_{LSR}$ |
|-------|--------------|---------------|-----------------|-----------|-----------|
| II    | 17:43:10.0988 ± 0.0003 | −29:51:45.608 ± 0.012 | 7.31 ± 0.36 | 5.95 ± 0.16 | −17.61 |
|       | 17:43:10.0988 ± 0.0003 | −29:51:45.616 ± 0.013 | 13.29 ± 0.64 | 10.31 ± 0.28 | −17.50 |
|       | 17:43:10.1053 ± 0.0003 | −29:51:45.616 ± 0.012 | 27.30 ± 1.20 | 18.48 ± 0.48 | −17.39 |

Note. (1) Table 8 is published in its entirety in the machine-readable format. A portion is shown here for guidance regarding its form and content. (2) The positional shift of ΔR.A. = −0.055, ΔDecl. = 0.022 (epoch II) was introduced to the data to prepare Figures 6, 10–11, and 13–15 (see Section 2).

(This table is available in its entirety in machine-readable form.)

Table 9

| Epoch | R.A.(J2000)  | Decl.(J2000)  | Integrated Flux | Peak Flux | V$_{LSR}$ |
|-------|--------------|---------------|-----------------|-----------|-----------|
| I     | 17:43:10.1055 ± 0.0001 | −29:51:45.720 ± 0.014 | 0.87 ± 0.03 | 0.82 ± 0.01 | −18.59 |
|       | 17:43:10.1054 ± 0.0001 | −29:51:45.720 ± 0.012 | 1.38 ± 0.04 | 1.19 ± 0.02 | −18.54 |
|       | 17:43:10.1051 ± 0.0001 | −29:51:45.734 ± 0.010 | 1.99 ± 0.05 | 1.63 ± 0.02 | −18.49 |

Note. (1) Table 9 is published in its entirety in the machine-readable format. A portion is shown here for guidance regarding its form and content. (2) The positional shifts of ΔR.A. = −0.005, ΔDecl. = −0.051 (epoch I) and ΔR.A. = −0.035, ΔDecl. = −0.040 (epoch II) were introduced to the data to prepare Figures 7, 10–11, and 13–15 (see Section 2).

(This table is available in its entirety in machine-readable form.)
data. The latest VLA B-array observation of Chen et al. (2020a) also reported a nondetection of Ku-band continuum emission in the direction of MM1 at the 3σ level of 20 μJy.

At the post-burst epoch, on 2019 April 12, in ALMA observations, the flux density was ∼282 mJy at 337 GHz (Brogan et al. 2019). Note, however, that the observations were made at different stages of the source’s activity, and therefore the results of the observations cannot be directly compared.

The K-band continuum images of MM1 at both epochs are shown in Figure 8, and a summary of the parameters of the detected continuum peak is presented in Table 3. The offset between the ALMA and VLA positions of MM1 is ∼0.2″ (Figure 9), which is similar to the absolute positional uncertainty reported in Brogan et al. (2019).

4. Discussion

4.1. The Accretion Burst

A unique feature of the burst in G358.93−0.03 is the discovery of new maser transitions (Breen et al. 2019; Brogan et al. 2019; MacLeod et al. 2019). Three of these, the maser transitions at 6.18, 12.23, and 20.35 GHz, were not even predicted by maser pumping calculations performed up to now. Others had been predicted in theoretical works (e.g., Sobolev et al. 1997a; Cragg et al. 2005) but had not been detected previously. The reasons for their rarity are not entirely clear.

Several of the newly detected methanol masers were imaged for the first time in the VLA observations presented here. The high sensitivity and moderate resolution of the VLA allow us to study the spatial structure of very weak masers, which are not accessible to VLBI imaging but are readily detectable by the VLA. We were able to image and precisely locate positions of faint masers at 6.18 and 12.23 GHz with flux densities of ∼0.1 Jy (Figures 2 and 5). Notably, not only do the imaged methanol masers, including the newly discovered ones, arise in the same region, but they also trace the same structures (Figure 10).

The VLA epoch I (2019 February 25) observations were carried out during the maximum flare activity of the 6.67 GHz methanol maser in G358.93−0.03, midway between the two peaks of the flare on February 14 and March 12 (iMet data; see Section 3). Thus, VLA epoch I can be considered as a flare epoch, while VLA epoch II (2019 June 4) is a post-flare one.

Pre-flare VLA data from early 2012 exist and were published by Hu et al. (2016). In the quiescent state, the peak 6.67 GHz maser flux density was ∼5 Jy (Hu et al. 2016). The data of Hu et al. (2016) were obtained with the ∼4″ beam of the VLA C-configuration, i.e., with much lower resolution than our VLA data, which precludes a comparison of the spot maps.

Our VLA data indicate that all of the flaring methanol masers originate from a single region of size ∼0.22″ (Figures 10 and 11), which coincides with the brightest millimeter source, MM1, detected with ALMA (Brogan et al. 2019). The close spatial association of the various flaring maser transitions is expected if caused by an accretion burst.
In order to analyze the maser density distribution at two VLA epochs and its evolution between the observations, we calculated the number of detected maser spots around MM1—see histograms in Figure 11. The blue markers on the map and blue histogram bars correspond to VLA epoch I, and the red markers/bars correspond to epoch II. The bin width of the histograms is 0.02, which is 1/10 of the area occupied by the maser emission and corresponds to the median position fitting error of our data (see Tables 4–9).

At the first VLA epoch, the flaring methanol maser emission consists of two linked subclusters, where the northern cluster hosts blueshifted velocity spots while the southern cluster has redshifted ones (Figure 10(a)). The analysis of the density of the maser spot distribution around MM1 (Figure 11) shows two density peaks located almost symmetrically around the source at separations of \( \sim 0.05 \). One “knot” is located to the NE and another to the SW of the MM1 position (Figure 10(b)). While the velocity pattern persisted (the blueshifted velocity spots are found to the north and the redshifted ones to the south), the region affected by the maser emission expanded. The histograms in Figure 11 show that the maximums of the maser spot density shifted outward to the radius of \( \sim 0.09 \) from the position of the central source.

To estimate the evolution of the maser distribution in the region, we compare the positions of the maser emission density “knots” evaluated from the histograms in Figure 11. The density peaks were found at a diameter of \( \sim 0.1 \) around MM1 at epoch I and a diameter of \( \sim 0.2 \) at epoch II. Thus, the region of physical conditions suitable to sustain maser emission doubled in size.

The drastic change between flare and post-flare epochs affected the entire masing region of \( \sim 1000 \) au (adopting the BeSSeL estimate of a near-kinematic distance of 6.75 kpc) and happened in a period of about 3 months. Assuming these parameters, the triggering event may have propagated at a speed of \( \sim 0.06c \) from the bursting source. Such a high speed is almost certainly not caused by any physical movement of material. Hence, the flare and spatial rearrangement of the maser emission must be caused by a radiative event from the protostar that propagated through regions of more favorable physical conditions, more distant from the protostar.
4.2. Comparison of the VLA Data with Other Observations

A thermal radiation “heat wave” emanating from an accreting high-mass protostar in G358.93–0.03, propagating at subluminal speed, has been inferred from multiepoch LBA observations of 6.67 GHz methanol masers (Burns et al. 2020). The lower spatial resolution of the VLA prohibits such a precise analysis of the spatial structure of the maser emission in the region. On the other hand, it provides a unique insight into an extended component of maser emission.

The comparison of the VLA cross-correlation spectra (with a synthesized beam size of $\sim 3.5$; see Table 1) and single-dish spectra obtained with the Hitachi 32 m radio telescope as a part of the iMet program shows that 100% of the single-dish flux density is recovered on the VLA baselines (Figure 12). In contrast, only $\sim 10\%$ of the maser flux density was recovered with the milliarcsecond synthesized beam of the LBA (Burns et al. 2020). Based on these results and in accordance with the core/halo hypothesis of the structure of class II methanol masers (e.g., Minier et al. 2002), we conclude that with the VLA baselines we detect both compact (core) and extended (halo) emission, while with the LBA baselines we detect only the compact core emission.

The comparison of the 6.7 GHz methanol maser spot maps obtained in the VLBI observations of Burns et al. (2020) and in our VLA observations (Figure 13) shows that compact and extended components of the maser emission trace the same region around MM1 but highlight rather different structures. Both compact (VLBI data) and extended (VLA data) emission can be divided into two clusters: an upper (northern) cluster consisting of blueshifted velocity spots, and a lower (southern) cluster consisting of redshifted velocity spots. However, the northern cluster of extended VLA maser emission is smaller than the southern cluster, while for the compact VLBI emission the two clusters have about the same size. Also noteworthy is that both extended and compact maser emissions trace roughly the same turning points in both the northern and southern clusters.

Nevertheless, the LBA (Burns et al. 2020) and VLA observations were carried out with a 3-day interval from each other during the period of high activity of the source. Therefore, it is possible that not all differences in the structure of the spot maps can be attributed to the extended/compact emission duality. For example, the most southern, linearly elongated maser cluster detected with the LBA has no counterpart in the VLA map. The iMet monitoring data indicated that the source shows daily/intraday variability. If we assume that a $\sim 0.05$ cluster was ignited by the propagation of the heat wave over 3 days between the observations, the wave speed must be $\sim 0.7 c$. On the one hand, a wave propagating through the low-density material is supposed to have a speed of light; thus, the speed of $\sim 0.7 c$ is achievable, especially in the lower-density outer regions. However, the absence of the elongated southern substructure is most likely due to the effect...
of centroid mapping. The most distant spot from MM1 with a particular velocity will be averaged in the synthesized beam with any other spots with the same velocity in the region, as a result that will bring the centroid map position to be closer to the center of the red cluster.

![Flare](image1.png)
**Figure 12.** Comparison of the single-dish and cross-correlation VLA spectra of the 6.7 GHz methanol maser emission detected in G358.93−0.03 (a) on 2019 February 25 (epoch I) and (b) on 2019 June 4 (epoch II). The single-dish data are obtained in the iMet program.

![Flare](image2.png)
**Figure 13.** Comparison of the spatial distribution of the methanol maser emission detected in G358.93−0.03 with the VLA on 2019 February 25 (this paper; epoch I) and LBA on 2019 February 28 (Burns et al. 2020).

It is also found that the centimeter-wavelength methanol masers detected with the VLA (this paper) and newly discovered high-frequency methanol masers detected with the SMA and ALMA (Brogan et al. 2019) trace similar spatial patterns (see Figure 14). Here we present a comparison of our VLA data with the 199.575 GHz methanol maser transitions are found in two subclusters separated by location and velocity, with the northern cluster containing the blueshifted maser spots and the southern cluster predominated by the redshifted velocity spots (Figure 14(a)). At the post-flare epoch, in 2019 April–June, all detected methanol masers trace a wider and less dense/more elongated formation, which can be interpreted as a spiral arm structure (Figure 14(b)).

The cross-matching of our data and the results from Chen et al. (2020b) showed that the spatial distribution of the methanol masers detected at the second VLA epoch closely reassembles that which Chen et al. (2020b) reported for the CH$_3$OH, HDO, and HNCO masers in G358.93−0.03 (Figure 15(b)). Note that despite the fact that the observations of Chen et al. (2020b) were conducted with the VLA on 2019 April 4, i.e., closer to our VLA epoch I (38 days apart—see Figure 15(a)), the data of VLA epoch II (61 days apart) appeared to be more fitting (Figure 15(b)). Chen et al. (2020b) argue that the rare masers detected in their VLA observations trace a two-armed spiral structure; in this scenario the arms reveal accretion flows falling onto the central star in spiral trajectories. According to theory (e.g., Meyer et al. 2019a; Jankovic et al. 2019), spiral arms, as well as accretion bursts, are products of gravitational instability of a disk around MYSOs. Our VLA data seem to suggest that the spiral arm features of the accretion disk are traced not only by rare maser species detected by Chen et al. (2020b) but also by more common methanol masers at 6.67 and 12.18 GHz. Note that the observations of Chen et al. (2020b) were performed still at the flare epoch (April 4), while our VLA observations took place at the post-flare epoch (June 4)—see Figure 1. In the period between observations, no drastic changes in the structure of the spectrum were observed for the methanol maser at 6.7 GHz, for example; the only striking difference was the gradual decrease in the maser flux density from ~500 to ~100 Jy. The

![Flare](image3.png)
two-arm spiral infall gas flow structure seems to still exist at the post-flare period, and the physical conditions (e.g., temperature) in these flows change with the flare propagation, making different types of masers (with different pumping conditions) gradually arise or disappear in the flows. The resemblance of the maser clusters detected in Chen et al. (2020b) and in our observations at epoch II (Figure 15(b)) indicates that the spatial distribution of the methanol masers remained roughly constant after 2019 April.

Figure 14. Comparison of spatial distribution of the methanol maser emission detected in G358.93−0.03 with (a) the VLA on 2019 February 25 (this paper; epoch I) and SMA on 2019 March 14 (Brogan et al. 2019) and (b) the VLA on 2019 June 4 (this paper; epoch II) and ALMA on 2019 April 16 (Brogan et al. 2019).

Note that the most recent VLBI/ALMA results obtained by the M2O indicate the presence of a more complex spatial structure of the regions traced by the methanol masers than that found with the VLA (R. A. Burns et al. 2021, in preparation; C. L. Brogan et al. 2021, in preparation). For example, VLBI observations suggest a four-arm system (Burns et al. 2021, in preparation), not the two-arm system that was discovered with the VLA (Chen et al. 2020b; this paper). Nevertheless, the VLBI and VLA results do not contradict each other, but rather indicate the limitations of spatially unresolved maser spot fitting when there is complex underlying spatial morphology in each channel. It is possible that the two arms on the blue side of the disk are averaged within the VLA synthesized beam into one arm, and the same for the two arms on the red side of the disk. Since the disk is almost face-on, the velocity differences across the disk are small, which worsens this effect, as the centroid mapping technique derives a single spot per velocity channel and many maser spots exist in different parts of the disk (in different arms) at the same velocity. A more detailed comparison of the VLA and VLBI/ALMA results obtained for the source will be presented in the future M2O publications.

Figure 15. Comparison of spatial distribution of the methanol maser emission detected in G358.93−0.03 with the VLA on 2019 March 24 (Chen et al. 2020b) and (a) the VLA on 2019 February 25 (this paper; epoch I) and (b) the VLA on 2019 June 4 (this paper; epoch II).
4.3. Centimeter Continuum Emission of MM1

The strong millimeter continuum emission of MM1 (Brogan et al. 2019), coupled with the lack of significant centimeter emission (Figure 8), indicates that the source is probably in a precursor state of the ultracompact H II region (Churchwell 2002), as indicated in Brogan et al. (2019).

Our continuum observations suggest a moderate decrease in the flux densities of MM1 in the period between the flare and post-flare epochs. As we indicated in Section 3, the ALMA millimeter observations and VLA centimeter observations were performed during different epochs of the source activity. The analysis is particularly difficult because the presumptive bursting source MM1 was detected only in K band and at one epoch of observation. Moreover, in contrast to S255 and NGC 6334I, centimeter continuum emission in G358.93−0.03 shows much lower flux densities.

Nevertheless, a decrease of the centimeter continuum flux density of a source can happen during the accretion event. In the case of NGC 6334I, for example, Hunter et al. (2017) reported a fourfold increase in the dust continuum emission, while the free–free emission (at 1.5 cm) fell by about the same factor (Brogan & Hunter 2018; Hunter 2019). Such a decrease would naturally occur if the ionizing photon flux from the young stellar object is reduced owing to the bloating of the star. At the high densities of these MYSO, the recombination timescale for the ionized gas can be of the order of days to weeks. Hence, the free–free continuum emission can track the same accretion events but show a decrease while the IR luminosity increases (Hunter 2019).

5. Summary

A multiepoch and multifrequency VLA imaging of maser and continuum emission in C, Ku, and K bands was performed for the massive star-forming region G358.93−0.03. Two observing sessions were conducted, at the maser flare epoch (VLA epoch I) and at a post-flare epoch (VLA epoch II). The main outcomes and scientific insights obtained from the observations are summarized as follows:

1. Maser emission is detected and imaged in several methanol transitions. Spatial structure evolution is studied for methanol masers at 6.67, 12.18, and 23.12 GHz at two observational epochs.
2. The first interferometric images are obtained for the new methanol maser transitions at 6.18, 12.23, and 20.97 GHz (the masers were discovered in G358.93−0.03 in single-dish and ATCA observations; Brogan et al. 2019; MacLeod et al. 2019).
3. Methanol maser emission in all detected transitions and at both epochs is found in a region with a diameter of ~0′′22 around the MM1 position and shows a velocity gradient in the N–S direction.
4. A drastic change in the spatial distribution of the detected methanol masers is found. At the flare epoch, the 6.67, 12.18, and 23.12 GHz methanol masers are found in elongated regions, aligned in an NE–SW direction. At the post-flare epoch, the methanol masers trace bow-shaped structures extending eastward from the MM1 position. During the transition from the first epoch to the second, the region traced by masers expanded while the velocity gradient decreased.
5. The obtained data suggest that the methanol masers detected with the VLA trace the spiral arm structures within the accretion disk, which were first discovered in rare maser lines in Chen et al. (2020b).
6. K-band continuum emission is detected at VLA epoch I toward the supposed bursting source and the most line-rich hot core, detected with ALMA by Brogan et al. (2019) as G358.93−0.03-MM1. A moderate decrease in the flux density of MM1 in the period between the flare and post-flare epoch is detected.

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