

Discovery of non-metastable ammonia masers in Sagittarius B2 (postprint)

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Abstract

We report the discovery of widespread maser emission in non-metastable inversion transitions of NH₃ toward various parts of the Sagittarius B2 molecular cloud/star forming region complex: We detect masers in the J,K= (6,3), (7,4), (8,5), (9,6), and (10,7) transitions toward Sgr B2(M) and Sgr B2(N), an NH₃ (6,3) maser in Sgr B2(NS), and NH₃ (7,4), (9,6), and (10,7) masers in Sgr B2(S). With the high angular resolution data of the Karl G. Jansky Very Large Array (JVLA) in A-configuration we identify 18 maser spots. Nine maser spots arise from Sgr B2(N), one from Sgr B2(NS), five from Sgr B2(M), and three in Sgr B2(S). Compared to our Effelsberg single dish data, the JVLA data indicate no missing flux. The detected maser spots are not resolved by our JVLA observations. Lower limits to the brightness temperature are >3000-K and reach up to several 10⁵-K, manifesting the lines' maser nature. In view of the masers' velocity differences with respect to adjacent hot molecular cores and/or UCH{II} regions, it is argued that all the measured ammonia maser lines may be associated with shocks caused either by outflows or by the expansion of UCH{II} regions. Overall, Sgr B2 is unique in that it allows us to measure many NH₃ masers simultaneously, which may be essential to elucidate their so far poorly understood origin and excitation.

Full Text

Preamble

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Letter to the Editor

Discovery of non-metastable ammonia masers in Sagittarius B2

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ABSTRACT

We report the discovery of widespread maser emission in non-metastable inversion transitions of NH_3 toward various parts of the Sagittarius B2 molecular cloud and star-forming region complex. We detect masers in the J, K = (6,3), (7,4), (8,5), (9,6), and (10,7) transitions toward Sgr B2(M) and Sgr B2(N), an NH_3 (6,3) maser in Sgr B2(NS), and NH_3 (7,4), (9,6), and (10,7) masers in Sgr B2(S). With the high angular resolution data of the Karl G. Jansky Very Large Array (JVLA) in the A-configuration, we identify 18 maser spots. Nine maser spots arise from Sgr B2(N), one from Sgr B2(NS), five from Sgr B2(M), and three in Sgr B2(S). Compared to our Effelsberg single-dish data, the JVLA data indicate no missing flux. The detected maser spots are not resolved by our JVLA observations. Lower limits to the brightness temperature are >3000 K and reach up to several 10^5 K, manifesting the lines' maser nature. In view of the masers' velocity differences with respect to adjacent hot molecular cores and/or UCHII regions, it is argued that all the measured ammonia maser lines may be associated with shocks caused either by outflows or by the expansion of UCHII regions. Overall, Sgr B2 is unique in that it allows us to measure many NH_3 masers simultaneously, which may be essential in order to elucidate their thus far poorly understood origin and excitation.

Key words. Masers -ISM: clouds -ISM: individual objects: Sgr B2 -ISM: H ii regions -Radio lines: ISM

1. Introduction

Since their discovery in the (J, K) = (3,3) metastable (J = K) line toward the high-mass star-forming region (HMSFR) W33 (Wilson et al. 1982), sources emitting maser emission in the ammonia molecule (NH_3) have attracted much attention. To date, metastable ammonia maser lines have been detected in 22 HMSFRs (see Yan et al. 2022, and references therein), while non-metastable (J > K) ammonia masers have only been found in ten sources. The NH_3 (6,3), (7,4), (8,5), and (9,6) maser lines, which will be discussed below, arise from energy levels of 551 K, 713 K, 892 K, and 1089 K above the ground state, respectively. These four maser transitions have only been detected, respectively, in three (NGC7538, W51, and Sgr B2(N)), in two (W51 and Sgr B2(N)), in two (W51 and Sgr B2(N)), and in seven (W51, NGC7538, W49, DR21 (OH), Sgr B2(N), Cep A and G34.26+0.15) HMSFRs (Madden et al. 1986; Henkel et al. 2013; Mei et al. 2020; Yan et al. 2022). The NH_3 (10,7) line, also observed by us, connects states as high as 1303 K above the ground state and has so far only been classified as a maser in W51 (Henkel et al. 2013). Among all the abovementioned regions of massive star formation, Sgr B2 hosts a particularly high number of active sites of star formation.

Sgr B2 is located at a projected distance of 100 pc from Sgr A* (Reid et al. 2009), the compact radio source associated with the supermassive black hole in the Galactic center at a distance of 8.178 ± 0.013 (stat.) ± 0.022 (sys.) kpc (Gravity Collaboration et al. 2019). This region is normally divided into three high-mass star-forming cores: Sgr B2(N), Sgr B2(M), and Sgr B2(S) (see our Fig. 1 [Figure 1: see original paper] for the location of these). In total, Sgr B2 contains more than 50 H ii regions, most of which are ultracompact H ii regions (Uchii) (Martín-Pintado et al. 1999; Mills et al. 2018; Mei et al. 2020). In the case of NH_3 , an ammonia maser in the metastable (3,3) transition was only detected in the southern part of Sgr B2(S) (Martín-Pintado et al. 1999). Another metastable ammonia maser, in the (2,2) line, was found toward Sgr B2(M) (Mills et al. 2018). Recently, 18 ammonia non-metastable maser lines at frequencies of 13.0–24.0 GHz were detected toward Sgr B2(N) with the Shanghai 65-meter Tianma radio telescope with characteristic beam sizes of 54×18.5 (GHz) arcseconds (Mei et al. 2020).

In this letter, we report the discovery of NH_3 (6,3), (7,4), (8,5), (9,6), and (10,7) masers in Sgr B2(M) and Sgr B2(N), an NH_3 (6,3) maser in Sgr B2(NS), as well as NH_3 (7,4), (9,6), and (10,7) masers in Sgr B2(S). All of these increase the number of (6,3), (7,4), (8,5), (9,6), and (10,7) maser detections in our Galaxy, respectively, from three to six, two to four, two to three, seven to nine, and one to four. Observations with the Effelsberg 100-meter telescope and the Karl G. Jansky Very Large Array (JVLA) are presented in Sect. 2. Results are described in Sect. 3. A comparison of the positions of the different ammonia masers with those of other relevant tracers of the interstellar medium is presented in Sect. 4. Our main results are summarized in Sect. 5.

2. Observations and Data Reduction

2.1. Effelsberg Observations and Data Reduction

The NH_3 (9,6) and (10,7) lines were observed toward Sgr B2 with the 100-meter Effelsberg telescope at 12 epochs in January 2020, February and August 2021, as well as in March, May, June, July, and August 2022. The observations were performed in position switching mode. The off position was 30' in azimuth away from the source. An S14mm double beam secondary focus receiver was employed. The half power beam width (HPBW) is $49 \times 18.5'$ (GHz) arcseconds, that is 49' at 18.5 GHz, the frequency of the NH_3 (9,6) line. Before August 2021, the spectrometer covered 2 GHz with a channel width of 38.1 kHz, corresponding to 0.62 km s^{-1} at 18.5 GHz. From August 2021, a high spectral resolution backend with 65536 channels and a bandwidth of 300 MHz was employed, providing a channel width of 0.07 km s^{-1} at 18.5 GHz. Pointing was checked every hour using NGC 7027. Focus calibrations were done at the beginning of the observations, and during sunset and sunrise, toward NGC 7027. The calibrator was measured between elevations of 30 and 56 degrees. The elevation on target was about 10 degrees, requiring only minimal ($\sim 2\%$) elevation-dependent flux density corrections. The system temperatures were 140–220 K in a main-beam brightness temperature, T_{MB} , scale. The flux density was calibrated assuming a T_{MB}/S ratio of 1.95 K/Jy, derived from continuum cross scans of NGC 7027 (its flux density was adopted from Ott et al. 1994). Calibration uncertainties were estimated to be 10%.

We used the GILDAS/CLASS package (Pety 2005) to reduce the spectral line data. A first-order polynomial was subtracted from each spectrum for baseline removal.

2.2. JVLA Observations and Data Reduction

Observations of six NH_3 lines—the (5,1), (6,3), (7,4), (8,5), (9,6), and (10,7) transitions (Table 1)—toward Sgr B2 were made on 5 March 2022 with the JVLA of the National Radio Astronomy Observatory (NRAO) in the A-configuration (project ID: 22A-106, PI: Yaoting Yan). Eight-bit samplers were used to perform the observations. For the NH_3 (9,6) and (10,7) line observations, we used two subbands with the eight-bit samplers covering a bandwidth of 16 MHz with full polarization, eight recirculations, and four baseline board pairs (BLBPs) to provide a velocity range of 260 km s^{-1} with a channel spacing of 0.13 km s^{-1} . Four additional subbands of bandwidth 16 MHz were used to cover the NH_3 (5,1), (6,3), (7,4), and (8,5) lines. The remaining ten subbands of the eight-bit sampler with a bandwidth of 128 MHz were used to measure the continuum emission between 18 and 20 GHz. The primary beam of the JVLA antennas is 150' (FWHM) at 18.5 GHz, covering all prominent star-forming regions in Sgr B2 simultaneously. 3C 286 was used as a calibrator for pointing, flux density, bandpass, and polarization (Perley & Butler 2013). J1745-2900 served as our gain calibrator during the observations. The on-source time was 30 minutes toward Sgr B2. A total of 27 antennas were employed for the observations. Data from two antennas were lost due to technical issues. The data from the remaining 25 antennas were reduced through the Common Astronomy Software Applications package (CASA; McMullin et al. 2007). We calibrated the data with the JVLA CASA calibration pipeline using CASA 6.2.1. The results were obtained after flagging and recalibrating data that contained artifacts. We inspected the phase, amplitude, and bandpass variations of the calibrated visibility data to search for additional artifacts before imaging. Then, the uvcontsub task in CASA was used to separate the calibrated visibilities into two parts: one with line-only data and the other with the line-free continuum data. The tclean task with a cell size of 0.02 and Briggs weighting with robust=0.5 was used to produce the images of spectral line and continuum emission. All of the images were corrected for primary beam response. The synthesized beams and the rms noises in a channel image for the observed lines are listed in Table 1. For the 1.6 cm (18–20 GHz) continuum emission, the synthesized beam is $0.22 \times 0.08'$ at P.A. = -10.61° . The typical absolute astrometric accuracy of the JVLA is 10% of the synthesized beam. The flux density scale calibration accuracy is estimated to be within 15%.

The maser spots were identified in two different ways and then cross-checked. First, we searched for masers by eye in channel maps with a velocity spacing of 0.5 km s^{-1} . Second, we used an automated source extraction code (SEC; Murugesan 2015; Nguyen 2015) running in CASA 5.4 to

find the maser features. Emission with signal-to-noise ratios (S/Ns) larger than six identified in this way was considered to be a real detection. A detailed description of the SEC code can be found in Sect. 3.1 of Nguyen et al. (2022).

3. Results

In January 2020, with the Effelsberg 100-m telescope, we observed two strong NH_3 (9,6) maser features with velocities of 77 km s^{-1} and 84 km s^{-1} , and a weaker one at 72 km s^{-1} , toward the equatorial position $\alpha\{J2000\} = 17\ 47\ 20.8$, and $\delta\{J2000\} = -28^\circ 23\ 32.1$, which is offset by $(+3.96, -26.19)$ from Sgr B2(M). In addition, maser emission at 77 km s^{-1} was also found in the non-metastable para- NH_3 (10,7) transition. The NH_3 (9,6) and (10,7) maser spectra are shown in Fig. A.1. In February 2021, we extended our observations to 20 positions to cover, in a fully sampled way, an area of 5.0 square arcminutes surrounding Sgr B2(M) with a spacing of 25, half the beam size. (9,6) maser emission was found to be quite widespread in Sgr B2, not only residing in Sgr B2(M), but also in Sgr B2(N) and Sgr B2(S), while (10,7) masers were detected in a more limited region comprising Sgr B2(M) and Sgr B2(N). The maps of NH_3 (9,6) and (10,7) spectra are presented in Figs. A.2 and A.3.

Effelsberg monitoring observations spanning 19 months show that the NH_3 (9,6) maser at $V_{\text{LSR}} = 72.5 \text{ km s}^{-1}$ toward Sgr B2(N) became weaker from February to August in 2021 and was not detectable from March 2022 at 3σ levels of 0.12 Jy with a 0.07 km s^{-1} channel width. A weaker (9,6) feature at $V_{\text{LSR}} = 63.8 \text{ km s}^{-1}$ was detected in March 2022. The (9,6) maser spectra from Sgr B2(N) are presented in Fig. A.4. NH_3 (9,6) line parameters obtained by Gaussian fits are listed in Table B.1. An NH_3 (10,7) maser was detected at a different velocity of 82.0 km s^{-1} toward Sgr B2(N). Its flux density was increasing from February to August 2021 but was decreasing from March to August 2022. In Table B.2, NH_3 (10,7) line parameters obtained from Gaussian fits are presented.

Toward Sgr B2(M), NH_3 emission at $V_{\text{LSR}} = 72.5 \text{ km s}^{-1}$ became stronger between February 2021 and March 2022, then weakened until August 2022. Higher spectral resolution data since March 2022 show the NH_3 (9,6) emission to be composed of three different components. The NH_3 (10,7) maser in Sgr B2(M) has a velocity offset with respect to the (9,6) maser, with a velocity of $V_{\text{LSR}} = 70.0 \text{ km s}^{-1}$. The flux density in the Effelsberg beam remained constant within the uncertainties during the 19 months. Spectra are shown in Fig. A.5 and line parameters obtained by Gaussian fits are listed in Tables B.3 and B.4.

The 1.6 cm continuum, derived from our JVLA A-configuration measurements, is shown in Fig. 1. A total of 22 known compact H ii regions (Gaume et al. 1995; De Pree et al. 1998, 2014, 2015) were detected by our observations. The locations and sizes of these sources, derived with the imfit task in CASA, are consistent with previous results from 7 mm continuum measurements (De Pree et al. 2015). Details are given in Table B.5.

The JVLA has better angular resolution compared to the Effelsberg 100-m single dish and those data reveal 18 maser spots in the NH_3 (6,3), (7,4), (8,5), (9,6), and (10,7) transitions. We did not find any emission in the NH_3 (5,1) line from Sgr B2. The 3σ upper limit for the NH_3 (5,1) line is $9.96 \text{ mJy beam}^{-1}$ (about 1800 K) for a channel width of 0.12 km s^{-1} . The JVLA NH_3 (9,6) and (10,7) line profiles toward Sgr B2(M), extracted from an Effelsberg-beam-size region (FWHM, 49), are shown in Fig. A.5. From the similarity of the flux density obtained at Effelsberg and the JVLA, measured in March 2022, we conclude that there is no “missing spacing” flux density in the JVLA data, that is, emission on angular scales larger than defined by the shortest JVLA baseline. NH_3 (6,3) masers arise from four different locations, named 63A, 63B, 63C, and 63D. NH_3 (7,4), (8,5), (9,6), and (10,7) masers are detected toward three, two, four, and five spots, respectively. Positions and spectral parameters of these masers are listed in Table B.6. The detected isolated maser spots are distributed over a 16×93 area in Sgr B2, corresponding to $0.6 \times 3.7 \text{ pc}$. Details related to the individual sources are given below.

Sgr B2(N): Among the 18 maser spots detected in Sgr B2, 50% are located in Sgr B2(N). These are seen in the NH_3 (6,3) transition toward 63A and 63B, in the (7,4) transition toward 74A, in the (8,5) line toward 85A, in the (9,6) transition toward 96A and 96B, as well as in the (10,7) line toward 107A, 107B, and 107C. Four of these sources, 85A, 96A, 96B, and 107C, are close to the UCH ii region K2 (see Fig. 2 [Figure 2: see original paper]). The two maser spots, 85A and 107C, share the same position and have similar velocity distributions. Three maser spots, 63A, 63B, and 74A, surround the compact continuum source K3. The two maser spots, 63A and 74A, share, within the uncertainties, the same position and have similar velocity distributions. One maser spot, 107A, originates from a region offset by $(-0.61 \pm 0.02'', +0.47'' \pm 0.01'')$ from the continuum source K7. These second maser spots in the (10,7) line, 107B, has the highest brightness temp

K and originates from a region without any centimeter continuum source. Spectra from these nine maser spots are presented in Fig. 3 [Figure 3: see original paper].

Sgr B2(NS): Only one maser spot, 63C, in the NH_3 (6,3) transition was detected in this region. It is the strongest among all the detected (6,3) masers in Sgr B2 and is at a position with an offset of $(-0.09 \pm 0.02'', +0.01'' \pm 0.01'')$ from the H ii region, Z10.24 (see Fig. A.6 and Table B.6). The spectrum is shown in Fig. A.7.

Sgr B2(M): We detected five maser spots in this area (see Fig. A.8). Three of them, 63D, 74B, and 96C, arise from similar positions close to the UCH ii region F10.39. These three maser features are distributed in the same velocity range, from 70.0 km s^{-1} to 70.4 km s^{-1} , while the (6,3) maser, 63D, extends spectroscopically down to the lower velocity of 68.0 km s^{-1} . Spectra are presented in Fig. A.9. Another two maser spots, 85B and 107D, in the (8,5) and (10,7) transitions are located in regions close to the UCH ii region F10.39.

Sgr B2(S): Three maser spots, 74C, 96D, and 107E, in the NH_3 (7,4), (9,6), and (10,7) transitions, are detected in this region. These are close to each other and are found slightly off the head of the cometary UCH ii source (Fig. A.10). Spectra are shown in Fig. A.11.

4. Discussion

As shown in Figs. A.4 and A.5, and claimed in Sect. 3, our JVLA data of NH_3 (9,6) and (10,7) lines are not affected by missing flux. All of the detected maser spots are spatially unresolved, so the derived brightness temperatures are lower limits. Nevertheless, lower limits to the brightness temperature are $>3000 \text{ K}$ and reach $6 \times 10^5 \text{ K}$ (107B). A comparison with the NH_3 (6,3), (7,4), (8,5), and (9,6) observations toward Sgr B2(N), using the TMRT 65-m telescope in March 2020 (Mei et al. 2020), reveals that almost all maser spots in our JVLA data are new detections at different velocities, with the exception of 74A. This strongly suggests substantial variations of the NH_3 (6,3), (8,5), and (9,6) masers since March 2020.

Maser spots from other molecules— H_2O (McGrath et al. 2004), class II CH_3OH (Caswell 1996; Hu et al. 2016; Lu et al. 2019), H_2CO (Mehring et al. 1994; Hoffman et al. 2007; Lu et al. 2019), and OH (Gaume & Claussen 1990)—are presented in Figs. 2, A.6, A.8, and A.10. The class I CH_3OH masers at 44 GHz toward the Sgr B2(M) and N regions from Mehringer & Menten (1997) are outside the scales of Figs. 2, A.6, and A.8, and are therefore not shown. The SiO maser (Morita et al. 1992; Zapata et al. 2009) and the metastable NH_3 (2,2) masers in Sgr B2(M) (Mills et al. 2018) originate from a region around the radio object F3, which is more than two arcseconds north of source F10.39. These sources are, therefore, also not shown in Fig. A.8. The ammonia (3,3) masers are located in an area more than 15 arcseconds south of Sgr B2(S) (Martín-Pintado et al. 1999) and outside the region shown in Fig. A.10. It is noteworthy that they are not spatially related to any (6,3) maser component, another transition within the same $K = 3$ ladder. Our detected non-metastable NH_3 masers and previously detected metastable NH_3 masers arise from different regions. This indicates that these types of ammonia masers are excited in different ways.

There are no apparent space and velocity correlations between our detected non-metastable NH_3 maser spots and other molecular masers. The locations of the hot cores Sgr B2(N1), N2 and N3 in Sgr B2(N), as well as Sgr B2(N5) in Sgr B2(NS), derived from the 3 mm imaging line survey “Exploring Molecular Complexity with ALMA” (EMoCA, Bonfand et al. 2017), are shown in Figs. 2 and A.6. A bipolar outflow in an east-west direction was found around the UCH ii region K2, also known as Sgr B2(N1) (Higuchi et al. 2015; Bonfand et al. 2017). Bipolar outflows are also observed in a north-south direction and a northeast-southwest direction in the hot cores of Sgr B2(N3) and N5, respectively (Bonfand et al. 2017). There is a class II CH_3OH maser spot and an H_2O maser spot close to the hot core Sgr B2(N3). Seven NH_3 maser spots—63A, 63B, 74A, 85A, 96A, 96B, and 107C—are close to the hot core Sgr B2(N1). 107A and 107B originate from regions near the hot cores Sgr B2(N2) and N3, respectively. 63C arises from an area close to the hot core Sgr B2(N5). None of the NH_3 masers are spatially coincident with the hot cores in projection. The redshifts seen in 63B, 96A, and 107B, as well as blueshifts seen in 63A, 63C, 74A, 85A, 96B, 107A, and 107C with respect to the systemic velocities of the associated hot cores, may suggest that these maser spots are related to the outflows. The line profiles from these ten maser spots are shown in Figs. 3 and A.7. Bonfand et al. (2017) did not find any sign of an outflow around Sgr B2(N2), while our maser spot 107A, with a blueshifted velocity of $V_{\text{LSR}} = 65.5 \text{ km s}^{-1}$ ($V_{\text{sys}} = 74.0 \text{ km s}^{-1}$), could indicate the presence of an outflow.

All detected NH_3 maser spots in Sgr B2(M) show redshifted velocities with respect to the systemic velocity of Sgr B2(M), $V_{\text{LSR}} = 62 \text{ km s}^{-1}$ (Belloche et al. 2013). This supports the suggestion that NH_3 masers in Sgr B2(M) are also related to outflows.

Toward Sgr B2(S), the ammonia maser spots 74C, 96D, and 107E also have redshifted velocities with respect to the systemic velocity of Sgr B2(S), $V_{\text{LSR}} = 60 \text{ km s}^{-1}$ (Meng et al. 2022), which may indicate that this emission takes part in outflows. Several hot cores were identified by Jeff et al. (in prep.) in Sgr B2(S) in ALMA data (project code: 2017.1.00114.S, PI: A. Ginsburg). No hot cores were found to be close to the ammonia masers. This indicates that the presence of hot, dense gas alone is not sufficient to excite these masers. The ammonia masers detected in Sgr B2(S) are close to the head of the cometary UCH ii region, similar to the NH_3 (9,6) maser M1 in G34.26+0.15 (Yan et al. 2022). The maser spots in Sgr B2(S) show almost twice the angular distance compared to M1, with an offset of $(+0.36 \pm 0.13'', -0.07'' \pm 0.11'')$ in G34.26+0.15. In view of the different distances of G34.26+0.15 (D = 3.3 kpc; Yan et al. 2022) and Sgr B2 (8.2 kpc; see Sect. 1), the linear distance is even five times larger in Sgr B2(S), that is 0.03 pc. The velocity difference between the masers and the cometary UCH ii regions is ten times higher in Sgr B2(S) than in G34.26+0.15 ($\Delta V_{\text{SgrB2}}(S) \geq 17.4 \text{ km s}^{-1}$ and $\Delta V_{\text{G34}.26} = -1.3 \text{ km s}^{-1}$). That indicates that the cometary UCH ii region in Sgr B2(S) is more active than the one in G34.26+0.15.

Overall, the detected non-metastable ammonia masers in Sgr B2 are consistent with the discussion on pumping scenarios in Yan et al. (2022). Therefore, we speculate that the detected NH_3 masers in the non-metastable (6,3), (7,4), (8,5), (9,6), and (10,7) transitions in Sgr B2(N), Sgr B2(NS), Sgr B2(M), and Sgr B2(S) appear to be associated with shocks caused either by outflows or UCHII expansion.

5. Summary

We report the discovery of NH_3 non-metastable (6,3), (7,4), (8,5), (9,6), and (10,7) masers in Sgr B2(M) and Sgr B2(N), an NH_3 (6,3) maser in Sgr B2(NS), as well as NH_3 (7,4), (9,6), and (10,7) masers in Sgr B2(S). High angular resolution data from the JVLA A-configuration reveal 18 maser spots. Nine maser spots arise from Sgr B2(N), one from Sgr B2(NS), five from Sgr B2(M), and three originate in Sgr B2(S). All of these increase the number of (6,3), (7,4), (8,5), (9,6), and (10,7) maser detections in our Galaxy from three to six, two to four, two to three, seven to nine, and one to four. Compared to the Effelsberg 100-m telescope data, the JVLA data indicate no missing flux. The detected maser spots are not resolved by our JVLA observations. Lower limits to the brightness temperature are $>3000 \text{ K}$ and reach up to $6 \times 10^5 \text{ K}$, manifesting their maser nature. Long-term Effelsberg monitoring (19 months) indicates that the intensities of the (9,6) masers in Sgr B2(M), as well as the (9,6) and (10,7) masers in Sgr B2(N), show noticeable variations. However, the (10,7) maser in Sgr B2(M) is stable. While the NH_3 masers all arise near hot cores, there are many hot cores that do not exhibit NH_3 maser emission. All of these non-metastable ammonia maser lines show redshifted or blueshifted features that may be related to outflows or UCHII expansion.

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References

- Belloche, A., Garrod, R. T., Zingsheim, O., Müller, H. S. P., & Menten, K. M. 2022, *A&A*, 662, A110
 Belloche, A., Menten, K. M., Comito, C., et al. 2008, *A&A*, 482, 179
 Belloche, A., Müller, H. S. P., Menten, K. M., Schilke, P., & Comito, C. 2013, *A&A*, 559, A47
 Bonfand, M., Belloche, A., Menten, K. M., Garrod, R. T., & Müller, H. S. P. 2017, *A&A*, 604, A60
 Caswell, J. L. 1996, *MNRAS*, 283, 606
 Caswell, J. L., Green, J. A., & Phillips, C. J. 2013, *MNRAS*, 431, 1180

- Cotton, W. D. & Yusef-Zadeh, F. 2016, ApJS, 227, 10
 De Pree, C. G., Goss, W. M., & Gaume, R. A. 1998, ApJ, 500, 847
 De Pree, C. G., Peters, T., Mac Low, M. M., et al. 2014, ApJ, 781, L36
 De Pree, C. G., Peters, T., Mac Low, M. M., et al. 2015, ApJ, 815, 123
 Gaume, R. A. & Claussen, M. J. 1990, ApJ, 351, 538
 Gaume, R. A., Claussen, M. J., de Pree, C. G., Goss, W. M., & Mehringer, D. M. 1995, ApJ, 449, 663
 Ginsburg, A., Bally, J., Barnes, A., et al. 2018, ApJ, 853, 171
 Gravity Collaboration, Abuter, R., Amorim, A., et al. 2019, A&A, 625, L10
 Henkel, C., Wilson, T. L., Asiri, H., & Mauersberger, R. 2013, A&A, 549, A90
 Higuchi, A. E., Hasegawa, T., Saigo, K., Sanhueza, P., & Chibueze, J. O. 2015, ApJ, 815, 106
 Hoffman, I. M., Goss, W. M., & Palmer, P. 2007, ApJ, 654, 971
 Hu, B., Menten, K. M., Wu, Y., et al. 2016, ApJ, 833, 18
 Lazio, T. J. W. & Cordes, J. M. 2008, ApJS, 174, 481
 Lu, X., Mills, E. A. C., Ginsburg, A., et al. 2019, ApJS, 244, 35
 Madden, S. C., Irvine, W. M., Matthews, H. E., Brown, R. D., & Godfrey, P. D. 1986, ApJ, 300, L79
 Martín-Pintado, J., Gaume, R. A., Rodríguez-Fernández, N., de Vicente, P., & Wilson, T. L. 1999, ApJ, 519, 667
 McGrath, E. J., Goss, W. M., & De Pree, C. G. 2004, ApJS, 155, 577
 McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in *Astronomical Society of the Pacific Conference Series*, Vol. 376, *Astronomical Data Analysis Software and Systems XVI*, ed. R. A. Shaw, F. Hill, & D. J. Bell, 127
 Mehringer, D. M., Goss, W. M., & Palmer, P. 1994, ApJ, 434, 237
 Mehringer, D. M. & Menten, K. M. 1997, ApJ, 474, 346
 Mei, Y., Chen, X., Shen, Z.-Q., & Li, B. 2020, ApJ, 898, 157
 Meng, F., Sánchez-Monge, Á., Schilke, P., et al. 2022, arXiv e-prints, arXiv:2208.07796
 Meng, F., Sánchez-Monge, Á., Schilke, P., et al. 2019, A&A, 630, A73
 Mills, E. A. C., Ginsburg, A., Clements, A. R., et al. 2018, ApJ, 869, L14
 Morita, K.-I., Hasegawa, T., Ukita, N., Okumura, S. K., & Ishiguro, M. 1992, PASJ, 44, 373
 Murugesan, C. 2015, Master's thesis, University of Bonn
 Nguyen, H. 2015, Master's thesis, University of Bonn
 Nguyen, H., Rugel, M. R., Menten, K. M., et al. 2021, A&A, 651, A88
 Nguyen, H., Rugel, M. R., Murugesan, C., et al. 2022, arXiv e-prints, arXiv:2207.10548
 Ott, M., Witzel, A., Quirrenbach, A., et al. 1994, A&A, 284, 331
 Perley, R. A. & Butler, B. J. 2013, ApJS, 204, 19
 Pety, J. 2005, in *SF2A-2005: Semaine de l' Astrophysique Francaise*, ed. F. Casoli, T. Contini, J. M. Hameury, & L. Pagani, 721
 Reid, M. J., Menten, K. M., Zheng, X. W., Brunthaler, A., & Xu, Y. 2009, ApJ, 705, 1548
 Reid, M. J., Schneps, M. H., Moran, J. M., et al. 1988, ApJ, 330, 809
 Rickert, M., Yusef-Zadeh, F., & Ott, J. 2019, MNRAS, 482, 5349
 Walsh, A. J., Purcell, C. R., Longmore, S. N., et al. 2014, MNRAS, 442, 2240
 Wilson, T. L., Batrla, W., & Pauls, T. A. 1982, A&A, 110, L20
 Yan, Y. T., Henkel, C., Menten, K. M., et al. 2022, A&A, 659, A5
 Zapata, L. A., Menten, K., Reid, M., & Beuther, H. 2009, ApJ, 691, 332

Appendix A: Figures

[Figure 1: see original paper] JVL A 1.6-cm continuum map of Sgr B2, shown in gray. The synthesized beam is 0.22×0.08 , P.A. = -10.61° .

[Figure 2: see original paper] JVL A 1.6 cm continuum map of Sgr B2(N), shown by the gray shaded areas and black contours with levels of 5, 10, 30, and 50×0.2 mJy beam $^{-1}$. The reference position is $\alpha\{J2000\} = 17\ 47\ 19.883$, and $\delta\{J2000\} = -28^\circ 22' 18.412$, the peak position of the continuum source K2. The crosses, thin diamonds, diamonds, stars, and circles show the positions of NH₃ (6,3), (7,4), (8,5), (9,6), and (10,7) emissions. H₂O (McGrath et al. 2004), class II CH₃OH (Caswell 1996; Lu et al. 2019), H₂CO (Mehringer et al. 1994; Hoffman et al. 2007; Lu et al. 2019), and OH (Gaume & Claussen 1990) masers are presented as triangles, squares, pentagons, and hexagons, respectively. The color bar indicates the velocity range (V_{LSR}) of maser spots. Red crosses mark the positions of the hot cores Sgr B2(N1), N2, and N3, taken from the 3 mm imaging line survey "Exploring Molecular Complexity with ALMA" (EMoCA, Bonfand et al. 2017). The systemic velocities of the hot cores N1, N2, and N3 are $V_{\text{LSR}} = 64$ km s $^{-1}$, $V_{\text{LSR}} = 74$ km s $^{-1}$ and $V_{\text{LSR}} = 74$ km s $^{-1}$, respectively (Bonfand et al. 2017).

[Figure 3: see original paper] JVL A A-configuration spectra of NH₃ transition lines toward Sgr B2(N). The dashed red lines indicate the systemic velocities of the associated hot cores. V_{LSR}

= 64 km s⁻¹ for N1, and V_{LSR} = 74 km s⁻¹ for N2 and N3 (Bonfand et al. 2017). Main beam brightness temperature scales are presented on the left hand side of the profiles.

Appendix B: Tables

Table 1. Summary of the JVLA observations.

Transition (J, K)	Frequency (GHz)	E _{low} /k (K)	Synthesized beam Baseband (arcsec)	Linear resolution (AU)	P.A. (deg)	T _{B/S} (K mJy ⁻¹)	rms (mJy beam ⁻¹)
(5,1)	19.006	408	A0/C0 0.198 × 0.085	1624 × 697	-9.807	1.222 × 10 ^{(3)/ν}	0.36
(6,3)	19.888	551	A0/C0 0.203 × 0.087	1665 × 713	-9.806	...	0.40
(7,4)	20.720	713	A0/C0 0.209 × 0.089	1714 × 730	-9.661	...	0.49
(8,5)	21.507	892	B0/D0 0.214 × 0.091	1755 × 746	-9.527	...	1.14
(9,6)	22.251	1089	B0/D0 0.215 × 0.097	1763 × 795	-7.385	...	0.62
(10,7)	22.956	1303	B0/D0 0.220 × 0.094	1804 × 771	-9.874	...	0.48

Notes. Columns (1) and (2): observed lines and corresponding rest frequencies, taken from Henkel et al. (2013). Column (3): E_{low}/k: energy above the ground state of the lower level of a given inversion doublet; k is the Boltzmann constant; (E_{up} - E_{low})/k 1.0-1.5 K. Column (4): baseline board pairs' setup, see details in VLA resources page. Column (5): synthesized beam. Column (6): linear resolution at a distance of 8.2 kpc. Column (7): position angle of the synthesized beam. Column (8): conversion factor from mJy to Kelvin for each transition was calculated with 1.222 × 10^{(3)/ν} (ν is the frequency in units of GHz; ν_{maj} and ν_{min} are the major and minor axis of the synthesized beam in units of arcseconds. Column (9): rms noise in a channel image.

Table B.1. Summary of NH₃ (9,6) maser observations toward Sgr B2(N)

Source	Telescope	Beam Size	Epoch	Channel Spacing (km s ⁻¹)	S _{dv} (Jy km s ⁻¹)	V _{LSR} (km s ⁻¹)	ΔV _{1/2} (km s ⁻¹)
Sgr B2(N)	Effelsberg	49	2021, Feb. 15	0.62	1.03 ± 0.09	72.34 ± 0.07	1.83 ± 0.21
Sgr B2(N)	Effelsberg	49	2021, Feb. 27	0.62	0.92 ± 0.06	72.54 ± 0.05	1.65 ± 0.12
Sgr B2(N)	Effelsberg	49	2021, Aug. 12	0.62	1.16 ± 0.09	63.02 ± 0.50	12.14 ± 0.88
Sgr B2(N)	JVLA	0.215 × 0.2092	2022, Mar. 05	0.13	0.34 ± 0.06	58.09 ± 0.09	2.17 ± 0.39
...

Notes. The spectral parameters are obtained from Gaussian-fitting. (a) The JVLA spectrum is extracted from a region of radius 35.

Table B.6. NH₃ maser positions in Sgr B2, derived from the JVLA observations.

Spot ID	Transition	α _{J2000} (h m s)	δ _{J2000} (° ')	V _{LSR} (km s ⁻¹)	S _{dv} (Jy beam ⁻¹)	T _B (10 ⁴ K)	ΔV _{1/2} (km s ⁻¹)
63A	(6,3)	17 47	-28 22	62.09 ± 0.02	0.60 ± 0.04	0.37 ± 0.005	0.72 ± 0.02

Spot ID	Transition	$\alpha_{\{J2000\}}$ (h m s)	$\delta_{\{J2000\}}$ ($^{\circ}$)	$V_{\{LSR\}}$ (km s $^{-1}$)	$S_{\{Jy\}}$ beam $^{-1}$	$T_{\{B\}}$ (10 4 K)	$\Delta V_{1/2}$ (km s $^{-1}$)
63B	(6,3)	17 47	−28 22	68.94 ±	0.40 ±	0.72 ±	0.54 ±
		19.918 ±	17.037 ±	0.01	0.02	0.02	0.01
		0.002	0.008				
63C	(6,3)	17 47	−28 22	57.26 ±	0.49 ±	0.88 ±	0.34 ±
		20.036 ±	41.135 ±	0.01	0.01	0.17	0.07
		0.001	0.004				
63D	(6,3)	17 47	−28 23	69.02 ±	1.14 ±	2.12 ±	0.95 ±
		20.200 ±	06.500 ±	0.12	0.12	0.14	0.08
		0.002	0.008				
...

Notes. (+) These nine maser spots originate in Sgr B2(N). (×) 63C arises in Sgr B2(NS). (*) These five maser sources belong to Sgr B2(M). (**) These three maser spots originate in Sgr B2(S). The flux density scale calibration accuracy is estimated to be within 15%.

Note: Figure translations are in progress. See original paper for figures.

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