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Linear polarisation of Class I methanol masers in massive star formation regions

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Abstract. We present the results of the linear polarisation observations of methanol masers at 44 and 95 GHz towards 39 massive star forming regions (Kang *et al.* 2016). These two lines are observed simultaneously with the 21-m Korean VLBI Network (KVN) telescope in single dish mode. About 60% of the observed showed fractional polarisation of a few percents at least at one of the two transition lines. We note that the linear polarisation of the 44 GHz methanol maser is first detected in this study including single dish and interferometer observations. We find the polarisation properties of these two lines are similar as expected, since they trace similar regions. As a follow-up study, we have carried out the VLBI polarisation observations toward some 44 GHz maser targets using the KVN telescope. We present preliminary VLBI polarisation results of G10.34-0.14, which show consistent polarisation properties in multiple epoch observations.

Keywords. masers, polarisation, stars: formation, magnetic fields

1. Introduction

Masers (OH, H2O, SiO, and CH3OH) are the tracers that can be used to study the physical conditions of dense regions ($n_H = 10^{5-11}\mathrm{cm}^{-3}$), close to protostellar disks or outflows, that are embedded in thick dust envelopes. Class I methanol masers, including 44 and 95 GHz transitions, are known to trace the regions where the outflow of a massive young stellar object is interacting with the surrounding medium, while Class II methanol masers are tightly correlated with the central (proto)stars (Plambeck & Menten 1990).

The polarimetric observations of Class II methanol masers have increased during the last decade (e.g., Vlemmings 2012) and have been able to provide information about the magnetic fields near the central objects. However, the polarisation studies of Class I methanol masers have been very limited. For example, the detection of linear polarisation at 95 GHz has been reported only for two sources before our study (Wiesemeyer *et al.* 2004). No linear polarisation has been reported for 44 GHz methanol maser sources. Circular polarisation at 44GHz, detected with the Very Large Array (VLA), has been presented only for one object, OMC2 (Sarma & Momjian 2011).

In this paper, we report on single-dish measurements of linear polarisation toward 44 and 95 GHz methanol maser sources. The full results are published in Kang *et al.* (2016). We also report on the preliminary results of follow-up VLBI observations, especially on the G10.34-0.14.

2. Observations and Calibration

We observed the Class I methanol $7_0 - 6_1 A+$ (44.06943 GHz) and $8_0 - 7_1 A+$ (95.169463 GHz) maser transitions in full polarisation spectral mode towards 39 massive star forming regions. The observations were conducted simultaneously in both transitions using the KVN 21 m telescope at the Yonsei station in single-dish mode from August to December in 2013. The beam sizes of data are $65''$ and $30''$, at 44 and 95 GHz, respectively. The typical rms levels (1σ) of final spectra are 0.5 Jy and 1.2 Jy at 44 and 95 GHz at a velocity resolution of 0.2 km s^{-1} , respectively .

The instrumental cross talk and phase offset were corrected using planets (Jupiter, Venus, or Mars) and the Crab nebula, which were observed at least once a day as calibrators. The polarized intensity (PI) given here is $(Q^2 + U^2)^{1/2}$, and the given error is the standard deviation of the measurement sets. Detection criterion is that $PI > 3\sigma$. The measured position angle was derived by $\chi = \frac{1}{2}\arctan(\frac{U}{Q}) + 152°$. Here the latter term is the absolute position angle of the Crab nebula, which is known to be nearly constant near the brightest region from millimeter to X-ray wavelengths. (Aumont *et al.* 2010)

3. Results

We detected fractional linear polarisation toward 23 (59%) of the 39 Class I methanol maser sources at 44 and/or 95 GHz. Figure 1 shows the spectral profiles of the total flux (I), the polarized intensity (PI), the polarisation degree (P_L), and the polarisation position angle measured counterclockwise from north (χ) of G10.34-0.14 and G18.34+1.78SW at both transitions. The profiles of the total flux and the polarized intensity tend to peak at similar velocities. At 44 and 95 GHz, 21 (54%) and 17 (44%) sources show linear polarisation, respectively. We emphasize that this is the first detection of linear polarisation of the 44 GHz methanol masers. Fifteen (38%) sources were detected at both frequencies.

The rms weighted means of the fractional linear polarisation detected sources are $2.7 \pm 0.3\%$ and $4.8 \pm 0.1\%$ at 44 and 95 GHz, respectively. All sources have $P_L < 11\%$ except W33Met (24.6%), which has a large error of 6.9% (1σ). The ranges of polarisation fractions are 1.1% – 9.5% and 2.0% – 24.6% at 44 and 95 GHz, respectively. The polarisation detection rate tends to increase with the total flux at both transitions. The polarisation fraction and the total flux do not show clear correlation, whereas the error of P_L increases as I decreases, because $P_L \propto I^{-1}$ while the observational noise is relatively constant for all sources.

Since we observed the two transition lines at the same time, our data are ideal to compare their polarisation properties. The polarisation degrees of the two transitions appear to have a positive linear correlation, although the correlation is not very tight. The polarisation fractions of the 95 GHz masers tend to be greater than those of the 44 GHz masers. The polarisation angles of the 44 and the 95 GHz maser transitions are well correlated. In general, the polarisation properties of the 44 and 95 GHz transitions are similar, indicating that the masers at these two transition lines are indeed experiencing magnetic fields of similar regions.

4. Discussion

We have not detected any source with linear polarisation above 30% that Wiesemeyer *et al.* (2004) has reported at 132 GHz Class I and 157 GHz Class II maser transitions. Linear polarisation above 33% is expected to be rare (Elitzur 2002). Nedoluha & Watson (1990) indicated that about 30% would be the highest for an angular momentum $J = 2-1$ and higher transitions, unless significant anisotropic pumping is present. Weisemeyer *et al.*(2004) found that a large fractional linear polarisation ($P_L > 33\%$) is not rare (2 out

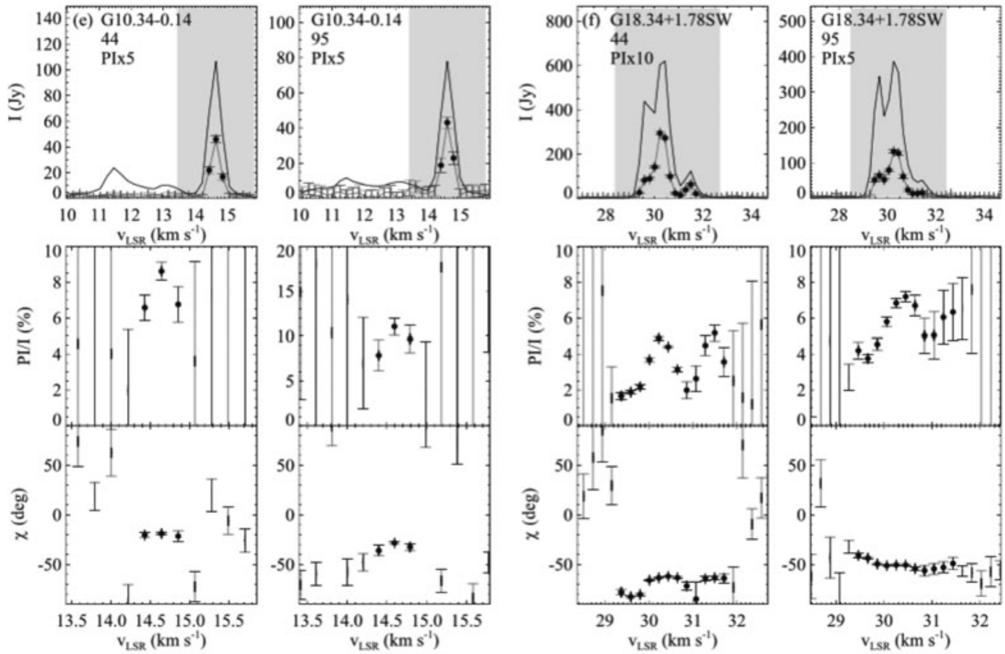

Figure 1. Polarisation-detected maser profiles of G10.34-0.14 and G18.34+1.78SW at 44 GHz and 95 GHz. For each source, the polarized intensity (PI) in grey line with errors (1σ) and the total flux intensity (I) in black solid line (top), and the polarisation fraction P_L (middle) and angle χ (bottom) are presented. The multiplication factor of PI is presented under the line frequency. The points with $PI > 3\sigma$ are indicated with filled circles. The gray-shaded area in the top panel indicates the velocity range for the middle and bottom panels.

of 10 for Class I and 1 out of 3 for Class II), giving an impression that anisotropic pumping or loss may be commonly achievable due to an unequal population of the magnetic substates of the maser levels (Nedoluha & Watson 1990). Since transitions at higher frequencies tend to have a higher fraction of polarisation, we cannot directly compare our results with those of Wiesemeyer *et al.* (2004). However, our observational results, which lacked high fractional polarisation, out of 23 polarisation-detected sources, still suggest that the anisotropic pumping or loss mechanism may not be common for 44 and 95 GHz maser transitions.

We have found that the degree of linear polarisation at 95 GHz tends to be greater than that at 44 GHz. The reduced fractional polarisation at the lower frequency transition compared to higher frequency transitions seems to be general trend in maser polarisation observations (e.g., McIntosh & Predmore 1993, Wiesemeyer *et al.* 2004). The depolarisation due to the Faraday rotation and the different beam size effects are negligable, because the internal/external Faraday rotation at these frequencies are generally smaller than the angle measurement errors and maser features of our targets are mostly confined within the beam of the 95 GHz transition in the previous VLA observations (Kogan & Slysh 1998, Kurtz *et al.* 2004). The fractional linear polarisation of the 44 and 95 GHz transitions could be intrinsically different. Pérez-Sánchez & Vlemmings (2013) and Nedoluha & Watson (1990) showed that the linear polarisation fraction of masers depends on intrinsic properties of individual transitions, such as the degree of maser saturation R/Γ and the ratio between the Zeeman splitting rate and the stimulated emission rate, etc. These are not well known and needs future studies.

We have tried to investigate the association between the orientations of linear polarisation and outflows. We have found 7 sources, i.e., OMC2, S255N, NGC2264, G49.49−0.39 (W51 e2), DR21W, DR21, and DR21(OH), where the direction of maser-associated outflow is rather simple in the literature when searched using the SIMBAD website (Wenger *et al.* 2000). Although the sample size is small, we tried the Kolmogorov-Smirnov (K-S) statistics to see whether the angle differences are similar to or different from the projected angles of aligned, perpendicular, or randomly aligned samples, by comparing the observed angle difference to the results from the Monte Carlo simulations as discussed in Hull *et al.* (2014). The K-S tests rule out the scenario where the outflows and polarisation angles are tightly aligned ($P < 0.01$). The probability of them being perpendicular ($P = 0.7$) appears to be higher than that of them being random ($P = 0.4$).

DR21(OH) and G82.58+0.20 appear to be interesting targets because they show the 90° polarisation angle flip in the 44 GHz polarisation profiles, while it is not visible in their 95 GHz polarisation profiles. The high angular resolution polarimetry observations in both frequencies and the theoretical studies will reveal whether these polarisation properties are due to the van Vleck angle crossing or change of maser saturation level, providing more information on the not-well-known methanol maser polarisation physics.

As a follow-up, we have carried out the VLBI observations of 7 targets in multiple epochs with a resolution of a few mas with full polarisation modes. In case of G10.34-0.14, observations of 3 epochs (2014-2017) showed consistent flux and polarized intensity profiles at $v_{\rm LSR} \sim +14.6$ km s^{-1} with a fractional polarisation of about 13%, indicating successful performance of the KVN polarisation system. More VLBI observations have been performed, whose results will be soon published.

5. Summary

We have been investigating the linear polarisation properties of a significant number of Class I methanol masers at 44 and 95 GHz using the KVN telescope in single dish and VLBI modes, which enables us to understand the polarisation properties of the Class I methanol masers in a statistical sense. Follow-up observations of the VLA and the ALMA telescopes would help to understand the magnetic fields of individual maser features. We have obtained the ALMA polarisation data in the 95 GHz methanol maser transition line for G10.34-0.14, which shows maser features at the tip of outflows and also near the central source. This will help us to improve our understanding on the magnetic field environment of G10.34-0.14.

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