A 6.7 GHz Methanol Maser Survey at High Galactic Latitudes

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Abstract

We performed a systematic 6.7 GHz Class II methanol maser survey using the Shanghai Tianma Radio Telescope toward targets selected from the all-sky Wide-Field Infrared Survey Explorer (WISE) point catalog. In this paper, we report the results from the survey of those at high Galactic latitudes, i.e., $|b| > 2^\circ$. Of 1473 selected WISE point sources at high latitude, 17 point positions that were actually associated with 12 sources were detected with maser emission, reflecting the rarity (1%–2%) of methanol masers in the region away from the Galactic plane. Out of the 12 sources, 3 are detected for the first time. The spectral energy distribution at infrared bands shows that these new detected masers occur in the massive star-forming regions. Compared to previous detections, the methanol maser changes significantly in both spectral profiles and flux densities. The infrared WISE images show that almost all of these masers are located in the positions of the bright WISE point sources. Compared to the methanol masers at the Galactic plane, these high-latitude methanol masers provide good tracers for investigating the physics and kinematics around massive young stellar objects, because they are believed to be less affected by the surrounding cluster environment.

Key words: ISM: molecules – masers – radio lines: ISM – stars: formation

Supporting material: figure set, machine-readable table

1. Introduction

Methanol masers are very useful tools for investigating physics and kinematics in massive star-forming regions. Methanol masers have been divided into two classes (Class I and Class II, Batrla et al. 1987). Voronkov et al. (2010, 2014) concluded that Class I methanol masers are pumped by collision excitation in mildly shocked molecular gas and reside on scales of ~1 pc in a single star formation region. On the contrary, Class II methanol masers are pumped by infrared radiation and located close to high-mass young stellar objects (within 1", Caswell et al. 2010).

The 6.7 GHz transition is an extensively studied Class II methanol maser and is one of the strongest masers known in our universe (Menten et al. 1988a, 1988b; Norris et al. 1988; Menten 1991). Unlike other maser species (OH and H$_2$O masers associated with both star-forming regions and evolved stars), the 6.7 GHz methanol maser is only associated with massive star-forming regions (Minier et al. 2003; Xu et al. 2008). A large number of observations suggest that 6.7 GHz methanol maser is a powerful tool for studying massive star-forming regions (e.g., Ellingsen 2006).

In the past few decades, there were several 6.7 GHz methanol maser surveys in our Galaxy, including targeted surveys (e.g., Menten 1991; MacLeod et al. 1992; Caswell et al. 1995; Caswell 1996; Ellingsen et al. 1996; van der Walt et al. 1996; Walsh et al. 1997; Ellingsen 2007) and unbiased surveys (e.g., Green et al. 2009, 2010, 2012). Targeted surveys mainly observed infrared sources or star-forming regions associated with known tracers such as H$_2$O or OH masers (e.g., Menten 1991), while unbiased surveys are performed toward specific areas. The Methanol Multibeam (MMB) Survey conducted with the Parkes telescope is an unbiased survey of 6.7 GHz methanol maser in a relatively wide region of the Galactic plane ($186^\circ < l < 60^\circ$, $|b| < 2^\circ$, Green et al. 2009). A catalog of about 519 6.7 GHz methanol masers is compiled by Pestalozzi et al. (2005), and the MMB survey has detected 954 sources (Caswell et al. 2010, 2011; Green et al. 2010, 2012; Breen et al. 2015). Up to now, about 1000 Class II methanol maser sources have been detected in our Galaxy.

Since star-forming regions are considered to be located mainly in the Galactic plane, those 6.7 GHz methanol maser surveys in our Galaxy were conducted in the regions at low Galactic latitudes ($|b| < 2^\circ$). In the catalog of Pestalozzi et al. (2005), only 14 sources are at high Galactic latitudes, suggesting the decrease of methanol maser sources toward high latitude. The MMB survey was also conducted toward the Galactic plane with $|b| < 2^\circ$. Further systematic survey toward high-latitude regions are necessary to further check whether or not methanol masers are rare at high latitudes.

Many previous interferometric observations (including connected element interferometers and VLBI) have revealed that some Class II methanol maser spots are distributed predominately in lines or arcs with a near-monotonic velocity gradient along the structure (Norris et al. 1998; Phillips et al. 1998; Bartkiewicz et al. 2009, 2014, 2016; Fujisawa et al. 2014; Sugiyaama et al. 2016). Bartkiewicz et al. (2009) reported that about one-third of their sample sources show a new class of “ring-like” methanol maser spot distribution. The new morphology suggests that methanol maser emission is produced by shocked material associated with a disk or a torus. However, some other observations also show that the methanol maser spot distribution has other morphologies, such
as complex and pair morphologies (Bartkiewicz et al. 2014, 2016). The complex methanol morphologies may be formed under the complicated cluster or neighbor environment around the massive star-forming regions where the methanol masers locate. Therefore, a relatively clean environment with less clustering is helpful to better investigate the origin of 6.7 GHz methanol masers. The 6.7 GHz methanol maser sources at high-latitude ($|b| > 2^\circ$) regions would provide potential candidates for such study, because they have quite a simple cluster environment compared to star-forming regions at the Galactic plane.

Several infrared surveys toward specific regions have been carried out, such as the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire infrared survey (Benjamin et al. 2003) of the Galactic plane (−65° ≤ l ≤ 65°, |b| < 2°) by Spitzer and the survey carried out by the Midcourse Space Experiment satellite (|b| < 5°). The all-sky Wide-Field Infrared Survey Explorer (WISE) catalog covers the entire sky (Wright et al. 2010), and it is an up-to-date database. It observes at four mid-infrared bands: 3.4 μm, 4.6 μm, 12 μm, and 22 μm, with resolutions of 6′, 6′, 6′, 5′, and 12″, respectively. These all make WISE a good database for the methanol maser survey. In this paper, we report a survey of 6.7 GHz methanol masers toward a sample of WISE-selected sources at high-latitude (|b| > 2°) regions. Sections 2 and 3, describe the sample selection and observations. We present the results in Section 4, followed by discussions in Section 5 and a summary in Section 6.

2. Sample Selection

We used the MMB survey catalog as a starting sample to select the WISE point source candidates, which harbor the 6.7 GHz methanol maser. The MMB survey catalog has a position accuracy of 0".1 by ATCA (Green et al. 2009) and the astrometric precision of the WISE point sources is better than 0".15 for high signal-to-noise ratio (S/N) sources and there is an additional error of about FWHM/(2 S/N) for S/N < 20 sources (Wright et al. 2010), the FWHM represents the full width at half maximum of the point-spread function. The positions of the maser sources in the MMB catalog were determined at an accuracy of sub-arcsecond. The MMB catalog includes a total of 684 masers in the range of longitude 186° ≤ l ≤ 20° and latitude |b| < 2°. We cross-matched the MMB catalog sources with the AllWISE catalog sources using 7″ radius as the criteria. The AllWISE source catalog has accurate positions and four-band fluxes for ~750 million sources extracted from its all-sky surveys (Mainzer et al. 2011). We select 7″ radius as a matching criterion based on the spatial resolution of WISE at shorter wavelengths and the possible spatial distribution of 6.7 GHz methanol masers (usually less than 1″; e.g., Caswell 2009). As a result, we found that a total of 502 methanol maser sources in the MMB catalog have WISE counterparts. There are five maser sources, each of which is matched with two WISE point sources. For them, the angular separation of the two WISE point sources associated with each of them is usually larger than 3″ and we kept the closest WISE point source only. Furthermore, we only considered those WISE point sources (473 in total) with all the four-band flux measurements available.

On the basis of the magnitude and color–color analysis for the selected 473 WISE sources with 6.7 GHz MMB methanol maser associations, we further try to build up the criteria for the candidate WISE sources that may have the 6.7 GHz methanol masers on the full sky. Figure 1 shows the diagrams of the magnitudes of the WISE four bands (3.4, 4.6, 12, and 22 μm) and the [3.4]–[4.6] versus [12]–[22] color of the selected sources. As a comparison, the corresponding distributions of those within a 1° diameter of the two locations of l = 90°, b = 70° (denoted G90+70), and l = 0°, b = 0° (denoted G00+00) are overlaid on Figure 1. The comparison fields contain 13,627 and 18,939 WISE sources for G90+70 and G00+00, respectively. First, we select the WISE sources with the magnitude criteria: [3.4] < 14 mag; [4.6] < 12 mag; [12] < 11 mag; [22] < 5.5 mag (see Figure 1(a) and Figure 1(b)). Almost all of (455/473 = 96%) the known methanol masers lie toward the regions of these magnitude criteria; in contrast, for the comparison (G90+70) field, only about 0.4% (53/13,627) of sources with the 3.4 and 4.5 μm data meet these criteria, and only one source satisfies the 12 and 22 μm criteria. Second, we further select the sample with the WISE color criteria: [3.4]–[4.6] > 2, and [12]–[22] > 2. Toward this defined color region, we found that the majority of the methanol masers (330/455 = 73%) fall in, whereas only nine WISE sources from the comparison field of G90+70 locate (Figure 1(c)). Figure 2 shows the histogram of the distribution of the angular separations between the 330 WISE sources and their associated MMB masers. We found that most of them (288/330 = 87%) are associated with the MMB masers within an angular scale of less than 3″. Even for the comparison field of G00+00, where the background of the Galactic center is very complicated, there is still only a very small fraction (111/18939 = 0.6%) of the WISE sources in this color region (Figure 1(d)). By applying the above criteria to the full sky, we found a total of ~13,000 candidate WISE sources. This is about 0.0017% (13,000/750 × 10^6) of the ALLWISE sources. Notably, in order to detect as many methanol masers as possible, we select ALLWISE sources satisfying the above criteria without considering the photometric accuracy factor of the WISE sources. We also checked the WISE sources with low S/Ns, e.g., S/N < 3, associated with the MMB masers, and found that most of these sources also meet our selection criteria.

From these candidate WISE sources, we further select a total of 3348 WISE sources as our targeted sample of the 6.7 GHz class II methanol masers to be observed by the Shanghai TianMa radio telescope (TMRT). This sample excluded the sources in the Parkes MMB survey and those with a declination of less than −30°. In this targeted sample, 1473 sources locate at the high Galactic latitude region with $|b| > 2^\circ$ (Table 1).

3. Observations

The observations were performed between 2015 September and 2016 July with the TMRT in Shanghai, China. This telescope is a new fully steerable radio telescope with a diameter of 65 m. We used a cryogenically cooled receiver covering the frequency range of 4–8 GHz and the Digital Backend System (DIBAS) to receive and record signals. The DIBAS is an FPGA-based spectrometer that is designed on the base of the Versatile GBT Astronomical Spectrometer (VEGAS; Bussa 2012). The rest frequency of the methanol $SJ_1 \rightarrow 6_0 A^+$ transition line (66685192 GHz) was covered with a spectral window of a bandwidth of 23.4 MHz. The window has 16,384 channels and the spectral resolution is 1.431 kHz, corresponding to a velocity resolution of ~0.09 km s$^{-1}$. The temperature of this system is about 20–30 K. The aperture
The efficiency of the TMRT is $\sim 55\%$ and the corresponding sensitivity is $1.5\ Jy\ K^{-1}$. The beam size is $\sim 3''$ (HPBW) at the frequency of 6.7 GHz. The flux densities for the sources may have an uncertainty of less than $20\%$, estimated from the observed variation of the calibrators.

A position-switching mode was used in our observations. Each source was observed with two ON-OFF cycles. Procedures of both the ON position and the OFF position in each cycle take $\sim 2$ minutes. For each source, the OFF position was set to $(0^\circ.0, -0^\circ.4)$ from the ON position in (R.A., decl.).

We used the GILDAS/CLASS package to process the observed spectral data. We fitted and subtracted the linear baseline of the spectrum. The root-mean-square (rms) noise level is about 20–40 mJy.

For the detected methanol maser sources (12 in total, see below), we used the on-the-fly (OTF) mode (Dong et al. 2016) to map a large region (usually 5') to obtain a position of the methanol maser. The TMRT under the OTF mode moved in a given region along the direction of R.A. first, then the direction...
of decl. Only one spectral window is used to cover the methanol maser.

4. Results

4.1. Detections

We detected 6.7 GHz methanol masers toward positions of 17 WISE point sources, within actually 12 sources. The properties of these detected methanol maser sources are listed in Table 2. Three sources are newly detected and Figure 3 shows their spectra. We confirmed that another nine methanol maser sources detected by the TMRT observations were already reported after taking their similar positions (within 1') and spectral velocity ranges into account. Their spectra are shown in Figure 4. Below are short descriptions of these 12 sources.

4.1.1. Three Newly Detected Sources

G97.527+3.184. This source has three peaks at −73.0, −70.9, and −69.7 km s\(^{-1}\), within a velocity range of −78.4 km s\(^{-1}\) to −67.6 km s\(^{-1}\). G110.196+2.476. This weak source has a peak flux density of 0.5 Jy at −56.9 km s\(^{-1}\). G137.068+3.002. This source has a peak flux density of 1.6 Jy at −59.0 km s\(^{-1}\).

Compared to previously known sources, all three new sources show relatively weak maser intensity. G110.196+2.476 and G137.068+3.002 have a simple spectral feature.

G97.527+3.184 has also been studied by Hachisuka et al. (2015) through the 22 GHz H\(_2\)O maser and it is located in the Outer Arm. So, this source may provide a good candidate to study the massive star formation that occurred in the regions at the edge of our Galaxy.

Using the multi-band infrared data, including WISE and Herschel, we can estimate the related physical parameters for the newly detected sources. However, in the three sources, only one source, G110.196+2.476, is covered by Herschel.

We estimated the dust temperature of G110.196+2.476 from its spectral energy distributions (SED) in the WISE 22 \(\mu m\), Herschel PACS 70 and 160 \(\mu m\), and SPIRE 250, 350, and 500 \(\mu m\). The SED is fitted using a gray-body emission model (Hildebrand 1983)

\[ S_\nu = \kappa_\nu B_\nu(T_d)\Omega \mu m_{\text{H}} N_{\text{tot}} / g = \kappa_\nu B_\nu(T_d)M_{\text{core}} / gD^2, \]

wherein \(S_\nu\) is the flux density at the frequency \(\nu\), \(\Omega\) is the solid angle of the core or the selected area, \(B_\nu(T_d)\) is the Planck function of the dust temperature \(T_d\), \(\mu = 2.33\) is the mean molecular weight (Myers & Benson 1983), \(m_{\text{H}}\) is the mass of the hydrogen atom, \(g = 100\) is the gas-to-dust mass ratio, \(N_{\text{tot}}\) is the column density of the core, \(D = 5.1\) kpc is the source distance, \(\kappa_\nu\) is the dust opacity and is expected to vary with the frequency in the form \(\kappa_\nu = \kappa_{230\ GHz}(\nu/230\ GHz)^{\beta}\), with the reference value of \(\kappa_{230\ GHz} = 0.9\ cm^2 g^{-1}\), as adopted from dust model for the grains with coagulation for 10\(^5\) years with accreted ice mantles at a density of 10\(^6\) (Ossenkopf & Henning 1994).

The continuum emission of the core has a compact and isolated shape throughout all the wavebands. The flux density can be reproduced by a single temperature component, as shown in Figure 5. The derived physical parameters are \(M_{\text{core}} = 14\ M_\odot\), \(T_d = 49\ K\) and \(\beta = 1.4\) for G110.196+2.476. Therefore, the new detection of the 6.7 GHz methanol maser from this source is still associated with the massive star formation process.

4.1.2. 9 Previously Detected Sources

G16.872−2.154, G16.883−2.186. The methanol maser emission detected from these two positions actually should be from a common position close to G16.872−2.154. Previous observations from Caswell et al. (1995), Walsh et al. (1997, 1998), and Szymczak et al. (2000) also detected the 6.7 GHz maser emission from G16.872−2.154. Comparing our spectra to those in Szymczak et al. (2000), we found that these masers have similar velocity features, but peak flux density changed from 23 Jy to 16.0 Jy in G16.872−2.154.

G17.021−2.402. This source was detected by Szymczak et al. (2000), named 18277−1517. Both observations detected maser emission at the same velocity range, but flux density
changed significantly. The peak flux density was 3.7 Jy at 23.3 km s\(^{-1}\) and 8.9 Jy at 20.6 km s\(^{-1}\) in Szymczak et al. (2000) and our observations, respectively.

\(G78.122+3.633\). This source was detected by MacLeod et al. (1992), Slysh et al. (1999), Szymczak et al. (2000), and Minier et al. (2000, 2001), named 20126+4104, TMRT measured a peak flux density of 39.9 Jy at −7.7 km s\(^{-1}\), similar to 38 Jy at −6.1 km s\(^{-1}\) in Szymczak et al. (2000).

\(G108.184+5.518\). It was detected by MacLeod et al. (1998), Slysh et al. (1999), and Szymczak et al. (2000). This source has a peak flux density of 49.2 Jy at −10.7 km s\(^{-1}\) by the TMRT. In Szymczak et al. (2000), it named 22272+6358 had a peak flux density of 69.4 Jy at −11.1 km s\(^{-1}\).

\(G109.839+2.134, G109.868+2.119\). The spectra of these two separate sources show that most maser emission is from G109.868+2.119, which has a very strong peak flux density of 766.7 Jy at −2.4 km s\(^{-1}\). G109.868+2.119 was detected by Slysh et al. (1999) and Szymczak et al. (2000). Szymczak et al. (2000) reported G109.868+2.119 (named 22543+6145) with a feature of peak flux density of 815 Jy.

\(G123.055-6.355, G123.050-6.310\). The maser emission detected toward these two positions are from the same source: G123.050–6.310. Slysh et al. (1999) and Szymczak et al. (2000) detected G123.050–6.310. Szymczak et al.’s (2000) detection, with the name 00494+5617, has a similar spectrum but with a peak flux density of 24 Jy, compared with our detection of 66.9 Jy.

\(G173.482+2.446\). This 6.7 GHz methanol maser site was detected by Menten (1991), Szymczak et al. (2000), and Minier et al. (2000), named S231. In Szymczak et al. (2000), it showed a much stronger flux density (a peak flux density of 208 Jy) than our detection (41.5 Jy), with a quite different spectrum.

\(G173.596+2.823\). The spectra at both positions clearly show that most emission is from G173.617+2.883, with a velocity range of −24.8 km s\(^{-1}\) to −18.1 km s\(^{-1}\). G173.617+2.883 was detected by Szymczak et al. (2000), and was named 05358+3543.

\(G121.706–12.602\). These two positions have features at the same velocity range and the emission is mostly from G121.706–12.602. G121.706–12.602 was detected by Szymczak et al. (2000), and was named 06053–0622, with a peak flux density of 166 Jy at −10.5 km s\(^{-1}\). However, we found two peaks with peak flux densities of ~120 Jy at both 10.5 and 12.7 km s\(^{-1}\). This source, named Mon R2, was also detected in Menten (1991), Caswell et al. (1995), Walsh et al. (1997, 1998), and Minier et al. (2001).
4.2. Maser Positions Determined from the OTF Observations

The center coordinates and the side length of the square regions chosen for the OTF observations toward these 12 sources are listed in Table 3. Figure 6 shows the velocity-integrated intensity map from the OTF observation and the 6.7 GHz methanol maser spectra in the fitting center toward G97.527+3.184, the peak positions in each region can be found in Table 3. Considering the pointing error of the telescope (about 10") and the fitting error from the OTF mapping observation (typically 10"), we can obtain a positional accuracy at a level of better than 20" with the TMRT OTF observations.

Minier et al. (2000, 2001) and Hu et al. (2016) have studied eight of these sources through interferometric observations with the European VLBI Network (EVN), the Very Long Baseline Array, and the Very Large Array (VLA). For comparison, the interferometric positions of these eight sources are also listed in Table 3, along with their position difference from our OTF measurements. The positions of the six sources (G17.021–2.402, G78.122+3.633, G108.184+5.518, G109.868+2.119, G123.050–6.310, and G173.482+2.446) determined from our OTF observations have offsets in the range of 10"–20", with regard to the positions determined from the interferometric observations. This is consistent with a positional uncertainty of less than 20" from the OTF observations. For G16.872–2.154 and G213.706–12.602, the position accuracy determined from the OTF observations are 3" and 10", respectively.

5. Discussions

5.1. Rarity of High-latitude Methanol Masers

In total, 17 methanol maser sources at high latitudes, including known sources from the Pestalozzi et al. (2005) catalog and those first reported in this work, have been detected to date. The distribution of 6.7 GHz methanol maser sources at high latitude is shown in Figure 7. It can be seen that about three-fourths (13 of 17 sources) are located at Galactic latitudes of $2^\circ \sim 4^\circ$ and $-2^\circ \sim -4^\circ$. According to statistics (Pestalozzi et al. 2005; Caswell et al. 2010, 2011; Green et al. 2010, 2012; Breen et al. 2015), there are about 1000 Class II methanol maser sources detected in our Galaxy, suggesting a $\sim 1.7\%$ fractional distribution of high-latitude sources.

The latitude distribution of 519 methanol masers listed in Figure 3 in Pestalozzi et al. (2005) has a Gaussian fit with an FWHM of 0.52°, consistent with the rarity (1.7%) of 6.7 GHz methanol masers at high altitude. However, this situation may be related to the fact that previous methanol maser surveys were mainly concentrated near the Galactic plane. Our survey detected twelve 6.7 GHz maser sources toward the region of $0^\circ \leq l \leq 220^\circ$ and $|b| > 2°$. Assuming a uniform distribution of methanol masers along the galactic longitude, then a total number of 20 is estimated to be detected in the whole high-latitude region ($0^\circ \leq l \leq 360^\circ$, $|b| > 2°$) toward the WISE-selected sample. Because the detection rate is estimated to $\sim 73\%$ (see Section 2), the expected number of methanol masers would be 27 in the region of $|b| > 2°$. Thus, our survey strongly suggests that the 6.7 GHz methanol maser is really rare in the high-latitude region.

5.2. Profile Variability of Methanol Masers

As described in Section 4.1.2, 9 of 12 TMRT detected methanol maser sources were previously observed by Szymczak et al. (2000) with the 32 m Torun radio telescope with an HPBW of 5.5° at 6.7 GHz. These sources are not accurately pointed from the same coordinate position, which may cause differences in flux density. Our discussion will mainly focus on the variations of their spectral profiles. We also list the source names in parenthesis from Szymczak et al. (2000) at the beginning of the description of each source.

G16.872–2.154 (18265–1517). The spectra of both G16.872–2.154 and 18265–1517 show structures with several features and, the peak flux densities are 19.3 Jy and 23 Jy, respectively. The features at about 15.0, 17.3, and 18.6 km s$^{-1}$ of G16.872–2.154 are quite similar to those at about 14.7, 17.0, and 18.3 km s$^{-1}$ of 18265–1517 with a velocity offset of 0.3 km s$^{-1}$. Such an offset may not be significant compared to the reported error of $\pm 0.4$ km s$^{-1}$ in the absolute radial velocity.

G17.021–2.402 (18277–1517). From the spectra of this source and 18277–1517, their peak flux densities are 9.2 Jy and 3.7 Jy, respectively. Profiles have changed a lot. In the Szymczak et al. (2000) observation, there was a feature at about 23.3 km s$^{-1}$ and an obscure feature at about 20.6 km s$^{-1}$.
However, our spectra show features at 19.4, 20.6, 21.7, 23.3, and 24.4 km s$^{-1}$.

G78.122+3.633 (20126+4104). The peak flux densities of G78.122+3.633 and 20126+4104 are 40.9 Jy and 38 Jy, respectively. Except for a stable feature at $-6.1$ km s$^{-1}$, 20126+4104 did not show any other features seen in G78.122+3.633 at $-8.2$, $-7.6$, $-6.5$, and $-5.0$ km s$^{-1}$.

G108.184+5.518 (22272+6358). The peak flux densities of G108.184+5.518 and 22272+6358 are 49.2 and 91 Jy, respectively. Compared to Szymczak et al. (2000), features at about $-10.7$ km s$^{-1}$ and $-10$ km s$^{-1}$ remain unchanged in our observation, whereas a new feature at about $-12.7$ km s$^{-1}$ arose in our observation.

G109.868+2.119 (22543+6145). We can see that the spectra of G109.868+2.119 and 22543+6145 have similar features and flux densities. It seems that this source has not changed a lot.

G123.050–6.310 (00494+5617). From the spectra of G123.050–6.310 and 00494+5617, we can see that the peak flux densities are 97.2 Jy and 24 Jy, respectively. The features at $-36.0$ km s$^{-1}$ and $-30.8$ km s$^{-1}$ have similar flux density ratios, but become stronger now.

G173.482+2.446 (05358+3543). The peak flux densities of G173.482+2.446 and 05358+3543 are 41.5 and 256 Jy, respectively. We can clearly see features at $-14.7$, $-13$, and $-10.5$ km s$^{-1}$ in both observations. Moreover, there is a new feature at about $-7.5$ km s$^{-1}$. In addition, the peak flux densities have decreased a lot.

G173.617+2.883 (05382+3547). The peak flux density has changed from 7.5 Jy in 05382+3547 to 4.5 Jy in G173.617+2.883 and a new feature arose at $-20.1$ km s$^{-1}$.

G213.706–12.602 (06053–0622). The peak flux densities of G213.706–12.602 and 06053–0622 are 127 Jy and 166 Jy, respectively. The features at about 11.6 km s$^{-1}$ and 12.5 km s$^{-1}$ disappeared and the new feature at about 12.7 km s$^{-1}$ showed up with a flux density as strong as that of the feature at about 10.5 km s$^{-1}$.

The 3σ noise level was typically 1.5–1.9 Jy in Szymczak et al. (2000), and ours is less than 0.2 Jy, which is much better. This may explain the appearance of some new features in the TMRT observations.
| Name       | OTF Parameters         | Properties of the Fitting Centers | Properties of 8 Sources by Interferometric Observation | Difference |
|------------|------------------------|-----------------------------------|-------------------------------------------------------|------------|
|            | R.A. (J2000)           | Decl. (J2000)                      | R.A. (J2000)                                          |            |
|            | (h m s)                | (° ° °)                            | Decl. (J2000)                                         | R.A.       |
|            | (2)                    | (3)                               | (h m s)                                              | (J2000)    |
|            | (° ° ″)                 | (′ ″ ′)                            | (km s⁻¹)                                             | (° ° °)    |
|            | (4)                    | (5)                               | (Jy)                                                 | (′ ″ ′)    |
|            | (6)                    | (7)                               | (Jy km s⁻¹)                                          | (° ° °)    |
|            | (8)                    | (9)                               | (Jy km s⁻¹)                                          | (° ° °)    |
|            | (10)                   | (11)                              | (J2000)                                              | (° ° °)    |
|            | (12)                   | (13)                              | (° ° °)                                              | (° ° °)    |
|            | (14)                   |                                    |                                                     |            |
| G16.872−2.154 | 18:29:24.3             | −15:15:30.0                       | 6 16 Jul 14 18:29:24.20                              | 15:16:03.6 |
|            | 17.4                   | 19.0                              | 5.3                                                  |            |
| G17.021−2.402 | 18:30:36.2             | −15:14:26.9                       | 5 16 Jul 16 18:30:36.96                              | −15:14:41.4 |
|            | 20.6                   | 9.2                               | 6.3                                                  |            |
| G78.122+3.633 | 20:14:26.2             | +41:13:32.1                       | 5 16 Jul 14 20:14:26.96                              | +41:13:49.0 |
|            | −7.7                   | 40.9                              | 64.7                                                 |            |
| G97.527+3.184 | 21:32:11.3             | +55:53:39.6                       | 5 16 Jul 14 21:32:11.18                              | +55:53:32.0 |
|            | −73.0                  | 0.9                               | 0.3                                                  |            |
|            | 70.9                   | 1.0                               | 0.4                                                  |            |
|            | 69.7                   | 0.8                               | 0.3                                                  |            |
| G108.184+5.518 | 22:28:51.5             | +64:13:40.2                       | 5 16 Jul 15 22:28:52.07                              | +64:13:58.3 |
|            | +64:13:40.2            | −10.7                             | 50.0                                                 | 19.8       |
| G109.868+2.119 | 22:56:15.8             | +62:01:59.4                       | 6 16 Jul 15 22:56:18.96                              | +62:01:39.6 |
|            | +62:01:59.4            | −2.4                              | 838.8                                                | 327.9      |
| G110.196+2.476 | 22:57:29.8             | +62:29:45.1                       | 5 16 Jul 16 22:57:32.88                              | +62:29:51.9 |
|            | +62:29:45.1            | −56.9                             | 0.9                                                  | 0.4        |
| G123.050−6.310 | 00:52:17.2             | +56:33:42.6                       | 6 16 Jul 16 00:52:25.45                              | +56:33:33.8 |
|            | +56:33:42.6            | −29.3                             | 97.2                                                 | 43.1       |
| G137.068+3.002 | 02:58:13.3             | +62:20:31.9                       | 5 16 Jul 18 02:58:14.91                              | +62:20:42.8 |
|            | +62:20:31.9            | −59.0                             | 1.8                                                  | 1.6        |
| G173.482+2.446 | 05:39:13.0             | +35:45:50.9                       | 5 16 Jul 18 05:39:12.84                              | +35:46:09.1 |
|            | +35:45:50.9            | −13.0                             | 42.3                                                 | 21.8       |
| G173.617+2.883 | 05:41:13.0             | +35:51:02.9                       | 7 16 Jul 23 05:41:22.75                              | +35:52:31.5 |
|            | +35:51:02.9            | −18.2                             | 5.0                                                  | 3.1        |
| G213.706−12.602 | 06:07:46.8             | −06:23:08.3                       | 6 16 Jul 23 06:07:48.41                              | −06:22:51.3 |
|            | 10.5                   | 127.4                             | 38.4                                                 |            |
|            | 12.7                   | 127.2                             | 62.0                                                 |            |

**Note.** Column 1: source name; Columns 2–5: the pointing center coordinates, the side length of each region for the TMRT OTF observations, and the epoch of observation; Columns 6–10: the fitting center positions with the velocity of peak emission, the peak flux density, and the integrated flux density; Columns 11–13: the positions determined by interferometric observation (Hu et al. 2016) with references H (Hu et al. 2016), M (Minier et al. 2000), and M1 (Minier et al. 2001); Column 14: the separation between the fitting centers and interferometric positions for eight sources.
Compared with Szymczak et al. (2000) observations, except for G109.868+2.119, 8 of 9 sources have shown significant profile changes. Many 6.7 GHz methanol maser sources have been observed to be variable (e.g., Goedhart et al. 2004, 2009, 2014; van der Walt et al. 2009, 2016; Szymczak et al. 2011, 2015; Maswanganye et al. 2015, 2016). Several possibilities might cause such variabilities: (i) pulsation of a young high-mass star (Inayoshi et al. 2013; Sanna et al. 2015), (ii) a colliding-wind binary system (van der Walt et al. 2009), and (iii) rotating spiral shocks in the gap region of a binary system (Parfenov & Sobolev 2014).

5.3. WISE Infrared Environment Source Associations

The infrared three-color images of these 12 TMRT detected methanol maser sources at high latitude, $|b| > 2^\circ$. The red “▲” represents previously detected sources (Pestalozzi et al. 2005). The blue “+” represents sources detected in our work.

Figure 6. Left: the velocity-integrated intensity map of G97.527+3.184 for the 6.7 GHz methanol maser. We derived the velocity intensity from the spectra of this source from $-78.4$ to $-67.6$ km s$^{-1}$. The “o” represents the position of the WISE source in the single-point-survey, and the “+” represents the fitted peak position of the methanol emission from the TMRT OTF observation. Right: spectra in the fitting center. (The complete figure set (12 images) is available.)

Figure 7. Galactic coordinates’ distribution of the 6.7 GHz methanol maser sources at high latitude, $|b| > 2^\circ$. The red “▲” represents previously detected sources (Pestalozzi et al. 2005). The blue “+” represents sources detected in our work.

The infrared three-color images of these 12 TMRT detected methanol maser sources are shown in Figure 8 with the fitting centers of methanol emission determined from the TMRT OTF observations marked. Two sources (G17.021–2.402 and G173.617+2.883) do not have bright counterparts in the WISE infrared image. The positions of three sources (G108.184+5.518, G110.196+2.476, and G173.482+2.446), determined from the TMRT OTF observations are within 20″ from the nearby bright infrared sources. All of the remaining seven methanol maser sources locate in the bright WISE sources.
Figure 8. Infrared three-color images of the 12 detected methanol sources. The blue, green, and red colors represent 3.4, 4.6, and 12 μm bands in WISE. The “▲” represents the fitted peak position of methanol emissions by the TMRT OTF observation (Table 3), the “■” represents the positions of WISE point source used in TMRT pointing observation (Table 2), and the “♀” represents the position determined from interferometric observations (Table 3). The field of view of each region is equal to that in the OTF observation (Table 3).
Considering the $20''$ positional accuracy of TMRT OTF observations (see Section 4.2), 10 of the 12 detected sources are associated with bright WISE sources.

Furthermore, with more accurate interferometric positions for eight sources (see Section 4.2), we found that seven sources are well associated with the WISE sources, with an exception of G17.021–2.402. For six out of the eight sources (the two exceptions are G16.872–2.154 and G123.050–6.310), we also found that methanol masers are located very close to the WISE sources, which were targeted in our survey. Therefore, we could also refine a methanol maser source at a positional accuracy of about $10'' \sim 20''$, by solely matching to the WISE source positions. This is especially important for those maser sources without any high accuracy position measurements, such as those from surveys toward a sample selected from WISE sources at a low-latitude region.

5.4. Spatial Distribution of Methanol Maser Spots

The 6.7 GHz methanol maser distributions toward eight sources have been studied with interferometric observations (see Section 4.2) and we can compare the distribution of the maser spots from all these eight sources obtained from the JVLA at C-array configuration (Hu et al. 2016). There are four sources, G16.872–2.154, G17.021–2.402, G78.122+3.633, and G213.706–12.602, showing the maser distribution in a linear morphology, and three sources, G108.184+5.518, G109.868+2.119, and G123.050–6.310 seem to distribute along a ring-like structure. In addition, the distribution of G173.482+2.446 looks complex. The linear or ring-shaped distribution of the masers may be associated with jet/outflow or disk/torus structures (e.g., Bartkiewicz et al. 2016) from isolated massive young stellar objects. However, the complex structure of the masers should be affected by the neighborhoods in a complicated cluster environment in the massive star-forming regions.

Of the 63 low-latitude sources with the EVN imaging of 6.7 GHz methanol masers (Bartkiewicz et al. 2009, 2014, 2016), 1 source shows simple morphology, 11 sources show ring morphology, 13 sources show linear morphology, 5 sources show arched morphology, 29 sources show complex morphology, and 4 sources show pair morphology. This proportion is quite different from our high-latitude ones, especially for the complex morphology group: only one in 8 sources from our sample, compared to about half (29/63) in Bartkiewicz et al. (2009, 2014, 2016) samples. This is likely to be due to the fact that the sources at low latitudes usually have more complicated cluster environments. The physical and kinematic contributions from the neighborhoods around the host of methanol masers would complicate the morphology of methanol masers. This makes it difficult to use a methanol maser as a useful probe to the physics and kinematics that are solely associated with its host. From this point of view, the detected methanol maser sources at high latitudes from our observations would serve as better candidates for studying the physics and kinematics during the massive star formation in our further work using VLA observations.

6. Summary

Using the newly built TMRT in Shanghai, we undertook a systematic survey of 6.7 GHz methanol masers toward high-latitude ($|b| > 2\degree$) targets in our Galaxy. The target sample contains 1473 high-latitude sources selected from the WISE source catalog. We detected 12 methanol masers with 3 new detections, suggesting that the 6.7 GHz methanol masers are really rare at the high-latitude region. The peak flux densities of the detected sources are from 0.9 to 838.8 Jy, while new detections have peak flux densities in the range of 0.9 to 1.8 Jy. Comparing with previous detections toward nine sources, we found that the spectra and flux densities of eight sources have changed significantly. Combining our OTF observations and previous interferometric observations, we concluded that most methanol masers are associated with bright WISE point sources in the infrared images. The published interferometric observations revealed that almost all of these high-latitude sources do not have complex morphology in the methanol maser spot distribution, in contrast to those at low latitudes. Therefore, high-latitude methanol masers might serve as an efficient tracer for studying physics and kinematics of their hosts during the massive star formation.

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