New Methanol Maser Transitions and Maser Variability Identified from an Accretion Burst Source G358.93-0.03

Dan Miao1, Xi Chen1,2,3,4,5, Shi-Min Song2,4,6, Andrej M. Sobolev5, Shari L. Breen6, Gordon C. MacLeod7,8, Bin Li2, Sergey Parfenov5, Anastasia Bisyarina5, and Zhi-Qiang Shen2

1 Center for Astrophysics, Guangzhou University, Guangzhou 510006, People’s Republic of China; chenxi@gzhu.edu.cn
2 Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, People’s Republic of China
3 Peng Cheng Lab, Shenzhen, 518066, People’s Republic of China
4 University of Chinese Academy of Sciences, 19A Yuquanlu, Beijing 100049, People’s Republic of China
5 Ural Federal University, 19 Mira Street, 620002 Ekaterinburg, Russia
6 SKA Observatory, Jodrell Bank, Lower Withington, Macclesfield, SK11 9FT, UK
7 The University of Western Ontario, 1151 Richmond Street, London, ON N6A 3K7, Canada
8 Hartebeesthoek Radio Astronomy Observatory, P.O. Box 443, Krugersdorp 1741, South Africa

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Abstract

The high-mass young stellar object G358.93-0.03 underwent an accretion burst during the period from 2019 January to June. Given its extraordinary conditions, a number of new maser transitions may have been naturally excited during the burst stage. Searching for new maser lines and monitoring maser variability associated with the accretion burst event are important for understanding the complex conditions of the massive star formation toward G358.93-0.03. In this work, using the Shanghai 65 m Tianma Radio Telescope, we continuously monitored the multiple maser (including methanol and water) transitions toward G358.93-0.03 during the burst in the period from 2019 March 14 to May 20. There were 23 CH$_3$OH maser transitions and one H$_2$O maser transition detected from the monitoring. Nearly all the detected maser transitions toward this source have dramatic variations in their intensities within a short period of ∼2 months. Eight new methanol transitions from G358.93-0.03 were identified to be masering in our observations based on their spectral profile, line width, intensity, and the rotation diagram. During the monitoring, the gas temperature of the clouds in the case of saturated masers can show a significant decline, indicating that the maser clouds were going through a cooling process, possibly associated with the propagation of a heat wave induced by the accretion burst. Some of the maser transitions were even detected with the second flares in 2019 April, which may be associated with the process of the heat-wave propagation induced by the same accretion burst acting on different maser positions.

Unified Astronomy Thesaurus concepts: Interstellar masers (846); Star formation (1569); Massive stars (732); Accretion (14); Young stellar objects (1834)

Supporting material: figure sets, machine-readable table

1. Introduction

Episodic accretion comprises prolonged quiescent and transient periods punctuated by intense bursts of accretion. Generally, the quiet stage has a low accretion rate and luminosity along with a cooling of the disk. However, most of the prestellar mass is accumulated in the burst stage with luminosity outbursts and the heating and stabilization of the surrounding disk (Vorobyov & Basu 2006; Stamatellos et al. 2011). There is observational and theoretical evidence that accretion of material is often episodic in early evolution for low-mass star formation (Herbig 1977; Peneva et al. 2010). Further evidence for episodic accretion comes from the periodically spaced knots seen in bipolar jets (Reipurth 1989). Apart from that, the luminosity problem provides indirect observational support for episodic accretion (Kenyon et al. 1990; Evans et al. 2009), as the luminosity outbursts are intermittent and most protostars are observed between bursts. Recent studies have shown that massive star formation can also experience phenomena similar to episodic accretion and accretion bursts that occur in low-mass star formation. The discoveries of accretion bursts in three massive young stellar objects (MYSOs), NGC6334I–MM1 (Hunter et al. 2017), S255IR–NIRS3 (Caratti o Garatti et al. 2017), and G358.93–0.03 (Chen et al. 2020a), provide vital evidence for episodic accretion in massive star formation (Cesaroni et al. 2018; Brogan et al. 2018). The accretion burst source studied in this paper (G358.93–0.03) has a central protostar mass of ∼12 M$_\odot$ in its MM1 region (Chen et al. 2020a), a bolometric luminosity in a range of 5700–22,000 L$_\odot$ (Brogan et al. 2019), and an accretion rate of 3.2 × 10$^{-3}$ M$_\odot$ yr$^{-1}$ (Stecklum et al. 2021). Observational studies of the Orion molecular clouds show that episodic accretion accounts for >25% of a star’s mass (Fischer et al. 2019). And even theoretical considerations show that massive stars can gain 40%–60% of their mass during accretion bursts (Meyer et al. 2021), suggesting that they are an essential rather than serendipitous process for massive star formation (Cesaroni et al. 2018; Brogan et al. 2018; Chibueze et al. 2021). If we are to gain a clear understanding of whether episodic accretion is a common phenomenon in the formation of all young stars, the study of episodic accretion bursts in massive star-forming regions (MSFRs) is crucial. So far, due to the lack of sufficient
observational evidence, this process of high-mass star formation is still poorly understood.

It is relatively difficult to observe bursts of accretion in massive protostars due to their rapid evolution (much shorter timescales than low-mass stars), and the fact that accretion bursts tend to be relatively short compared to the more common quiescent periods (Stamatellos et al. 2011). Moreover, these MYSOs are usually buried in very dense clouds of dust and gas. Therefore, accretion bursts in MSFRs are very difficult to capture from a temporal and environmental point of view. Fortunately, masers are powerful tracers of several astronomical events, as they are commonly believed to be extremely sensitive to changes in the physical conditions of their natal clouds, especially those caused by the enhancement of radiation fields and collisions of matter. The increased local radiation field due to the stellar luminosity burst induced by an accretion burst will result in the increase of incident photons, thus enhancing the maser emission. Class II CH$_3$OH (methanol) masers are pumped by infrared radiation and are thought to be closely associated with massive protostellar luminosity outbursts. Additionally, class II methanol masers are well established as tracers of the early stage of massive star formation (Minier et al. 2001; Ellingsen 2006) and exclusively observed near MYSOs (Minier et al. 2002; Xu et al. 2008; Paulson & Pandian 2020). It is worth mentioning that a direct link between 6.7 GHz class II CH$_3$OH maser flaring and an accretion burst has recently been established for the three known MYSOs (NGC6334I-MM1, S255IR-NIRS3, and G358.93-0.03) with accretion burst events (Moscadelli et al. 2017; Hunter et al. 2018; Sugiyama et al. 2019).

The target source of this paper, G358.93-0.03 (hereafter G358), was identified as undergoing an accretion burst from variability monitoring of the 6.7 GHz methanol maser by the Maser Monitoring Organization (M2O, which is a global cooperative of maser monitoring programmers). The 6.7 GHz maser burst started in 2019 January (10 Jy; Sugiyama et al. 2019), reached its peak emission (1156 Jy) in a short period of ~2 months (MacLeod et al. 2019), and subsequently decayed rapidly returning to a normal accretion state. The burst thus lasted only about 5 months, such a rapid timescale that no current theory can adequately explain. Therefore, further methanol maser monitoring is needed to inform a theoretical explanation of episodic accretion process in MSFRs. Monitoring maser variability can also yield valuable information on changing conditions around the maser regions and the potential kinematics of the maser clouds.

In addition to the 6.7 GHz methanol maser, multiple new maser transitions have been detected in G358, such as the new class II methanol maser transitions, some of which are in torsionally excited states ($v_1=1$ and 2), at both centimeter (Breen et al. 2019; MacLeod et al. 2019; Volvach et al. 2020) and millimeter wavelengths (Brogan et al. 2019), and new molecular maser species $^{13}$CH$_3$OH, HDO, and HNCO (Chen et al. 2020a, 2020b). The latter three new species of masers accurately depict spiral-arm accretion flow structures tracing fragmentation caused by the instability of large-mass disks (Chen et al. 2020a). The discoveries of these new maser transitions suggest that the episodic accretion process of G358 has a special physical environment to effectively excite new and rare masers from methanol and other molecule species. Nearly all these new maser transitions have dramatic changes within a short period. The rapid variability of the maser emission suggests that it is a transient phenomenon, probably associated with rapid changes in the thermal radiation field due to an accretion outburst (Chen et al. 2020a; Burns et al. 2020). Moreover, the accretion burst in G358 was decisively confirmed by multiepoch SOFIA observations (Stecklum et al. 2021). The event is found to be the first near infrared (NIR)/(sub)millimeter-dark and far infrared (FIR)-loud MYSO accretion burst, showing an increase in the flux of the source only in the FIR, and not in the NIR or (sub)millimeter (Stecklum et al. 2021). The dense monitoring of methanol masers at multiple transitions will help us to further investigate more details of the accretion burst phenomenon in this source.

In this paper, we reported the monitoring results for the multiple methanol maser lines accompanied with accretion burst phase using the Shanghai 65 m Tianma Radio Telescope (TMRT) toward G358 during the period of 2019 March 14 to May 20. We detected eight new methanol maser transitions that have not previously been known to show maser emission.

2. Observations

The TMRT was used to conduct monitoring observations of a series of molecular lines, including masers, toward the flaring 6.7 GHz maser, G358 (J2000 position: $17^\text{h}43^\text{m}10^\text{s}10\text{.14}, 29^\circ 51' 45''693$; Brogan et al. 2019). These observations began on 2019 March 14, and concluded on 2019 May 20, with a number of epochs in order to sample the different phases of the bursting source. We used the cryogenically cooled C-, K-, Ka- and $Q$-band receivers covering a frequency range of 4–50 GHz and the Digital Backend System (DIBAS) to receive and record signals. DIBAS is an FPGA-based spectrometer designed on the basis of the Versatile GBT Astronomical Spectrometer (Bussa 2012). Observations were first made in the wideband mode with bandwidths of 187.5 MHz in $C$ band, 500 MHz in $Ka$ band, and 1500 MHz in the $K$, $Ka$ and $Q$ bands, and detected emission was monitored using zoom-band mode with a high spectral resolution. In the zoom-band mode, each narrowband window has a bandwidth of 23.4 MHz. Using the active surface correction system, the achieved aperture efficiency of the TMRT ranges from 53% to 65%, corresponding to a sensitivity ranging from 1.28 to 1.59 Jy K$^{-1}$. The uncertainty in the absolute flux density for both wideband and zoom-band spectra is less than 10% by checking the flux density of nearby continuum calibrators. More details of our TMRT observations are listed in Table 1.

All observations were performed in position-switching mode, as a series of 1 or 1.5 minutes ON/OFF cycles. For each epoch, the total on-source time ranges from 12 to 56 minutes, depending on the signal-to-noise ratio of each detected line.

The GILDAS/CLASS package was used to perform the spectral line data reduction. The linear baseline of the spectrum was first fitted and then removed from the averaged spectrum of all scans. The rms noise levels achieved for each line are listed in Tables 2 and 3.

3. Eight New Methanol Transitions

In total, eight new class II methanol transitions at rest frequencies of 26.12, 27.28, 28.97, 31.98, 34.24, 41.11, 46.56, and 48.71 GHz were detected toward G358 in our observations. In addition to the 28.97 GHz transitions, all of the others are

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9 https://www.masermonitoring.com
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Table 1
Details of the TMRT Observations

| Band | Mode | Channel Number | Spectral Window (MHz) | Channel Spacing (km s\(^{-1}\)) | System Temperature (K) | Sensitivity (Jy K\(^{-1}\)) | Aperture Efficiency (%) | Beam Size (\(^{\circ}\)) | Integration Time (minutes) |
|------|------|----------------|-----------------------|-------------------------------|------------------------|--------------------------|--------------------------|-----------------|---------------------------|
| C    | 6    | 131072         | 187.5                 | 0.055–0.069                  | 20–30                  | 1.28                     | 65                       | 147.8–187.3    | 12–20                     |
| Ku   | 3    | 16384          | 500                   | 0.746–0.749                  | 50–60                  | 1.33                     | 62                       | 94.7–95.0      | 36                         |
| 24   |      | 65536          | 23.4                  | \(~<0.009\)                   |                        |                          |                          |                 |                            |
| K    | 2    | 16384          | 1500                  | 1.048–1.371                  | 150–200               | 1.52                     | 55                       | 44.3–48.0      | 42–49                     |
| 22   |      | 16384          | 23.4                  | 0.016–0.022                  |                        |                          |                          |                 |                            |
| Ka   | 2    | 16384          | 1500                  | 0.856–1.003                  | 200–300               | 1.59                     | 53                       | 33.8–42.4      | 30                         |
| 22   |      | 16384          | 23.4                  | 0.013–0.016                  |                        |                          |                          |                 |                            |
| Q    | 2    | 16384          | 1500                  | 0.562–0.757                  | 200–300               | 1.59                     | 53                       | 23.8–32.0      | 14–22                     |

Note. Column (1): C, Ku, K, Ka, Q indicate the different cryogenically cooled receivers of TMRT with the frequency ranges of 4–8 GHz, 12–18 GHz, 18–26.5 GHz, 26–35 GHz, and 35–50 GHz, respectively. Columns (2)–(9): inherent parameters in different backend modes including channel number, bandwidth, and velocity resolution. Columns (6)–(9): system temperature, sensitivity, aperture efficiency, and beam size at the corresponding receiver band. Column (10): total integration time.

Table 2
Spectral Properties of the Eight Newl Detected CH\(_3\)OH Maser Transitions

| Methanol Transition | Rest Freq. (Err) (MHz) | Epoch | \(V_{\text{range}}\) (km s\(^{-1}\)) | \(V_{\text{peak}}\) (km s\(^{-1}\)) | \(S_{\text{peak}}\) (Jy) | \(S_{\text{int}}\) (Jy km s\(^{-1}\)) | rms (Jy) | \(\delta V\) (km s\(^{-1}\)) |
|---------------------|------------------------|-------|-----------------------------------|---------------------------------|------------------------|--------------------------------------|----------|---------------------------|
| 10_1–11_2 A\(^{-}\) \(v_{i} = 1\) | 26,120.557(0.021)       | 2019/3/17 | \((-18.85, -15.03)\) | \(-17.44\) | 593.81 | 646.57(0.09) | 0.35 | 0.02                      |
|                     | 4/8                    | \((-18.29, -15.23)\) | \(-17.55\) | 195.84 | 165.74(0.10) | 0.42 | 0.02                      |
|                     | 4/12                   | \((-18.71, -15.10)\) | \(-17.53\) | 1218.00 | 1016.50(0.08) | 0.35 | 0.02                      |
|                     | 5/3                    | \((-18.94, -14.31)\) | \(-15.79\) | 1265.00 | 946.37(0.05) | 0.19 | 0.02                      |
|                     | 5/7                    | \((-18.26, -15.03)\) | \(-15.63\) | 467.19 | 362.03(0.15) | 0.20 | 0.02                      |
| 14\(_2\)–15\(_1\) E \(v_{i} = 0\) | 27,283.154(0.013)       | 2019/4/1 | \((-20.09, -13.03)\) | \(-15.05\) | 211.76 | 444.57(0.01) | 0.01 | 1.01                      |
|                     | 5/3                    | \((-18.17, -14.83)\) | \(-17.14\) | 247.49 | 170.20(0.05) | 0.20 | 0.02                      |
| 8\(_2\)–9\(_1\) A\(^{-}\) \(v_{i} = 0\) | 28,969.966(0.012)       | 2019/4/1 | \((-20.82, -14.18)\) | \(-16.08\) | 14.24 | 40.25(0.08) | 0.04 | 0.95                      |
|                     | 5/3                    | \((-18.19, -14.67)\) | \(-16.00\) | 23.45 | 22.96(0.05) | 0.18 | 0.01                      |
| 19\(_{−}\)–20\(_{−}\) E \(v_{i} = 0\) | 31,977.789(0.014)       | 2019/4/1 | \((-19.39, -15.96)\) | \(-16.82\) | 0.83 | 1.81(0.04) | 0.02 | 0.86                      |
|                     | 5/3                    | \(-19.39, -15.96\)   | \(-16.82\) | 1.81(0.04) | 0.02 | 0.86                      |
| 14\(_{−}\)–15\(_{−}\) E \(v_{i} = 0\) | 34,236.947(0.012)^

Note. Columns (1)–(2): methanol maser transitions and adopted rest frequency with uncertainties given in parentheses from CDMS https://cdms.astro.uni-koeln.de/ and JPL (denoted with ^) https://spec.jpl.nasa.gov/. Column (3): observation epoch (YY/MM/DD). Columns (4): velocity range of the emission, which is determined by those velocity channels with emission above 3 \(\sigma_{\text{rms}}\). Columns (5)–(6): peak velocity and peak-flux density, which are directly measured for the brightest component of the emission at the given transition. Column (7): integrated flux density, which is the area enclosed by spectral profile within the velocity range in Column (4). Column (8): observational rms noise. Column (9): velocity resolution of each spectral line.

also discovered for the first time in interstellar space. Spectra of the eight new CH\(_3\)OH transitions are shown in Figure 1 and their line properties are summarized in Table 2. The parameters and profiles of the Gaussian fits for the new transitions detected with the zoom-band mode are given in Appendices A and B, respectively. The new transitions have \(E_{\text{nu}}/k\) ranging from 121.3 to 950.7 K and the majority are from the torsional ground state \(v_{i} = 0\), with two from the first torsionally excited state \(v_{i} = 1\). As seen in Figure 1, the flux density of these methanol transitions changed significantly within ~1 month, but the velocity extent was always contained within the range of \(-18.9\) to \(-14.3\) km s\(^{-1}\).

26.12 GHz (101–112 A\(^{-}\) \(v_{i} = 1\)): This transition was monitored over five epochs from March 17 to May 7. According to the Gaussian fit, the three velocity components of this emission are detected near \(-17.5, -16.4\), and \(-15.7\) km s\(^{-1}\). All three velocity components have shown significant variability in flux density during the monitoring (see Figure 4). The peak-flux density reached 1218 Jy on April 12 at \(-17.5\) km s\(^{-1}\), and on May 3 the velocity component at \(-15.8\) km s\(^{-1}\) reached 1265 Jy,
| Molecule | Transition | Rest Freq. (MHz) | Epoch | \(V_{\text{range}}\) (km s\(^{-1}\)) | \(V_{\text{peak}}\) (km s\(^{-1}\)) | \(S_{\text{peak}}\) (Jy) | \(S_{\text{lim}}\) (Jy km s\(^{-1}\)) | rms (Jy) |
|----------|------------|-----------------|-------|-------------------------------|-------------------|----------------|---------------------|--------|
| CH\(_3\)OH | 17\(_2\)–18\(_3\) E \(v_1 = 1\) | 6181.146\(^a\) | 2019/4/5 | \(-17.93\) to \(-14.85\) | \(-15.77\) | 986.09 | 541.52 (0.05) | 0.21 |
| CH\(_3\)OH | 5\(_1\)–6\(_0\) A\(^+\) \(v_1 = 0\) | 6668.5192 | 2019/3/17 | \(-19.20\) to \(-14.52\) | \(-17.19\) | 669.68 | 790.88 (0.02) | 0.06 |
| CH\(_3\)OH | 12\(_2\)–13\(_1\) A\(^-\) \(v_1 = 0\) | 7682.246\(^a\) | 2019/3/17 | \(-18.55\) to \(-14.69\) | \(-15.36\) | 670.71 | 695.21 (0.01) | 0.06 |
| CH\(_3\)OH | 12\(_2\)–13\(_1\) A\(^+\) \(v_1 = 0\) | 7830.848\(^a\) | 2019/3/17 | \(-18.53\) to \(-14.66\) | \(-15.33\) | 657.10 | 730.16 (0.01) | 0.06 |
| CH\(_3\)OH | 2\(_3\)–3\(_2\) E \(v_1 = 0\) | 12,178.597 | 2019/3/14 | \(-19.27\) to \(-14.36\) | \(-17.09\) | 1166.40 | 1298.80 (0.02) | 0.09 |
| CH\(_3\)OH | 16\(_5\)–17\(_4\) E \(v_1 = 0\) | 12,229.348 | 2019/3/14 | \(-17.98\) to \(-14.93\) | \(-15.39\) | 1358.60 | 623.21 (0.02) | 0.10 |

\(^a\) denotes observational uncertainties.
thereby also changing the velocity component showing the peak emission. It is worth noting that the emission of this line is a little brighter than the usually known brighter methanol maser transitions of 6.67 and 12.18 GHz (see Section 4) in this source, suggesting that the physical conditions during the accretion burst of this MYSO are special. This transition is an A\(^+\) counterpart of the 20.97 GHz 10\(_{1}^{-1}11_{2} A^{+} \, v_{1} = 1\) transition detected in Breen et al. (2019) according to the modeling predictions made in Section 4.

| Molecule | Transition | Rest Freq. (MHz) | Epoch | \(V_{\text{range}}\) (km s\(^{-1}\)) | \(V_{\text{peak}}\) (km s\(^{-1}\)) | \(S_{\text{peak}}\) (Jy) | \(S_{\text{int}}\) (Jy km s\(^{-1}\)) | rms (Jy) |
|----------|------------|-----------------|--------|-----------------|-----------------|-----------------|-----------------|----------|
| CH\(_{3}\)OH | \(2_{1}-3_{0} \, E \, v_{1} = 0\) | 19,967.3961 | 2019/3/17 | \(-18.02, -15.51\) | \(-16.68\) | 0.22 | 0.07 | 0.15 |
| CH\(_{3}\)OH | \(17_{c}-18_{b} \, E \, v_{1} = 0\) | 20,346.83 | 2019/4/5 | \(-17.64, -15.09\) | \(-15.43\) | 227.19 | 94.97 | 0.11 |
| CH\(_{3}\)OH | \(10_{1}-11_{2} A^{+} \, v_{1} = 1\) | 20,970.62 | 2019/3/17 | \(-18.80, -15.04\) | \(-17.41\) | 1537.00 | 1653.40 | 0.36 |
| CH\(_{3}\)OH | \(9_{c}-10_{1} A^{+} \, v_{1} = 0\) | 23,121.0242 | 2019/3/17 | \(-18.27, -14.85\) | \(-17.19\) | 74.44 | 90.17 | 0.11 |
| CH\(_{3}\)OH | \(4_{c}-3_{0} \, E \, v_{1} = 0\) | 36,169.29\(^{b}\) | 2019/4/1 | \(-20.97, -16.17\) | \(-18.22\) | 0.74 | 2.21(0.03) | 0.03 |
| CH\(_{3}\)OH | \(7_{c}-8_{-1} \, E \, v_{1} = 0\) | 37,703.696\(^{b}\) | 2019/4/1 | \(-19.06, -15.42\) | \(-17.60\) | 110.58 | 217.65 | 0.05 |
| CH\(_{3}\)OH | \(7_{c}-6_{1} A^{+} \, v_{1} = 0\) | 44,069.41\(^{c}\) | 2019/4/6 | \(-22.05, -18.31\) | \(-21.43\) | 0.80 | 1.59(0.07) | 0.04 |
| CH\(_{3}\)OH | \(2_{c}-3_{1} \, E \, v_{1} = 0\) | 44,955.80\(^{d}\) | 2019/4/6 | \(-17.96, -15.52\) | \(-15.43\) | 61.01 | 85.92 (0.11) | 0.07 |
| CH\(_{3}\)OH | \(9_{c}-10_{2} E \, v_{1} = 0\) | 45,843.519\(^{d}\) | 2019/4/6 | \(-17.82, -14.83\) | \(-17.22\) | 53.74 | 87.82 | 0.06 |
| H\(_{2}O\) | \(6_{1,6}-5_{2,3}\) | 22,235.1204 | 2019/3/17 | \(-19.52, -16.13\) | \(-17.36\) | 0.50 | 1.13(0.08) | 0.09 |

\(^{a}\) Breen et al. 2019; \(^{b}\) Xu & Lovas 1997; \(^{c}\) Muller et al. 2004; \(^{d}\) Breen et al. 2019.

Note. Column (1): Detected molecule. Columns (2)–(3): Transitions and the adopted rest frequency (including the CDMS catalog https://cdms.astro.uni-koeln.de/ and superscript references as follows: \(^{a}\)—Breen et al. 2019; \(^{b}\)—Xu & Lovas 1997; \(^{c}\)—Muller et al. 2004; \(^{d}\)—Breen et al. 2019). Column (4): Observation epoch (YY/MM/DD). Column (5): velocity range of the emission which is determined by those velocity channels with emission above 3 \(\sigma_{\text{min}}\). Columns (6)–(7): peak velocity and peak-flux density, which are directly measured for the brightest component of the emission at the given transition. Column (8): integrated flux density, which is the area enclosed by spectral profile within the velocity range in Column (4). Column (9): observational rms noise.
Cragg et al. (2005). The observations made on nearly same date around March 17−18 show that the spectral profile of the 26.12 GHz is similar, but with weaker emission compared to that of the 20.97 GHz presented in Volvach et al. (2020), in accordance with the model predictions of Cragg et al. (2005).

27.28 GHz (14−3−15−2 E): This transition was observed twice on April 1 with the wideband mode and on May 3 with the zoom-band mode. It has two strong velocity components around −17.1 and −15.2 km s$^{-1}$. In April, the peak-flux density at $\sim$−15 km s$^{-1}$ reached 212 Jy, stronger than that at $\sim$−17 km s$^{-1}$, whereas a month later this situation reversed with the $\sim$−17 km s$^{-1}$ component reaching 247 Jy, stronger than that at $\sim$−15 km s$^{-1}$. The line belongs to the same series as the previously detected line at 12.229 GHz (16−2−17−1 E) (MacLeod et al. 2019). Both the lines have similar spectra, thus suggesting that their excitation occurs under similar conditions.

28.97 GHz (8−2−9−1 A$^\circ$): This is the first detection of this transition in G358, observed twice on April 1 with the wideband mode and on May 3 with the zoom-band mode. The spectrum of this transition shows a complex profile with at least five velocity components detected with the zoom-band mode (see Appendices A and B). In order to determine if this source varied, we smoothed the zoom-mode data (0.015 km s$^{-1}$) to match the spectral resolution of the wideband data (0.95 km s$^{-1}$). At the same resolution, we found that the flux density of the $\sim$−16 km s$^{-1}$ component slightly decreased from 14.24 Jy to 10.68 Jy on April 1 and May 3, respectively. Notably, this transition has been detected in other sources. It was emitted in the quasi-thermal from the methanol emission center, about 10$^{0}$ south from the hot core region in Orion KL, and with a peak-flux density of about 1.1 Jy (Wilson et al. 1993). But toward W3(OH), the 28.97 GHz emission is masering and the peak-flux density reached 15 Jy (Wilson et al. 1993). Shuvo et al. (2021) detected 28.97 GHz emission toward NGC 7538 RS1, with a spectral profile similar to our G358 data but with a weaker emission of 0.26 Jy.

31.98 GHz (19−1−20−3 E): This transition was observed twice on April 1 with the wideband mode and on May 3 with the zoom-band mode. The wideband spectral profile of the 31.98 GHz transition is similar to that of the 28.97 GHz transition, showing a broad spectrum (see Figure 1). Such a broadband spectrum is likely to contain multiple overlapping components. The 31.98 GHz wideband spectrum consists of a peak at $\sim$−17 km s$^{-1}$, reaching 0.83 Jy on April 1. After a month, this line was not detectable with an rms noise of 0.13 Jy.

34.24 GHz (14−3−15−2 E): This transition was observed twice on April 1 with the wideband mode and on May 3 with the zoom-band mode. Maser emission in this line was predicted by Cragg et al. (2005). The spectrum of this transition is very similar to that of the 26.12 and 27.28 GHz transitions, which have three velocity components near −17.2, −16.0, and −15.8 km s$^{-1}$. In addition, the strongest feature of the 34.24 GHz line reached 201 Jy at −15.8 km s$^{-1}$ in April. One month later, the peak velocity component moved to −17.2 km s$^{-1}$ with a peak of 156 Jy.

41.11 GHz (9−4−10−1 E): This transition was observed twice on April 6 with the wideband mode and on May 2 with the zoom-band mode. It shows a complex line profile consisting of five narrow Gaussian components, similar to the 28.97 GHz transition in the component number (see Appendices A and B). On April 6 with the wideband mode, the peak-flux density reached 9.7 Jy at −15.9 km s$^{-1}$, then on May 2, the peak flux decreased to 6.3 Jy at −17.0 km s$^{-1}$ with the zoom-band mode. This is the line from the same series as the 229.589 GHz (15−2−16−1 E) line detected by Brogan et al. (2019). Comparisons of spectra of these lines is impossible because the 229.589 GHz line is weak and its spectrum is not shown. Anyhow, detection of the maser line from the same series can be considered as a support for the maser nature of the detected line.

46.56 GHz (20−7−21−6 A$^\circ$): This transition was observed twice on April 6 with the wideband mode and on May 2 with the zoom-band mode. The spectral profile of the wideband data shows a clear double-peaked structure (see Figure 1) with a peak-flux density of 2.6 Jy at −15.5 km s$^{-1}$. Zoom-band mode observations less than a month later with an rms noise of 0.09 Jy revealed no emission.
48.71 GHz \((21_{3}^{3}-22_{4} E \nu_1 = 1)\): This transition was observed twice on April 6 with the wideband mode and on May 2 with the zoom-band mode. It shows a special spectral profile because only one velocity component peaked at \(-15.1 \text{ km s}^{-1}\) is evident in its line profile. The peak-flux density reached 11.3 Jy and 1.7 Jy on April 6 and May 2, respectively. Therefore, the intensity of this transition declined sharply by a factor of about 7 within a month. It is the line from the same series as the two lines \((200.888 \text{ GHz } 18_{3}^{3}-19_{4} E \nu_1 = 1 \text{ and } 350.286 \text{ GHz } 15_{3}^{3}-16_{4} E \nu_1 = 1)\) detected by Brogan et al. \((2019)\). These two lines were also detected with peaks at around \(-15.1 \text{ km s}^{-1}\).

4. Previously Known Maser Transitions in G358

In this section, we report a series of previously known maser transitions including 15 methanol masers and 1 H2O maser detected in these observations toward G358. Figure 2 shows the spectra of previously known CH3OH and H2O maser transitions monitored over a period of 2 months associated with G358.93-0.03. Information on the molecule, transition, and frequency are given at the upper left of each panel and the dates are given at the upper right, similar to Figure 1. The spectra observed on different dates are shown in different colors.

The spectra observed varied significantly with their peak variations in the range of 30% to 100% during the monitoring. Their velocity ranges, however, remained relatively stable; the class II methanol maser transitions showed emission between \(-19.2 \text{ and } -14.5 \text{ km s}^{-1}\), the class I methanol maser transitions (including 36.17 and 44.07 GHz transitions) between \(-22.1 \text{ and } -16.2 \text{ km s}^{-1}\), and the H2O maser between \(-21.9 \text{ and } -12.5 \text{ km s}^{-1}\) in April. Additionally, it is easy to identify three main class II methanol maser features, common to most of the transitions, near \(-17.4, -16.2, \text{ and } -15.5 \text{ km s}^{-1}\). However, the H2O maser emission only has two main components at \(-19.2 \text{ and } -17.3 \text{ km s}^{-1}\) from March to April. While in May, three new components at \(-19.9, -15.2, \text{ and } -14.5 \text{ km s}^{-1}\) emerged. In terms of the number of the line velocity components, there are clear changes at 7.68, 7.83, and 23.12 GHz for methanol, and 22.24 GHz water transitions during the monitoring. In addition, three categories can be distinguished according to the changes in fluxes: (1) gradually decreasing; (2) decreasing first, then increasing followed by decreasing; (3) gradually increasing. Most of the class II methanol maser emissions showed their brightest intensity at the beginning of the observations in March and then gradually decreased (i.e., case 1). But there are some others such as at 19.97, 20.35, 20.97, and 23.12 GHz where their flux densities decreased first, then increased, and then decreased during the monitoring period (i.e., case 2), peaking around April 12 (see Section 5.2.1). In addition, for class I methanol maser transitions at 36.17 and 44.07 GHz, and...
a H$_2$O maser transition at 22.24 GHz, their flux densities gradually increase from April to May (i.e., case 3).

There were three first torsionally excited methanol maser transitions at 6.18, 20.97, and 44.96 GHz that were consistently detected from March to May. The 6.18 and 20.97 GHz emissions had higher peak intensities than a month ago (Brogan et al. 2019; Volvach et al. 2020). This also suggests that G358 has an specific pumping environment during the outburst.

### 4.1. Remarks on Individual Transitions

6.18 GHz: This transition has been monitored with five epochs from April 5 to April 11. This maser transition has four velocity components with the strongest feature at $-15.8 \text{ km s}^{-1}$ reaching 986 Jy on April 5. Breen et al. (2019) detected this transition on 2019 March 6 with three main velocity components at around $-16$, $-17$, and $-18 \text{ km s}^{-1}$, with the peak of 290 Jy at $-16.2 \text{ km s}^{-1}$. In less than 1 month, the $-17$ and $-18 \text{ km s}^{-1}$ components significantly weakened, the peak component moved from the $-16.2$ to the $-15.8 \text{ km s}^{-1}$, and the flux density increased from $-290$ to $-1000$ Jy.

6.67 GHz: This transition has been monitored with eight epochs from March 17 to April 11. It has four velocity components at $-15.5$, $-16.2$, $-17.2$, and $-18.4 \text{ km s}^{-1}$. The brightest feature peaked at $-17.2 \text{ km s}^{-1}$ with a flux density of 669 Jy on March 17, but was overtaken by the $-15.5 \text{ km s}^{-1}$ feature with a peak-flux density of 491 Jy on April 10. During this month, the flux density of $-17.2 \text{ km s}^{-1}$ decreased while that of $-15.5 \text{ km s}^{-1}$ increased slightly. This transition was also detected on 2019 March 6 by Breen et al. (2019) with a peak-flux density of 981 Jy at $-17.2 \text{ km s}^{-1}$. On 2019 March 11 MacLeod et al. (2019) observed this transition with the peak-flux density of 1156 Jy at $-17.4 \text{ km s}^{-1}$. We can therefore assume that the 6.67 GHz methanol maser emission should have reached its maximum on around March 11 and then gradually declined.

7.68 and 7.83 GHz: These two transitions have been monitored with eight epochs from March 17 to April 11. They are similar in terms of spectral profile, peak velocity, and peak-flux density. These transitions both had three spectral peaks in March, but in April the $-16 \text{ km s}^{-1}$ component disappeared. The 7.68 and 7.83 GHz transitions both reached their maximum flux density (679 Jy and 747 Jy, respectively) on April 1 at $-15.4 \text{ km s}^{-1}$. Notably, they are members of the $J_0 - (J + 1)_{h-1}$ A+/− transition group. The 7.68 and 8.83 GHz transitions were once predicted to exhibit maser emission under the same conditions (Cragg et al. 2005), suggesting that they were likely to be excited under the same physical conditions or cospatially. Based on the data from Breen et al. (2019), it can be seen that the spectra of the 7.68 and 7.83 GHz lines on 2019 March 6 are not the same; the peak component of the 7.68 GHz line is at $-15.9 \text{ km s}^{-1}$ while the 7.83 GHz line is at $-16.6 \text{ km s}^{-1}$, and they both essentially achieved a similar peak-flux density of $\sim 570 \text{ Jy}$. Whereas our data on March 17 show both transitions peaked at $-15.3 \text{ km s}^{-1}$ with a similar peak-flux density of $\sim 660 \text{ Jy}$.

12.18 GHz: This transition has been intensively monitored with 17 epochs from March 14 to May 20. Its spectrum is very similar to that of the 6.67 GHz and it also has four velocity components. The maximum emission reached was 1166 Jy on March 14 at a velocity of $-17.1 \text{ km s}^{-1}$. On March 12, MacLeod et al. (2019) reported this transition with a peak-flux density of 1270 Jy at the same peak velocity. We can therefore assume that the 12.18 GHz methanol maser emission reached its maximum around March 12 or before and then gradually decreased.

12.23 GHz: This transition has been intensively monitored with 17 epochs from March 14 to May 20. This transition has only two spectral components, with the maximum emission detected on March 14 with a peak-flux density of 1359 Jy at $-15.4 \text{ km s}^{-1}$. MacLeod et al. (2019) detected this transition on March 15 with a peak of 1344 Jy at $-15.5 \text{ km s}^{-1}$. It is consistent with our detection within the uncertainty of the flux scale. But 2 months later, on May 20, this maser disappeared almost completely in the flux density.

19.97 GHz: This transition has been monitored with seven epochs from March 17 to May 7. Due to its weak emission (with a peak from 0.22 to 3.4 Jy), we can only see two components in its line profile from March to May. However, Volvach et al. (2020) detected strong emission at this transition with a peak of 104 Jy at $-15.8 \text{ km s}^{-1}$ on February 8. But it fell below the detection limit of 0.9 Jy (3σ) on 2019 May 3 in their observations. Breen et al. (2019) detected this velocity component on 2019 March 5 with a peak-flux density of only 0.3 Jy. This maser was detected by TMRT on March 17 with a weaker emission of 0.22 Jy. On April 12, its peak-flux density increased again to 3.4 Jy and then on May 7 decreased to 1.24 Jy. Overall, this transition reached its strongest in February and then rapidly weakened, and presented a new flare with a small intensity increment on April 12 (see Section 5.2.1).

20.35 GHz: This transition has been monitored with six epochs from April 5 to May 7. Both the 20.35 GHz and 12.23 GHz hold the same spectra profile with only two components around $-17.3$ and $-15.4 \text{ km s}^{-1}$. Combining MacLeod et al. (2019) and our data, focusing on the $-15.4 \text{ km s}^{-1}$ velocity component, we can see its emission on March 21 at 549 Jy, on April 5 at 227 Jy, on April 12 at 597 Jy, and on May 7 at 18 Jy. Therefore, we have evidence of at least two flares of this line in the period 2019 March–April.

20.97 GHz: This transition has been monitored with seven epochs from March 17 to May 7. This transition has three velocity components and the strongest emission of 2929 Jy at $-17.5 \text{ km s}^{-1}$ detected on April 12. It is 2 times stronger than the maser emission at 12.18 GHz and 6.67 GHz toward this source. For the $-15.6 \text{ km s}^{-1}$ velocity component, the peak-flux density was $\sim 1400 \text{ Jy}$ on February 8 (Volvach et al. 2020), 978 Jy on March 5 (Breen et al. 2019), 2600 Jy on March 15 (Volvach et al. 2020), 676 Jy on April 5, 2450 Jy on April 12, and 907 Jy on May 7. This means that this maser transition underwent variability at least 3 times which occurred in February, March, and April.

23.12 GHz: This transition has been monitored with seven epochs from March 17 to May 7. This transition seems to show a more complex spectral profile than the other transitions, with extremely rich Gaussian velocity components that were detected in all observing epochs from March to May. Breen et al. (2019) and MacLeod et al. (2019) also detected this transition with complex spectral features. On May 5, the peak-flux density of the $-17.3 \text{ km s}^{-1}$ component was 36.1 Jy (Breen et al. 2019), and then on March 14 this component increased to 105 Jy (MacLeod et al. 2019). In our observations, the peak-flux density decreased to 18.2 Jy on April 8, but then there is a small increment on April 12 that reached 59 Jy. By
May, the components with a velocity larger than \(-16.5 \, \text{km s}^{-1}\) had completely disappeared.

36.17 GHz and 44.07 GHz: These two class I methanol maser transitions have been only monitored at two epochs, with the wideband mode in April and the zoom-band mode in May. The 36.17 GHz emission has three components close together covering a velocity range of \(-21.0\) to \(-16.2 \, \text{km s}^{-1}\), which is wider than the class II transitions. On March 7, the peak-flux density of the 36.17 GHz transition is 0.5 Jy at \(-19.5 \, \text{km s}^{-1}\) as detected by Breen et al. (2019) and it gets to 0.74 Jy at \(-18.2 \, \text{km s}^{-1}\) on May 2 as detected in our observations. Oddly enough, this transition was not detected on April 1 with the wideband mode, suggesting its flux was less than the threshold of 0.36 Jy (3\(\sigma_{\text{rms}}\)). When the zoom-band spectrum on May 2 was smoothed to the same velocity resolution as the wideband mode, the peak-flux density was \(-0.60\) Jy, which is still larger than the above threshold taken on April 1. It is suggested that after excluding the effect using different observing spectral modes, the flux of this transition really has little increment from April to May. The 44.07 GHz transition also has three components sharing a very similar velocity range to the 36.17 GHz transition. The \(-21.1 \, \text{km s}^{-1}\) component was detected with a peak of 4.5 Jy on March 5 by Breen et al. (2019), and 2.7 Jy on May 2 from our observations. Notably, the spectral and peak velocity, as well as the velocity range of these two class I methanol maser transitions, are different from that of the class II transitions detected toward this source. Both observational surveys and theoretical considerations show that the maser emission in 36.17 GHz and 44.07 GHz transitions comes from generally the same regions but their spectra do not coincide in detail, due to the different sensitivity to the pumping conditions (Sobolev et al. 2007; Voronkov et al. 2014; Leurini et al. 2016; Sobolev & Parfenov 2018). The locations of these two transitions (Breen et al. 2019) are close to the position of the water maser cluster components II \(-3\)–\(-4\) which occurred in 2019 May–June (Bayandina & Burns 2022b). Velocity of the 44.07 GHz line emission is close to the velocity of the water masers detected in May, suggesting that these masers might also have close locations. Occurrence of new water maser clusters is likely associated with the accretion burst in G358 (Bayandina & Burns 2022b). Both water masers and class I methanol masers are pumped by collisions, so the variability of the 36.17 GHz and 44.07 GHz is also likely associated with the accretion burst phenomenon. In particular, it can explain the occurrence of the 36.17 GHz maser only on May 2.

37.70 GHz: This methanol transition has been monitored with two epochs with the wideband mode on April 1 and with the zoom-band mode on May 2. It has two velocity components at \(-16.2\) and \(-17.6 \, \text{km s}^{-1}\). Its peak-flux density was 250 Jy detected on March 7 at \(-17.3 \, \text{km s}^{-1}\) (Breen et al. 2019), 111 Jy on April 1 at \(-17.6 \, \text{km s}^{-1}\), and 64 Jy on May 2 at \(-16.2 \, \text{km s}^{-1}\) detected in our observations. It seems that the emission of this transition gradually decreases from March to May.

44.96 GHz: This transition has been monitored with two epochs on April 6 and May 2 with the wideband mode. This transition appears to have a distinct double-peaked spectral structure with two velocity components peaked at \(-15.4\) and \(-17.1 \, \text{km s}^{-1}\) during the period from April to May. Breen et al. (2019) also detected this transition with a clear double-peaked structure on March 5, with the peak-flux density of 508 Jy at \(-15.4 \, \text{km s}^{-1}\). The emission at this same velocity component gradually decreased to 61 Jy on April 6 and then to \(-15 \, \text{Jy}\) on May 2.

45.84 GHz: This transition has been monitored with two epochs with the wideband mode on April 6 and with the zoom-band mode on May 2. This transition has two velocity components peaked at \(-16.2\) and \(-17.3 \, \text{km s}^{-1}\) seen from the zoom-band mode spectrum. On March 5, the peak-flux density of this transition reached 414 Jy at \(-15.4 \, \text{km s}^{-1}\) (Breen et al. 2019). On April 6, the peak-flux density reached 54 Jy at \(-17.2 \, \text{km s}^{-1}\) under a velocity resolution of 0.6 km s\(^{-1}\) from our observation. On May 2, at the same velocity component, the peak-flux density reached 86 Jy under a velocity resolution of 0.01 km s\(^{-1}\). When the zoom-band spectrum on May 2 was smoothed to a velocity resolution of 0.6 km s\(^{-1}\) similar to the wideband spectrum, the peak-flux density is 46 Jy. Therefore, the peak flux of this emission gradually decreased after March 5.

22.24 GHz: This H\(_2\)O maser transition has been monitored with seven epochs from March 17 to May 7. We can see that the H\(_2\)O maser emission has two components peaked at \(-17.3\) and \(-19.2 \, \text{km s}^{-1}\) with a velocity resolution of 0.15 km s\(^{-1}\) in April. The intensity of the H\(_2\)O maser emission is very weak (with a peak of 0.5 Jy) in March, until April 12, when it has a significant increment with a peak of 4.3 Jy, and then reaches 8.6 Jy on April 15 at \(-17.3 \, \text{km s}^{-1}\). On April 20, at the same velocity component, the peak-flux density reaches 24 Jy (MacLeod et al. 2019). Furthermore, on May 7, some new maser features were detected in the velocity range of \(-22\) to \(-17 \, \text{km s}^{-1}\) (with peak at \(-20 \, \text{km s}^{-1}\)) and \(-16\) to \(-13 \, \text{km s}^{-1}\) (with a peak at \(-14.5 \, \text{km s}^{-1}\)), which are close to that detected with the Very Large Array (VLA) in June by Bayandina & Burns (2022b) with the exception of a new maser component peaked at \(-21.5 \, \text{km s}^{-1}\) that appeared in June from the VLA detection. These new water components have the similar velocity ranges to those detected in both the 36.17 and 44.07 GHz methanol transitions, supporting the idea that they have the same pumping origination and are associated with accretion burst actions on the shocked regions where they are excited (see above). Overall, the water maser emission is barely visible in March until the flux density suddenly increases on April 12 and reaches a much higher intensity on April 20, with new velocity components detected in May–June, which is quite different from the class II methanol maser transitions. This means that the water maser emission burst occurred later than the methanol masers, likely because the water maser is distributed in regions far away from the burst source G358-MM1 compared to the methanol masers. This statement is supported by the VLA images of methanol and water masers (Chen et al. 2020a; Bayandina & Burns 2022b), thus there is an expected time delay between the heat-wave propagation to the methanol and to water maser regions.

5. Discussions

5.1. The Maser Characteristics of the Eight New Methanol Lines

G358.93-0.03 harbors two molecular hot cores, MM1 and MM3, and MM1 shows significantly richer molecular spectra and the brightest millimeter continuum emission (Brogan et al. 2019). So far, accretion bursts and all the discovered masers are detected toward the peak of MM1, implying this region is suitable for exciting the maser emission (Breen et al. 2019;
Brogan et al. 2019; Chen et al. 2020b). The majority of these new CH$_3$OH transitions show a velocity range from $-18.9$ to $-14.3$ km s$^{-1}$, which is similar to the 6.67 GHz spectrum in Figure 2. At the same time, some transitions (e.g., 26.12, 27.28, 34.24, 46.56, and 48.71 GHz) show similar velocity components to the 6.7 GHz transition at one of $-15.5$, $-16.0$, and $-17.3$ km s$^{-1}$ at least. It suggests that the region where the eight new lines possibly originate from the same as or close to the 6.67 GHz transition. Using a Gaussian fit, we obtain the line width of the strongest feature in each of the new transitions ranging from 0.27 to 0.55 km s$^{-1}$, except for the transitions at 31.98 and 46.56 GHz detected only with the wideband mode (see Table A1). For the two brightest spectral peaks at $-17.4$ and $-15.6$ km s$^{-1}$, the average line widths of the new transitions detected in the zoom band are 0.33 and 0.40 km s$^{-1}$, respectively. The line widths of the two main spectral features of the 6.67 GHz transition are 0.44 and 0.48 km s$^{-1}$, respectively. Therefore for the two main features, the average line widths of these new transitions are even narrower than the 6.67 GHz transition. In addition, like the other maser lines, the new transitions have complex spectral compositions and rapid variations.

The maser emission in all detected transitions resides in a region of $0''2$ around the bursting source (Bayandina et al. 2022a). Assuming that the new methanol emission originates in this region, we infer a lower limit of brightness temperature in the range $3 \times 10^4$ to $8 \times 10^3$ K for these new transitions through the equation: $T_B = S_\nu \lambda^2/2k\Omega$, where $S_\nu$ is flux density, $\lambda$ is wavelength, $k$ is the Boltzmann constant, and $\Omega$ is solid angle. They are much higher than the maximum kinetic temperatures (100–300 K) of the typical thermal emission associated with hot molecular cores in MYSOs. In addition, the typical thermal line width expected under such a high-temperature condition ($3 \times 10^4$ K) is $\sim 6$ km s$^{-1}$, through the relation: $\Delta\nu_{\text{FWHM}} = 0.2(T/\text{A})^{1/2}$ km s$^{-1}$, where $T$ is the temperature in kelvin and $\text{A}$ is the atomic mass number of the methanol molecule. It is much bigger than the average line width of our detections. These all suggest that the new emissions are unlikely to be thermal in nature. Beyond this, we performed the rotation diagram analysis to obtain additional evidence that the excitation of these transitions shows significant deviation from the local thermodynamic equilibrium. The rotation diagram of the newly detected CH$_3$OH transitions is shown in Figure 3 and the detailed method is described in Blake et al. (1987) and Chen et al. (2013). In general, the eight new transitions do not distinctly show a linear correlation between $\ln(3 \text{~kW}/(8\pi^3 c S_\nu \lambda^2))$ and $E_\nu/k$ expected from thermal conditions in the rotation diagram. In particular, when $E_\nu/k < 500$ K, the five transitions (observed at the same epoch on 2019 May 3) even show an inverse trend in the rotation diagram, inconsistent with thermal conditions (van Dishoeck et al. 1995; Ginsburg et al. 2017; Chen et al. 2019). Notably, the three transitions in the lower-right corner observed in April do not show an opposite trend to the above five transitions, probably because of their variabilities. Combining all these properties discussed above, we conclude that all the detected eight new methanol transitions from G358 deviate from the thermal condition.

There are two methanol maser transitions at 26.12 and 48.71 GHz from the first torsionally excited state ($v_t = 1$) detected in our observations. They were not included in the published lists of class II methanol maser candidates predicted from theoretical calculations (Cragg et al. 2005). The detection of such two torsionally excited transitions with bright intensities suggests that we were observing a special pumping regime for class II methanol masers and therefore the current observations offer substantial new information for methanol maser pumping models.

5.2. Maser Variability

Dynamic spectra of the 11 CH$_3$OH maser transitions and 1 H$_2$O maser transition with more than 5 epoch observations over 2 months from 2019 March to May associated with G358 are presented in Figure 4. It is clearly seen that these masers show temporal variations with different velocity components (see panels (a) and (b) of each transition in Figure 4).

5.2.1. The New Flare Event of the 19.97, 20.35, 20.97, 23.12, and 26.12 GHz Maser Transitions on April 12

From Figure 4, we can see that during the monitoring from 2019 March to May, the flux density shows a declining trend in general for most class II CH$_3$OH transitions with exceptions at the 19.97, 20.35, 20.97, 23.12, and 26.12 GHz transitions. These five transitions show a sharp increment in their flux densities in the April 12 observations. After this flare, the emission continues to gradually decay again. From the variability shown in Figure 4, we can derive that this new flare can be considered to start around April 8. In just 4 days, the maser emissions have increased by a factor of 5, 3.6, 3.25, 3.26, and 6.22 for the above five transitions, respectively.

To further confirm whether this new short-period flare event that occurred in these five maser transitions is real or not, we compared data observed with other telescopes at dates close in time to check the reliability of our measurements. No previous observation about the 19.97 GHz transition was available in April. For the 20.35 GHz transition at the velocity components of $-17$ and $-15$ km s$^{-1}$, the flux densities reached 92 and 244 Jy on April 15 in our observations, and then reached around 100 and 210 Jy on April 20 by MacLeod et al. (2019). The two observations are generally consistent with each other within the uncertainty of the flux scale. For the $-15$ km s$^{-1}$ velocity component of the 20.97 GHz transition, in mid-April, its peak-flux density reached $\sim 2000$ Jy as detected by the HartRAO and Simeiz telescopes (Volvach et al. 2020), which is consistent with our detections with the peak-flux density of 2450 Jy on April 12. For the 23.12 GHz transition at the

![Figure 3. Rotation diagram for the eight new detected methanol transitions. Different colors represent different transitions. The frequencies and dates (for example, 503 represents 2019 May 3) of the spectral lines are marked on the upper right. The five points in the upper-left corner were observed in May and the other three points in the lower-right corner were observed in April.](image-url)
velocity components of $-17$ and $-16$ km s$^{-1}$, our observations detected them with peak-flux densities of 30 and 60 Jy, respectively, on April 15, and they reached around 35 and 60 Jy on April 18 as detected by MacLeod et al. (2019). Therefore, these two close-date observations also show the similarity in the flux density within the uncertainty of the flux scale at the 23.12 GHz transition. By comparing the peak-flux densities for the above three transitions detected in close-date observations using different telescopes, their agreement supports the increment of the 19.97, 20.35, 20.97, 23.12, and 26.12 GHz maser transitions on April 12 being reliable.

Apart from the new line at 26.12 GHz, we have collected the peak-flux densities for the remaining four lines during the flare preceding the one on April 12. For the 19.97 GHz transition at $-15$ km s$^{-1}$, the peak-flux density was 104 Jy detected on February 8 (Volvach et al. 2020) and 3.4 Jy on April 12 in our observations. For the 20.35 GHz transition at $-15$ km s$^{-1}$, the peak-flux density was 549 Jy detected on March 21 (MacLeod et al. 2019) and 597 Jy on April 12 in our observations. For the 20.97 GHz transition at $-15$ km s$^{-1}$, the peak-flux density was 105 Jy on March 14 (MacLeod et al. 2019) and 40 Jy on April 12 in our observations. It can be found that the intensities of the two flares are essentially comparable for the two transitions at 20.35 and 20.97 GHz, while for the other two transitions, the intensity of the second flare is much smaller than the previous one.

A direct question related to the two maser flares concerns whether these flares are associated with two different accretion burst events, or are they the result of the influence of the same accretion burst in different maser locations? As suggested by Volvach et al. (2020), due to the changes in line width of the 20.97 GHz transition experienced at different flares, it is possible that the same accretion burst leads to the maser being excited in different regions along the path of the heat-wave passage. If the two flares of masers are the result of two different accretion bursts acting on the same maser locations, then it suggests that the maser

Figure 4. The dynamic spectrum, line width, and derived gas temperature of the CH$_3$OH and H$_2$O maser transitions were monitored over five epochs with the TMRT. Panels (a) and (b) of each transition are the peak-flux densities of the local maximum emission components of each maser line varied with observing time. The narrow white lines represent the monitoring observation being interrupted in the dynamic spectrum. Panel (c) of each transition shows the variations of the line widths (obtained from Gaussian fitting for the $-15$ and $-17$ km s$^{-1}$ velocity components) and gas temperature (calculated from the saturated masers) with observing time, respectively. The solid and dashed lines represent the line width and the gas temperature. Panel (d) presents variations of line widths with the logarithm of flux density.
spatial locations would not vary with different flares. However, the current interferometric observations have revealed that the spatial distributions of multiple methanol maser transitions are actually changed at different burst phases (Burns et al. 2020; Bayandina et al. 2022a). Therefore, we argue that the new flare detected in April in our monitoring is mainly contributed to by the same burst acting on different maser clouds.

5.2.2. A Cooling Process Possibly Associated with the Propagation of a Heat Wave

The variations of the line widths with observing time and line widths with the logarithm of flux density are shown in the Figures 4(c) and (d), respectively, for each transition. Two transitions are given as demonstrations and the complete figure set is available online. These line widths are obtained from the Figures 4. A Cooling Process Possibly Associated with the Propagation of spatial locations would not vary with different

5.2.3. 6.67 and 12.18 GHz: Transitions May Be Tracing Scarcely Different Physical Environments

The detected peaks of the 6.67 GHz maser emission were 981 (Breen et al. 2019), 1156 (MacLeod et al. 2019), and 670 Jy (this work) at the −17 km s⁻¹ component on March 5, 11, and 17, respectively. Meanwhile, the 12.18 GHz maser emission was detected at the same velocity with peaks of 1270 (MacLeod et al. 2019), 1166 (this work), and 991 (this work) on 2019 March 12, 14, and 21, respectively. Based on the fact that the general distributions of maser spots in both the 6.67 and 12.18 GHz transitions are similar (though detailed distributions show differences in G358; see Bayandina et al. 2022a), we can derive that both maser transitions might reach their brightest emission at the nearly same time around March 10, although no monitoring data were given for the 12.18 GHz transition before March 12.

It is also noted that the 12.18 GHz maser emission is generally stronger than the 6.67 GHz on the same observing dates (see Figure 4). Usually, the 6.67 GHz maser emission is stronger than the 12.18 GHz in almost all of the sources with both maser transition detections (Breen et al. 2012; Song et al. 2022). But our observations present a reversal detection in G358, suggesting that the physical conditions at the time of the accretion burst event in G358 might significantly change with respect to those expected in MSFRs without the accretion bursts.

6. Summary

Monitoring for multiple maser (including methanol and water) transitions was made with the TMRT during the period from 2019 March to May toward an accretion burst MYSO G358.93-0.03. This period mainly corresponds to the decay phase of this accretion burst. The main results and scientific insights obtained from this monitoring are summarized as follows:

1. The special conditions associated with the accretion burst are currently known to be able to excite new methanol maser transitions. Eight new methanol maser lines at 26.12, 27.28, 28.97, 31.98, 34.24, 41.11, 46.56, and 48.71 GHz were first detected during the accretion burst of MYSO G358.93-0.03. This large number of new methanol maser transitions are not reported for the other two accretion bursts in S255IR and NGC633I. So, the G358 burst has a kind of special condition. Indeed, it has a much shorter duration, suggesting that the accreted mass is smaller than in the other detected events. Sophisticated estimates in Stecklum et al. (2021) show that the accretion burst event was produced by accreting a clump with the planetary mass. In this case, the star does not experience substantial bloating and its emission during the burst can be considerably harder. This will result in the detection of unknown highly excited maser transitions.

2. Nearly all the maser lines have obvious and dramatic changes within a short period (~order of a month). Some of the maser transitions showed repeated flares in 2019 April. This may be related to the passage of the heat wave induced by the same accretion burst event acting on different maser positions.

3. During the monitoring, the gas temperatures of clouds under the hypothesis of saturated masers generally showed a significant decay. This indirectly proves that the maser flares are not due to a kinetic process in such a short period, but to the propagation of thermal radiation from the MYSO’S luminosity outburst, with a cooling process detected in our monitoring.

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Appendix A

A portion of the Gaussian fit parameters for all the detected methanol and water maser transitions are provided in Table A1. This table is available in its entirety in machine-readable form.
### Table A1
Gaussian Fit Parameters of All Transitions

| Rest Freq. (GHz) | Epoch (2019) | Velocity Components | Gaussian Fit Parameters |
|------------------|--------------|---------------------|------------------------|
|                  | (1)          | (2)                 | xc (km s\(^{-1}\)) (err) | A (Jy km s\(^{-1}\)) (err) | w (km s\(^{-1}\)) (err) | yc (Jy) (err) |
| 6.18             | 4/5          | peak1               | -17.66 (0.01)           | 42.79 (3.51)               | 0.21 (0.02)               | 193.42 (21.75) |
|                  |              | peak2               | -17.17 (0.08)           | 16.55 (4.93)               | 0.55 (0.20)               | 28.63 (13.31)  |
|                  |              | peak3               | -15.78 (0.01)           | 366.85 (3.33)              | 0.35 (0.01)               | 984.86 (13.6)  |
|                  |              | peak4               | -15.16 (0.01)           | 111.80 (2.91)              | 0.27 (0.01)               | 389.21 (15.43) |
| 4/6              |              | peak1               | -17.62 (0.01)           | 32.55 (2.10)               | 0.22 (0.02)               | 139.75 (13.67) |
|                  |              | peak2               | -17.05 (0.04)           | 8.97 (2.47)                | 0.30 (0.09)               | 28.47 (11.74)  |
|                  |              | peak3               | -15.75 (0.01)           | 285.00 (2.68)              | 0.35 (0.01)               | 765.35 (10.93) |
|                  |              | peak4               | -15.10 (0.01)           | 82.00 (2.29)               | 0.26 (0.01)               | 296.66 (12.6)  |
| 4/9              |              | peak1               | -17.69 (0.01)           | 25.14 (1.21)               | 0.23 (0.01)               | 102.37 (7.5)   |
|                  |              | peak2               | -17.06 (0.02)           | 8.09 (1.37)                | 0.29 (0.06)               | 26.40 (6.72)   |
|                  |              | peak3               | -15.80 (0.01)           | 250.01 (1.49)              | 0.34 (0.01)               | 690.94 (6.25)  |
|                  |              | peak4               | -15.19 (0.01)           | 70.79 (1.25)               | 0.24 (0.01)               | 273.47 (7.35)  |
| 4/10             |              | peak1               | -17.69 (0.01)           | 25.41 (1.27)               | 0.23 (0.01)               | 102.22 (7.79)  |
|                  |              | peak2               | -17.06 (0.03)           | 8.64 (1.48)                | 0.31 (0.06)               | 26.52 (6.75)   |
|                  |              | peak3               | -15.81 (0.01)           | 250.01 (1.55)              | 0.34 (0.01)               | 690.41 (6.5)   |
|                  |              | peak4               | -15.19 (0.01)           | 72.07 (1.32)               | 0.25 (0.01)               | 270.26 (7.55)  |
| 4/11             |              | peak1               | -17.69 (0.01)           | 23.20 (1.05)               | 0.24 (0.01)               | 93.05 (6.37)   |
|                  |              | peak2               | -17.03 (0.01)           | 7.66 (1.02)                | 0.22 (0.03)               | 32.31 (6.52)   |
|                  |              | peak3               | -15.81 (0.01)           | 220.01 (1.23)              | 0.32 (0.01)               | 646.11 (5.49)  |
|                  |              | peak4               | -15.19 (0.01)           | 67.88 (1.06)               | 0.24 (0.01)               | 266.28 (6.32)  |

**Note.** Column (1): adopted rest frequency of maser transitions. Column (2): observation epoch in 2019 (MM/DD). Column (3): different velocity components fitted by a Gaussian. Columns (4)–(7): all parameters of the Gaussian fit containing the center velocity (xc), integrated flux density (A), line width (w), and peak-flux density (yc) with their uncertainties.

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

### Appendix B

Gaussian fits for all spectral profiles at the methanol and water transitions taken with the zoom bands are shown in Figure 5 and its associated online-only figure set. The fit profiles of every distinguished velocity component and cumulative fit profile are given at the upper left of each panel with different colors.

![Figure 5. The four component fit of the methanol line at 6.181 GHz from 2019 April 5.](https://example.com/image.png)

(The complete figure set (111 images) is available.)

### ORCID iDs

- Xi Chen [https://orcid.org/0000-0002-5435-925X](https://orcid.org/0000-0002-5435-925X)
- Shi-Min Song [https://orcid.org/0000-0003-3640-3875](https://orcid.org/0000-0003-3640-3875)
- Zhi-Qiang Shen [https://orcid.org/0000-0003-3540-8746](https://orcid.org/0000-0003-3540-8746)

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Erratum: “New Methanol Maser Transitions and Maser Variability Identified from an Accretion Burst Source G358.93-0.03” (2022, ApJS, 263, 9)

Dan Miao1, Xi Chen1,2,3, Shi-Min Song2,4, Andrej M. Sobolev5, Shari L. Breen6, Gordon C. MacLeod7,8, Bin Li2, Sergey Parfenov5, Anastasia Bisyarina5, and Zhi-Qiang Shen2

1 Center for Astrophysics, Guangzhou University, Guangzhou 510006, People’s Republic of China; chenxi@gzhu.edu.cn
2 Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, People’s Republic of China
3 Peng Cheng Lab, Shenzhen, 518066, People’s Republic of China
4 University of Chinese Academy of Sciences, 19A Yuquanlu, Beijing 100049, People’s Republic of China
5 Ural Federal University, 19 Mira Street, 620022 Ekaterinburg, Russia
6 SKA Observatory, Jodrell Bank, Lower Withington, Macclesfield, SK11 9FT, UK
7 The University of Western Ontario, 1151 Richmond Street, London, ON N6A 3K7, Canada
8 Hartebeeshock Radio Astronomy Observatory, P.O. Box 443, Krugersdorp 1741, South Africa

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In the published article, some typing mistakes are present. We wish to correct them as follows:

1. PDF page 2, Section 2 (Observations), line 3: correct “29°51′45.693” to “−29°51′45.693”.
2. PDF page 7, Figure 2, 44955.807 MHz panel: correct “20 − 31” to “20 − 31”.
3. PDF page 8, left column, line 7: correct “(Brogan et al. 2019);” to “(Breen et al. 2019);”.
4. PDF page 8, right column, in the third paragraph “19.97 GHz”, line 7: correct “0.9 Jy (3σ)” to “5 Jy”.
5. PDF page 9, there are four errors of one reference “Bayandina & Burns 2022b” throughout the published article: correct all “Bayandina & Burns 2022b” to “Bayandina et al. 2022b”.
6. PDF page 12, left column, Section 5.2.3 (6.67 and 12.18 GHz Transitions May Be Tracing Scarcely Different Physical Environments), line 3: correct “March 5” to “March 6”.

These corrections do not have any effect on our final results. We thank O. S. Bayandina for bringing up the referencing error. We sincerely regret these errors.

ORCID iDs

Xi Chen https://orcid.org/0000-0002-5435-925X

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