Polarimetric survey of main-line OH masers in star-forming regions[★]

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ABSTRACT

Context. While there is evidence for considerable circular polarization of OH masers in star-forming regions, no systematic measurements of the four Stokes parameters have been done. Determining the full polarization properties of OH emission is vital to test polarization maser models and to select targets for high-angular resolution studies of magnetic fields.

Aims. The polarimetric measurements of a representative sample of star-forming regions were carried out in order to better characterize the properties of OH masers.

Methods. A sample of 99 star-forming regions was observed in the OH 1665 and 1667 MHz maser transitions using the Nancy radio telescope in full-polarization mode and high spectral resolution (0.07 km s^{-1}).

Results. We present a complete set of polarization spectra for all 98 and 81 sources detected at 1665 and 1667 MHz, respectively. All detections have circularly polarized features, whereas linear polarization is found in 80% and 62% of the 1665 and 1667 MHz sources, respectively. The median degree of linear polarization of 16% of both transitions is a factor of ~ 4 lower than that of circular polarization. In consequence, the probability of linear polarization clearly drops for sources with low total flux density because of the sensitivity limit. The linear polarization is almost always accompanied by circular polarization, i.e., elliptically polarized profiles are observed. The mean line-width at half-maximum of the linear polarization profile is 0.26 km s^{-1} . The polarization position angle (χ) shows large variations across the profile with a median amplitude close to 90° . The amplitude variations of χ decrease with increasing flux density. Large variations of the total flux density found in three sources are weakly associated with changes in polarization parameters.

Conclusions. The observational characteristics of linear polarization seem to be consistent with theoretical models where narrow profiles result from the overlap of σ -components traversed regions with appreciable velocity gradient and due to off resonance amplification.

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

1. Introduction

Our recent study (Szymczak & Gérard 2004a) revealed that the OH masers in star-forming regions (SFRs) identified by methanol emission show high circular polarization. This is consistent with earlier single-dish surveys where circular polarization of the OH ground-state transitions at 18 cm was common and often reached 100%. However, simple circular polarization and velocity patterns indicative of Zeeman splitting are rare (Cohen 1989, for a review). The examination of early observations resulted in finding 17 OH maser sources with convincing evidence for Zeeman pairs (Reid & Silverstein 1990).

High-angular resolution observations of individual sources or small samples of bright targets (e.g., Garcia-Barreto et al. 1988; Hutawarakorn & Cohen 1999, 2003; Fish et al. 2003) discovered a plethora of Zeeman pairs. However, only in the most northern group of OH masers in W75N was a full Zeeman triplet found (Hutawarakorn et al. 2002) and confirmed (Fish & Reid 2006). The latter finding and extensive discussion (e.g. Garcia-Barreto et al. 1988) suggest that most of the linearly polarized flux can be produced by σ -components. In such a case

the electric vector of the linearly polarized feature is perpendicular to the projected direction of the magnetic field on the plane of the sky.

OH sources with linearly polarized features are less frequent and their degrees of polarization are usually below 30% (Caswell & Forster 1983a,b; Cohen 1989). The most complete single-dish surveys of OH masers (Caswell & Haynes 1983a,b; Cohen et al. 1988) provided only circular polarization data with a spectral resolution $0.14\text{--}0.2 \text{ km s}^{-1}$. Other sensitive OH surveys (Slysh et al. 1994, 1997) also in dual circular polarization suffered from poor spectral resolution. Argon et al. (2000) reported sensitive circular polarization data for a sample of 91 objects taken with an angular resolution of $\sim 1''.5$ and spectral resolution of 0.14 km s^{-1} . Since then, no measurements of the complete polarization parameters have been made for a large sample of OH masers with high spectral resolution.

In this paper, we report on the properties of OH masers in a large sample of SFRs based on high sensitivity full-polarization observations with a $3''.5 \times 19'$ beam and spectral resolution of 0.07 km s^{-1} . Our previous study revealed that the main OH lines at 1665 and 1667 MHz predominate while the satellite lines at 1612 and 1720 MHz occur in only 10–15% of SFRs identified by the methanol emission (Szymczak & Gérard 2004a). Thus, the observations of the main lines should be adequate to

[★] Appendices A, B, C, and D are only available in electronic form at <http://www.aanda.org>

determine the intrinsic polarization properties of the OH maser emission. The new polarimetric data will be useful to select the candidate targets for high-angular resolution studies as well as to look for statistical trends in order to test the various polarization maser models.

2. Sample and observations

2.1. Selection of targets

Our source list relies primarily on a sample of 199 methanol maser sources detected at 6.7 GHz with the Toruń 32 m radio telescope. That sample consists of objects from the galactic region $8^\circ \leq l \leq 90^\circ$ and $|b| \leq 0.52$ with a 6.7 GHz peak flux density higher than 1.6 Jy observed during the period 2000–2003. The first part of this unbiased survey was published in Szymczak et al. (2002). In the follow-up observations, all of these 199 targets were searched for the four transitions of the OH ground state using the Nançay radio telescope (NRT). The resulting data were partly published in Szymczak & Gérard (2004a). 55% of the sample were detected at 1665 MHz and/or 1667 MHz. About 16.5% of detections were not included in the present sample because the peak total flux density is lower than 0.3 Jy at both OH main lines. Some objects were also excluded due to strong confusion effects within the NRT beam. Eventually, this resulted in the selection of 77 objects. 22 sources with $|b| \geq 0.5$ and/or $l \geq 90^\circ$ were added from the VLA survey (Argon et al. 2000). A total of 99 targets were chosen. The targets with a VLA position are distinguished in Table A.1 (online) with more accurate galactic coordinates in their names.

A comparison with the data of Caswell & Haynes (1983b) in the galactic range of $8^\circ \leq l \leq 40^\circ$ and $|b| \leq 0.3$ reveals 33 sources in common out of the 43 sources listed. We note that almost all of the 10 sources not detected with the NRT were weak (<5 Jy) OH sources in Caswell & Haynes (1983b). In this region we found 32 further sources not reported in their 1980–1981 survey; only 6 of them have a peak flux density below 1 Jy. This implies that OH sources exhibit considerable variability over ~ 2.5 decades; the OH flux density of 10 objects diminished below 0.3 Jy (our 5σ level) and in 26 objects the OH emission appeared with a peak flux density well above 1 Jy. We suggest that our sources in the range of $8^\circ \leq l \leq 90^\circ$ and $|b| \leq 0.52$ largely come from the same population as that studied by Caswell & Haynes (1983b) and is almost complete above the 75% level. Since there is evidence that the methanol masers appear earlier than the hydroxyl masers (Szymczak & Gérard 2004a) our sample may miss OH sources not yet associated with methanol emission. However, an inspection of Argon et al.’s sample implies that such an effect can be negligible: in their Table 1, among 35 OH sources lying in the above-mentioned galactic strip, only two objects G35.577–0.029 and G45.122+0.133 are not listed as methanol masers (Pestalozzi et al. 2005; Pandian et al. 2007).

2.2. OH line polarimetry

The NRT full polarization observations were carried out from March 2003 to October 2006. Some supplementary data were obtained up to September 2007. Details on the radio telescope, observing methods, polarization calibrations, data reduction and uncertainties on the Stokes parameters are given in Sect. 2 of Szymczak & Gérard (2004b). The focal system of the NRT is a dual-reflector offset Gregorian system fed by a corrugated horn and followed by an ortho-mode transducer providing two linear orthogonal polarizations. The feed box can be rotated with

a precision of 0.5° at any angle between -90° and $+90^\circ$ from the rest position 0° (where the position angles of the orthogonal electric vectors are 45° and 135°). The maximum level of the cross-polarization lobe is -22 dB. In parallel, a RF hybrid combines the two linear polarization and yields right hand circular (RHC) and left hand circular (LHC) polarizations with an isolation better than 20 dB between RHC and LHC. The four RF channels are then down converted and transported to the laboratory. This system directly provides 3 of the 4 Stokes parameters namely I , Q and V while the fourth parameter U is obtained by rotating the feed box by 45° .

The 1665.402 and 1667.359 MHz lines of OH were observed with a spectral resolution of 0.07 km s^{-1} and coverage of 30 km s^{-1} . The I , Q , U and V Stokes spectra were measured. The linearly polarized flux density $p = (Q^2 + U^2)^{0.5}$, the degrees of circular $m_C = V/I$ and linear $m_L = p/I$ polarization and the polarization position angle $\chi = 0.5 \cdot \tan^{-1}(U/Q)$ were then derived. All relevant parameters and the associated errors were calculated according to Eqs. (1)–(6) in Szymczak & Gérard (2004b). The typical 1σ noise level was 60 mJy in the I Stokes spectra. The errors on the OH polarization measurements were usually less than 8%. Each target was observed at least 2–5 times on an irregular basis to check the quality of the polarization data rather than to study the variability (Szymczak & Gérard 2004b). A few sources were observed more frequently (15–20 epochs) also for system monitoring purposes. Although an analysis of the variability of the OH polarized flux is beyond the scope of the present paper, we have obtained some intriguing results which are worth mentioning.

3. Results

3.1. Polarization parameters and spectra

The integrated parameters of the OH masers are summarized in Table A.1 (online). For each target and frequency (when emission is present) we list the integrated flux densities (S_i) for total emission (I Stokes), left- and right-circular (LHC, RHC), circular (V Stokes) and linear (p Stokes) polarizations.

Figure 1 shows an example set of the OH maser profiles for the I , Q , U and V Stokes parameters. There is a striking diversity of polarized spectra. For instance (i) in the bright sources (e.g. G10.624–0.385) all features are highly polarized with $|m_C| \leq 80\%$ and $m_L \leq 70\%$ so that the degree of total polarization ($m_T = (m_C^2 + m_L^2)^{0.5}$) is close to 100%; (ii) the strongest features usually have high linear ($m_L \leq 75\%$) and circular ($|m_C| \leq 95\%$) polarization although some weaker features are almost fully circularly polarized (e.g. G12.890+0.488); (iii) a single and strong feature has nearly complete ($m_L \leq 95\%$) linear and weak ($|m_C| \leq 10\%$) circular polarization (e.g. G13.72–0.52); (iv) complex features have high linear and weak circular polarization in a certain velocity range, while nearly fully circularly polarized emission at another velocity (e.g. G232.62+1.00); (v) the main features are highly ($|m_C| \leq 100\%$) circularly polarized with the admixture of linear polarization (e.g. G25.71+0.04); (vi) V Stokes spectra at 1665 MHz sometimes resemble those at 1667 MHz (e.g. G33.64–0.21) but p Stokes spectra are often different at both OH main lines (e.g. G33.64–0.21, G34.25+0.16). We note that the above-mentioned cases and Fig. 1 do not exhaustively depict the diversity and heterogeneity of the polarization OH spectra of the studied sources. Thus, we make all profiles available in electronic form (Fig. C.1, online) namely the spectra for the following parameters: I Stokes, LHC and RHC, V Stokes, m_C , Q

Fig. 1. Full polarization OH spectra of selected sources. The four Stokes parameters I , Q , U , V are shown. Velocities are in the LSR frame. The names of the sources and transition frequencies are given.

and U Stokes, p Stokes, m_L and χ . Machine readable spectra are available from the author upon request.

A comparison with the VLA data (Argon et al. 2000) suggests confusion in at least three cases (Fig. C.1, *online*). In the spectra of G0.658-0.043 the emission at velocities lower than $\sim 65 \text{ km s}^{-1}$ comes from source G0.666-0.034. In the spectra of G12.21-0.09 the emission at velocities higher than $\sim 25 \text{ km s}^{-1}$ arises from source G12.216-0.117 (in Table A.1 (*online*) they appear as separate entries). Towards G43.165-0.028 two other sources G43.148+0.015 and G43.167+0.010 are seen within the NRT beam.

3.2. Polarization statistics

All 99 targets show 1665 MHz emission, except G25.83-0.18. The emission at 1667 MHz occurs in 81 sources. The maser emission in both lines is always circularly polarized. Linearly polarized features occur in 78 and 50 sources at 1665 and 1667 MHz, respectively. The average and median values of the total integrated flux densities for groups of sources with and without linearly polarized features are given in Table 1. Figure 2 shows the number of sources with and without linearly polarized features as a function of the integrated total flux density. It is clear from Table 1 and Fig. 2 that the probability of detection of linear polarization increases with the total flux density. This does not necessarily imply that all bright sources have linearly polarized features. For instance, in the relatively strong source G0.547-0.852, linear polarization at 1665 MHz was marginally detected.

Table 1. Average and median values of the integrated I Stokes depending on the occurrence of linear polarization (p Stokes).

Line (MHz)	p Stokes	Number of sources	Mean(SE) (Jy km s ⁻¹)	Median (Jy km s ⁻¹)
1665	Y	78	49.7(16.4)	8.81
	N	20	0.80(0.14)	0.68
1667	Y	50	12.8(3.0)	4.43
	N	31	1.16(0.21)	0.90

Entries marked Y and N indicate groups of sources with and without linearly polarized emission respectively.

In order to determine in more detail the polarization properties of the whole sample we analyzed the degrees of circular and linear polarization of prominent features of the I Stokes spectra. The number of features, the average and median values of m_C and m_L for each frequency are given in Table 2. We note that the average values of m_C (56.4%) and m_L (22.1%) at 1665 MHz are very similar to those at 1667 MHz. The distribution of the maser features versus their degree of polarization is shown in Fig. 3. There is a steep decrease of the number of features with m_L for both maser lines. The distribution of m_C is nearly flat at 1667 MHz while at 1665 MHz there is an excess of features of $m_C \geq 70\%$. At both lines there are some features of weak ($\sim 0.3 \text{ Jy}$) I Stokes flux density for which m_C exceeds 100% (Fig. 3). In all these cases this is due to errors in flux measurements of the order of about 8%.

Figure 4 shows how the polarized flux density depends on the total flux density (S_T) for the 1665 and 1667 MHz maser features (Table 2). There is an essential difference in the

Fig. 2. Histograms showing the distribution of the integrated total flux densities for groups of the OH 1665 and 1667 MHz maser sources with and without linear polarization.

Table 2. Average and median values of the degrees of circular (m_C) and linear (m_L) polarization for the maser features clearly seen in the I Stokes spectra.

Line (MHz)	Parameter	Number of features	Mean(SE) (%)	Median (%)
1665	m_C	628	56.4(1.2)	61.5
	m_L	346	22.6(1.1)	15.7
1667	m_C	300	56.8(1.6)	58.1
	m_L	159	22.1(1.5)	16.0

Fig. 3. Distribution of the maser features versus the degree of linear (top) and circular (bottom) polarization for the 1665 and 1667 MHz lines.

distribution of the circular and linear fluxes. The circular emission closely follows the total emission. OH features of $S_T < 10$ Jy are usually strongly circularly polarized but some of them exhibit weak circular polarization ($m_C < 10\%$). In contrast, with increasing S_T only strongly polarized features are seen. The linear flux is notably lower with respect to the circular flux and shows a significant scattering for the whole range of the total flux observed. The differences in the circular and linear flux distributions are the same for both OH transitions.

We warn that the polarization statistics discussed here can be affected by spatial blending. VLA data show that the typical size for an OH maser source is a few arcseconds (Argon et al. 2000); therefore in such a case the NRT provides essentially no angular resolution.

Fig. 4. Circularly (top) and linearly (bottom) polarized flux density versus total flux density for the maser features at 1665 and 1667 MHz. The dotted lines show the lower and upper envelopes of the distribution.

3.3. Objects with high linear polarization

Table B.1 (online) lists 37 sources having features with $S_L > 0.5$ Jy and $m_L > 50\%$. For each feature, line frequency, peak velocity (V_p), linearly polarized flux, degree of linear polarization, position angle, degree of circular polarization, degree of total polarization and references for high-angular resolution observations are given.

All the features listed in Table B.1 (online) are elliptically polarized but several of them exhibit a marginal or small amount of circular polarization. One third of the targets were observed in all Stokes parameters using VLBI telescopes. In the following we comment on those sources having strongly polarized features ($m_T > 70\%$) dominated by linear polarization ($m_L > 70\%$) but with $m_C < 15\%$ as candidate targets for high-angular resolution studies.

G9.622+0.195. A 1.04 km s^{-1} feature at 1667 MHz has a peak flux density of 1.44 Jy. Linear polarization is high ($m_L = 72.7\%$) and circular polarization is marginal ($m_C = 3.3\%$). The VLBA data (Fish et al. 2005) revealed this emission as a single component of $S_L = 0.73$ Jy, $m_L = 86\%$ and $m_C = 1.9\%$. Within our beam this component is blended with a 0.26 Jy component at 1.00 km s^{-1} which is completely circularly polarized in the VLBA map. The consistency of the NRT and VLBA polarization data for this feature is impressive.

G12.890+0.488. There are two 1665 MHz features at 31.59 and 32.76 km s^{-1} of degree of linear polarization 87.3% and 76.7% , respectively. The first feature of ~ 1 Jy flux density is well separated in velocity and the second one is heavily blended, both are of low (-14.6% and -8.9%) circular polarization.

G13.72-0.52. The 1665 MHz spectrum consists of a single 14.9 Jy Gaussian feature at 48.39 km s^{-1} . It is one of the best candidate sources with very strong (92.7%) linear and weak (11.4%) circular polarization.

G23.26-0.24. The 1667 MHz spectrum consists of a relatively weak (~ 0.7 Jy) single feature of high linear polarization of 85.4% and circular polarization of -10.3% .

G24.79+0.09. Very complex 1665 MHz spectrum. A weak (~ 0.8 Jy) feature at 109.39 km s^{-1} has $m_L = 95.9\%$ and marginal circular emission.

G33.64-0.21. Two 1665 MHz features at 60.07 and 60.48 km s^{-1} are blended. Their degrees of linear polarization are 77% and 69% , respectively. Circular polarization is $\sim 14\%$.

G40.62-0.14. A 32.37 km s^{-1} feature of the complex spectrum at 1665 MHz has $m_L = 73.9\%$ and $m_C = -11.9\%$. It is heavily blended with a 32.65 km s^{-1} feature also of high

linear polarization (74.0%) but relatively low circular polarization (−26.1%). In the VLBA map (Fish et al. 2005) the latter component centred at $\sim 32.6 \text{ km s}^{-1}$ exhibits considerable circular ($m_C = -43.9\%$) and linear ($m_L = 46.0\%$) polarization. The possible counterpart of the 32.37 km s^{-1} feature in the VLBA map is composed of two fully circularly polarized components centred at 32.22 and 32.27 km s^{-1} . This case suggests that for complex and blended spectra the polarization properties inferred from the NRT and the VLBA are largely different. We suspect that spatial blending in the NRT beam is the culprit. In the same source, a 30.86 km s^{-1} feature at 1667 MHz is not blended in the NRT data. Its polarization properties $S_L = 1.88 \text{ Jy}$, $m_L = 62.5\%$ and $m_C = 0.9\%$ are roughly consistent with those of the VLBA counterpart at 30.86 km s^{-1} which is characterized by $S_L = 0.68 \text{ Jy beam}^{-1}$, $m_L = 39.0\%$ and $m_C = 1.4\%$. Thus, for this feature, the linearly polarized fluxes derived with the NRT and VLBA differ by a factor of 3. Plausible reasons for this difference are (i) a blending of other spots in the NRT beam; (ii) time variations and (iii) a diffuse emission resolved out by the VLBA beam.

G59.78+0.06. The 1665 MHz feature at 20.43 km s^{-1} feature is slightly blended and shows high linear (87.9%) and low circular (11.0%) polarization.

G109.87+2.12. A -6.91 km s^{-1} feature at 1665 MHz has $m_L = 75.6\%$ and $m_C = -6.7\%$. No VLBA counterpart was identified in Table 16 in Fish et al. (2005). A possible counterpart in the MERLIN data (Bartkiewicz et al. 2005) at -7.0 km s^{-1} has $m_L = 31\%$ and no circular polarization.

G111.53+0.76. A -57.74 km s^{-1} isolated feature at 1665 MHz is strongly linearly polarized with $m_L = 74.7\%$ but with marginal circular polarization (3.0%). In the VLBA map (Fish et al. 2005) it is a spatial blend of two components centred at -57.60 km s^{-1} and -57.89 km s^{-1} . The first component has considerable circular polarization of $\sim 48\%$ and $m_L = 48\%$. The second component has $m_L = 95\%$ and $m_C = -5\%$, therefore its polarization parameters agree well with those observed with the NRT.

G232.62+1.00. The 1665 MHz feature at 21.63 km s^{-1} is strongly linearly polarized ($m_L = 90.3\%$) with little circular polarization ($m_C = -8.5\%$).

3.4. Polarization position angle

An examination of the polarization spectra (Fig. C.1, online) reveals frequent variations of the polarization position angles across the linear polarization profiles. In many cases these variations seem to be random and their intrinsic changes are likely hidden by the strong blending of OH masers. Indeed, of the 505 features detected in linear polarization at the two OH transitions (see Sect. 3.2 and Table 2), only 46 features with amplitude larger than 0.5 Jy are well fitted with a Gaussian line shape.

A selection of unblended features is displayed in Fig. 5. The spectra of the total, linear emission, degree of linear polarization and polarization position angle are shown. The features of source G232.62+1.00 are deliberately added to exhibit that variations of the χ angle are also seen for obviously blended emission of high linear polarization.

There are large differences in the behaviour and amplitude variations of the χ angle and m_L across the profile of linear polarization. In G13.72−0.52, one of the most highly polarized sources in the sample ($m_L = 92.7\%$), the amplitude variation of χ is 29° while m_L varies from 88.9% to 97.4% (Fig. 5). For the strong ($S_L = 141 \text{ Jy}$) 1665 MHz feature near -47.44 km s^{-1} of source G133.95+1.06 (also known as W3(OH)) the χ angle

Table 3. Average and median values of the linear flux density (p), amplitude of the χ angle across the profile and line-width at half-maximum ($FWHM$) for a group of 46 linearly polarized features fitted with a Gaussian function.

Parameter	Average (SE)	Median
p (Jy)	8.24(3.59)	1.83
χ amplitude ($^\circ$)	86.5(9.0)	70.0
$FWHM$ (km s^{-1})	0.26(0.01)	0.25

changes by $3:5$ only (Fig. C.1, online). On the contrary, in the weak 1667 MHz feature in source G35.197−0.743 with $S_L = 0.77 \text{ Jy}$ near 29.2 km s^{-1} (Fig. 5), χ changes by $\sim 230^\circ$. Finally, the faint ($S_L = 1.3 \text{ Jy}$) profile of source G31.41+0.31 shows a non-linear χ variation of amplitude $\sim 110^\circ$ while m_L peaks at the centre of the p profile (Fig. 5).

Purely linearly polarized features are very rare; all features are elliptically polarized, frequently with some unpolarized emission. The degrees of linear and circular polarization range from 5 to 99% and from 0.2 to 95%, respectively. A perfect linear drift of the χ angle across the profile is not usual but in many cases it can be reasonably fitted by first or second order polynomials. We used a simplification; a linear least-squares fit is applied to all features. Then the amplitude of χ variation is calculated from the slope of the regression line and the profile width at a 1σ level. In this approximation the error of the fit provides a good measure of the departure of the χ angle drift from linearity.

Table 3 gives the mean and median values of the linear flux density, amplitude of the χ angle change across the profile (at 1σ level) and line width at half maximum ($FWHM$) for the set of 46 features. The average amplitude of the χ angle is close to 90° for the mean $FWHM$ of 0.26 km s^{-1} . The mean value of the $FWHM$ is generally consistent with estimates $0.2\text{--}0.4 \text{ km s}^{-1}$ deduced from the total emission profiles of VLBI observations (Wright et al. 2004a; Fish & Reid 2006). The amplitude of the χ angle changes decreases with the linear flux density (Fig. 6) with a large scatter of $\sim 60^\circ$ and $\sim 180^\circ$ for the bright and faint sources, respectively. As we mentioned, the error bars yield an estimate of the deviation of the χ angle drift from linear. This deviation appears to increase for weak sources. Plausible causes of this trend can be blending and/or signal-to-noise ratio limitations.

In summary, the OH features of linearly polarized emission commonly exhibit variations in the polarization position angle which depend on the linear polarized flux. This property can be explained by the magnetorotation effect (Goldreich et al. 1973).

3.5. Highly variable sources

Some of our sources were observed at several occasions in order to monitor the system performance. Here we report on three of them that have features of high amplitude variations. The data are discussed in the context of possible changes in the linear polarization parameters.

G53.14+0.07. 14 spectra covering the observation time-span of 412 days (27/08/2005–13/10/2006) were obtained. The total flux density of a 1665 MHz feature near 22.2 km s^{-1} (Fig. C.1) gradually diminished by a factor of 2.6 from 1.69 to 0.65 Jy . The degree of circular polarization was constant within 4.5% and the mean value was $92.6 \pm 1.2\%$.

G69.54−0.98. Three observations were made. Over 1077 days spanning March 2003 to February 2006 a 1665 MHz feature near 3.5 km s^{-1} increased from 12.1 to 25.4 Jy in the

Fig. 5. Cuts of the total flux density (I), linearly polarized flux density (p), degree of linear polarization (m_L) and polarization position angle (χ) spectra of selected sources. Note the monotonic variations of the χ angle across the profile of linear polarization (p).

Stokes I parameter. The circular and linear polarization fluxes increased by a factor of 2.3 and 2.8, respectively. The degrees of circular and linear polarization changed from -84.8% to -93.9% and from 6.5% to 9.2% , respectively. The polarization position angle changed from $-3^\circ.4$ to $-9^\circ.9$. We conclude that, in this feature, large changes in the flux densities were associated with marginal changes in the degrees of polarization and polarization position angle. Over this time period a feature near 14.2 km s^{-1} showed variations in the Stokes parameters by less than 23% but the m_C , m_L and χ were constant within 8%. The rest of the 1665 MHz features in the source did not show measurable variation.

G81.87+0.78 (W75N). This source was reported as experiencing a strong flare at 1665 MHz (Alakoz et al. 2005). Our observations revealed that the 1665 MHz emission is continuing its peculiar behaviour (Fig. D.1, *online*). A feature near 0.21 km s^{-1} was the most prominent in the period from August 2005 to December 2006; its peak flux in the Stokes I parameter varied from 1383 to 501 Jy (Fig. 7). Another feature near 2.08 km s^{-1} , seen as the strongest one in 2003, then declined (Alakoz et al. 2005) and increased again from 51 to 396 Jy during our observations.

The feature at 0.21 km s^{-1} was elliptically polarized with a degree of total polarization of 100% ($m_T > 100\%$ resulted from the measurement errors, typically $\sim 8\%$). The degree of circular polarization increased from -56 to -79% while that of linear polarization varied from 78 to 87% . The polarization position angle varied slightly from 48 to 54° .

We conclude that some features at 1665 MHz continued to show very large changes of highly polarized emission while the feature near 0.21 km s^{-1} exhibited only marginal variations in the degree of linear polarization and polarization position angle.

Fig. 6. Changes of polarization position angle (χ) across the profile versus the linearly polarized flux density for unblended OH features. The large error bars indicate those sources for which the χ angle drift is far from linear. The dotted line marks a 90° amplitude of the χ angle variation.

4. Discussion

4.1. Summary of statistical results

The present study corroborates previous findings that circular polarization of interstellar OH masers is widespread and strong (Caswell & Haynes 1983a,b; Argon et al. 2000). Indeed, all the sources detected in either OH lines exhibit circularly polarized emission. Our observations of a large sample reveal that the occurrence of linear polarization is also frequent (80% and 62% of the sources at 1665 MHz and 1667 MHz, respectively). In the sample the degrees of circular and linear polarization show significant differences; the median values of m_L ($\approx 16\%$) are about a factor of 4 lower than m_C at both OH lines. Therefore, the absence of linearly polarized flux in weak OH masers can be due to

Fig. 7. Variation of the polarization parameters of the 1665 MHz feature with the LSR velocity of 0.21 km s^{-1} in source G81.87+0.78 (W75N). The Stokes parameters I , $-V$, $p = (Q^2 + U^2)^{0.5}$ (top), the degrees of circular ($-m_c$) and linear (m_l) polarization and the polarization position angle (χ) (bottom) are shown.

the limited sensitivity of the observations. Furthermore, the linearly polarized profiles are usually narrow ($\sim 0.26 \text{ km s}^{-1}$) and could not be detected with a low spectral resolution (Manchester et al. 1970).

We found that the relationship between circular and total density flux is essentially different from that between linear and total density flux. The circular polarization flux is tightly correlated with the total flux while linear polarization flux shows a large dispersion for a given total flux (Fig. 4). No features of low circular polarization are observed for strong OH masers. We realize that those statistical trends, however, should be treated with caution because the NRT beam is large and our polarization data can be affected by spatial blending. To check this effect quantitatively for some of our targets, we have analyzed the interferometric polarization observations which are largely free of spatial blending.

4.2. Comparison with high-angular resolution data

For six targets in our sample we compiled OH 1665 and 1667 MHz maser polarization data obtained with an angular resolution of $0''.16$ and a spectral resolution of $0.21\text{--}0.35 \text{ km s}^{-1}$ using MERLIN. The following sources G35.2-0.74N (Hutawarakorn & Cohen 1999), G34.3+0.2 (Gasprong et al. 2002), W75N (Hutawarakorn et al. 2002), NGC 7538 (Hutawarakorn & Cohen 2003), Cep A (Bartkiewicz et al. 2005) and AFGL2591 (Hutawarakorn & Cohen 2005) were used to plot the circular and linear fluxes vs. total flux for all OH maser components (Fig. 8, top panel). The sources show large amounts of circular polarization; the mean m_c for individual sources ranges from 35% to 78% while the average is 56.4%. Within errors, the circularly polarized flux exactly follows the total flux. One can conclude that the degree of circular polarization of OH maser components observed with MERLIN does not differ significantly from that obtained with the NRT. The MERLIN data, like the NRT data, show a large scattering of the flux of linearly polarized emission. However, due to a spectral resolution worse than ours by a factor of 3–5, MERLIN missed narrow features.

VLBI observations with an angular resolution of a few milliarcseconds and a spectral resolution of 0.5 kHz provide

polarization data free of spatial and spectral blending. Figure 8 (bottom panel) shows a plot of the polarized fluxes versus total flux of OH 1665 MHz components in W3(OH) (Wright et al. 2004a). In general, total polarization and circular polarization are closely tied. The linear polarization is weak and a large dispersion of the linear flux is seen. We conclude that the VLBA data well confirm the trend observed in the MERLIN and NRT data. Thus the statistical relationships for polarization properties of OH masers are well determined with the NRT data taken with high spectral resolution.

4.3. Linear polarization

4.3.1. Observational constraints

The present data provide evidence for a plethora of linearly polarized features in OH masers in our sample. Nearly half of the features identified in the I Stokes parameter spectra show linear polarization. It is in contrast with old data where linear polarization was rarely detected (see Cohen 1989, for a review). As the mean line-width of linear polarization features is 0.26 km s^{-1} it is likely that in older observations the emission was smeared by the lack of spectral resolution. The effect of this factor is clearly seen when one compares the linear polarization spectra of source G109.87+2.12 (alias Cep A) taken with the NRT and those obtained with a spectral resolution of 0.35 km s^{-1} with MERLIN (Bartkiewicz et al. 2005, their Fig. 1). We argue that differences due to non-simultaneous observations and angular resolution should be much smaller than those resulting from spectral resolution.

The OH maser emission tends to be blended in the NRT observations. This is why we have selected only about 9% of features with linear polarization for a detailed analysis. These features do not show deviations from a Gaussian shape. The difficulty with Gaussian fitting also occurs in VLBI data; for instance in source W3(OH) at 1665 MHz of the 211 components detected, 87 failed to be fitted with a Gaussian profile shape (Wright et al. 2004a). Their spectral resolution was only slightly worse than ours.

4.3.2. Internal Faraday rotation

Internal Faraday rotation was proposed as an important mechanism that may destroy linear polarization (Goldreich et al. 1973; Fish & Reid 2006). The existence of several linearly polarized features does not imply that this mechanism is not effective in our sources. We observe objects of a wide range of OH polarization properties; at the extreme, G13.72-0.52, highly linearly polarized emission is detected while in G213.71-12.60 linear polarization is very low. This suggests that Faraday rotation differs significantly among our sources. Furthermore, in several objects the polarization parameters vary rapidly across the spectrum, suggesting the differentiation of Faraday rotation in various parts of the same source.

The calculations by Nedoluha & Watson (1990) suggest that linear polarization can vanish due to the overlap of different Zeeman components producing unpolarized emission. Our observations show considerable amounts of unpolarized emission in some linearly polarized features. Therefore this mechanism can be efficient in some of the OH sources. However, it fails to explain the presence of unpolarized emission in a separated Zeeman pair where the components do not overlap (Wright et al. 2004a).

Fig. 8. Polarized flux versus total flux for the maser components at 1665 and 1667 MHz (*top*) in six sources observed with MERLIN (Hutawarakorn & Cohen 1999, 2002, 2005; Gasiprongs et al. 2002; Bartkiewicz et al. 2005) and (*bottom*) in W3(OH) observed with the VLBA (Wright et al. 2004a). Note that the data plotted are the fluxes of maser components from MERLIN and the fluxes of spots in all spectral channels from VLBA. Symbols show the circularly (black circle) and linearly (red cross) polarized flux densities. The dashed blue lines indicate degrees of polarization of 100% and 10% from top to bottom.

4.3.3. Polarization position angle

The main results of our statistical analysis of the sample of 46 unblended features of strong S_L and/or high m_L can be summarized as follows: (i) drifts of χ angle across the profile are common and can be fitted by a linear relation in many cases; (ii) the amplitude of the χ variations decreases with increasing S_L .

Large changes in the polarization position angle across OH maser features can be deduced from very early observations (Manchester et al. 1970). In their source G284.2–0.8 a 1665 MHz feature near -27 km s^{-1} shows characteristic changes in the Stokes Q and U parameters implying a drift of the χ angle. They also reported four sources with very narrow features of the Stokes parameters Q and U unresolved with a 0.18 km s^{-1} resolution. Goldreich et al. (1973) have explained the drift in χ angle by magnetorotation. For off-resonance amplification, the plane of linear polarization rotates due to the different indices of refraction for the right-handed (and left-handed) circularly polarized waves. This effect depends on the frequency offset from resonance and is most important for unsaturated radiation. For a typical set of parameters of the maser medium of $B = 10 \text{ mG}$, $v_k = 0.5 \text{ km s}^{-1}$ and a 4 km s^{-1} shift from resonance a differential rotation of 0.025 radians per kHz is produced over one optical depth (Goldreich et al. 1973). Here B is the strength of the magnetic field and v_k is the kinetic velocity of the gas. If one assumes that an optical depth of ~ 25 is typical for OH masers (e.g. Cohen 1989) i.e. the gain factor is of order 10^{10} , then the rate of χ angle is $0.6 \text{ radian kHz}^{-1}$. This value is perfectly consistent with the mean rate of the χ angle of $0.52 \text{ radian kHz}^{-1}$ ($86.5^\circ/0.6 \text{ km s}^{-1}$) that we observe (Table 3).

The calculations of OH maser profiles as a function of the velocity difference through the maser (which causes the overlap of Zeeman components) for a set of the physical parameters such as optical depth and the angle θ between the magnetic field and the line of sight (Nedoluha & Watson 1990) demonstrated that

at large θ , σ -components contain comparable amounts of linearly and circularly polarized emission. The linear polarization is not eliminated in favour of circular polarization. The intensities of the Stokes Q , U and V components vary rapidly depending on the various parameters of the models, so that drift in the polarization angle is easily produced. The presence of significant Faraday rotation does not destroy the large component of the linear polarization that arises for $\theta > 60^\circ$ without destroying circularly polarized emission (Nedoluha & Watson 1990).

We conclude that the behaviour of the polarization position angle observed in our data is well explained by the mechanism of magnetorotation. The propagation of the σ components in regions with a velocity gradient across the OH transition when the Zeeman splitting is comparable to the local thermal line-width appears as a plausible cause of the narrow profiles observed. The detailed modelling of the χ angle behaviour across narrow profiles from the interferometric polarization data appears to be a useful tool to constrain the model parameters.

4.3.4. Comparison with VLBI data

High spectral resolution (0.5 kHz) VLBI data are only published for W3(OH) (Wright et al. 2004a). They found only one bright 1667 MHz feature near -44.45 km s^{-1} where the polarization angle varies gradually through 90° across the line profile (Wright et al. 2004b). This is well seen in the NRT spectra (Fig. C.1, *online*); the profile is obviously blended and the χ angle shows a drift of amplitude of $\sim 110^\circ$. Wright et al. (2004b) reported a 1665 MHz feature near -45.95 km s^{-1} where the polarization angle changes little with velocity. The NRT spectrum well confirms this behaviour (Fig. C.1, *online*). Their general conclusion is that polarization angles where they are reliable are generally stable across the maser line shape (Wright et al. 2004b). However, their suggestion that the variations of χ angle are related to changes in the magnetic field direction with the propagation length of the maser is poorly consistent with the prevalence of χ angle variations in the NRT spectra. There are also several example sources that show organized magnetic fields (e.g. Fish & Reid 2006).

We note that W3(OH) is one of the brightest sources in the sample and the lack of χ angle drift or its small amplitude variations appears to be consistent with the model predictions by Nedoluha & Watson (1990, e.g. their Fig. 3) where the oscillations in the Stokes Q and U spectra are less pronounced for high gain, strongly saturated OH masers than for weaker unsaturated sources. If we assume that weak OH features are due to less saturated amplification, then the trend visible in the model results are fully consistent with that observed in Fig. 6.

4.4. Elliptical polarization

The NRT observations revealed that, in all sources, the linear polarization is always associated with some fraction of circular polarization, i.e. only elliptically polarized emission was detected. In principle, the linear polarization can be produced by both π - and σ -components of the Zeeman pattern. However, the VLBI data suggest that the linearly polarized emission is produced by σ -components (e.g. Garcia-Barreto et al. 1988; Fish et al. 2003). There is a scarcity of unambiguous detections of π -components (Hutawarakorn et al. 2003; Fish & Reid 2006; Slysh et al. 2002). Therefore, in most cases, the electric vector of a linearly polarized feature is perpendicular to the direction of the magnetic field projected on the plane of the sky. The presence of linearly polarized features with an admixture of circular emission in the

NRT spectra may suggest that some of them are produced by π -components. Fish & Reid (2006) have speculated that almost all π -components acquire a circular polarization due to the superposition of two masing clumps along the line of sight; if the emission from a π -component feature intersects a region of OH appropriately shifted in velocity, it may stimulate emission in a σ mode. Since the Zeeman splitting of the 1665 and 1667 MHz transitions is respectively 1.64 kHz and 0.98 kHz for a 1 mG magnetic field, the amount of circular polarization added by this process should be different at 1665 and 1667 MHz; i.e. a larger velocity gradient is required at 1665 MHz to align σ - and π -components. Future VLBI observations of carefully selected sources in our sample may help to test this hypothesis.

5. Conclusions

Sensitive and high spectral resolution observations of the 1665 and 1667 MHz OH masers from a sample of 99 star-forming regions have provided new information on the polarization patterns.

The 1665 and 1667 MHz lines were detected in 98 and 81 sources, respectively. Circularly polarized features were found in all of these sources, while linearly polarized features were detected in 80% and 62% of the targets at 1665 MHz and 1667 MHz, respectively.

Generally the maser features are elliptically polarized; the degree of linear polarization is usually low ($<15\%$), but in some features can be as high as 50–80%, whereas the degree of circular polarization is usually high ($>15\%$). The linearly polarized features are usually narrow ($<0.4 \text{ km s}^{-1}$) and weak ($<4 \text{ Jy}$). The median degree of linear polarization of 16% of the both transitions is a factor of ~ 4 lower than that of circular polarization. The mean line-width at half-maximum for a sample of the linear polarization profiles well fitted with Gaussians is 0.26 km s^{-1} . We argue that insufficient spectral resolution and moderate sensitivity explain why only small degrees of linear polarization have been found so far in relatively narrow profiles.

The polarization position angle significantly varies across the profile with amplitude decreasing when the flux increases. The average amplitude is close to 90° . The variations of χ angle is reasonably explained when σ -components of the Zeeman pairs overlap due to a velocity gradient over the maser regions

and when they propagate off-resonance in not fully saturated masers.

A fair number of sources with high linear polarization and enough flux density are found to be appropriate for high-angular resolution studies. Some of the sources show features of peculiar behaviour which are worth being carefully studied.

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Appendix A: Table A.1**Table A.1.** Integrated polarization parameters of the OH maser emission.

Source	Epoch (mm/yy)	Line (MHz)	$S_i(I)$ (Jy km s ⁻¹)	$S_i(\text{LHC})$ (Jy km s ⁻¹)	$S_i(\text{RHC})$ (Jy km s ⁻¹)	$S_i(V)$ (Jy km s ⁻¹)	$S_i(p)$ (Jy km s ⁻¹)	Note
G0.375+0.041	04/03	1665	22.90	25.78	19.91	-2.87	2.77	
		1667	16.73	17.28	15.83	-0.36	0.77	
G0.547-0.852	04/03	1665	15.27	18.10	12.46	-2.82	0.07	
		1667	18.37	22.14	14.54	-3.75	0.79	
G0.658-0.043	05/03	1665	527.8	829.5	227.7	-300.6	10.10	
		1667	47.60	63.02	32.49	-15.33	1.03	
G2.143+0.010	05/03	1665	13.70	12.52	14.90	1.18	0.60	
		1667	1.15	0.59	1.77	0.56	0.0	
G6.049-1.447	05/03	1665	12.48	11.10	13.87	1.39	0.32	
		1667	1.02	1.03	1.00	0.0	0.0	
G9.622+0.195	05/03	1665	19.58	18.06	21.11	1.52	4.93	
		1667	12.05	14.83	9.30	-2.78	4.28	
G10.624-0.385	05/03	1665	21.37	17.14	25.21	4.23	11.00	
		1667	14.66	16.51	13.63	-1.72	4.45	
G10.96+0.02	04/05	1665	9.49	3.48	15.50	5.96	0.98	
G11.90-0.16	08/05	1665	3.56	5.57	1.66	-1.96	0.28	
		1667	0.90	1.02	0.69	-0.18	0.0	
G12.216-0.117	05/03	1665	10.27	9.64	10.71	0.64	2.46	
		1667	10.00	11.27	8.81	-1.18	1.43	
G12.21-0.09	10/05	1665	6.39	6.72	5.99	-0.28	1.30	
		1667	1.02	0.52	1.39	0.41	0.0	
G12.680-0.181	05/03	1665	46.30	60.29	32.30	-13.95	1.20	
		1667	18.19	21.04	15.47	-2.91	0.38	
G12.890+0.488	05/03	1665	7.56	9.10	6.04	-1.52	3.20	
		1667	1.37	1.66	1.02	-0.32	0.25	
G12.908-0.259	06/03	1665	163.0	135.2	190.8	27.97	31.78	
		1667	49.94	65.75	34.10	-15.83	7.97	
G13.72-0.52	10/05	1665	5.46	4.63	5.25	0.81	4.43	
		1667	1.63	1.23	2.07	0.27	0.0	
G16.58-0.05	09/05	1665	0.75	0.57	0.92	0.19	0.05	
		1667	0.30	0.40	0.18	-0.15	0.0	
G18.46-0.01	09/05	1665	5.15	2.70	7.60	2.48	0.96	
		1667	1.30	1.02	1.59	0.33	0.05	
G19.49+0.14	09/05	1665	6.20	5.89	6.73	0.52	1.36	
		1667	2.02	1.97	2.17	0.17	0.18	
G19.61-0.13	09/05	1665	1.31	0.96	1.68	0.35	0.33	
G20.08-0.14	07/04	1665	12.26	15.29	9.25	-3.01	0.25	
		1667	0.76	0.60	0.93	0.17	0.0	
G20.24+0.07	03/03	1665	5.30	2.70	7.82	2.66	0.59	
		1667	0.71	0.48	0.85	0.14	0.06	
G21.57-0.03	03/03	1665	0.23	0.05	0.42	0.19	0.0	
G22.34-0.16	06/03	1665	0.21	0.23	0.19	-0.02	0.07	
G22.35+0.06	03/03	1665	0.59	0.0	1.19	0.56	0.0	
		1667	0.42	0.34	0.52	0.09	0.13	
G22.45-0.17	03/03	1665	6.52	8.59	4.41	-2.10	1.91	^a
G23.01-0.41	03/03	1665	6.23	4.28	8.03	1.81	0.64	
		1667	4.78	3.19	6.45	1.65	0.27	
G23.19-0.38	06/03	1665	1.60	1.07	2.13	0.53	0.18	
		1667	0.21	0.14	0.30	0.10	0.0	
G23.26-0.24	04/03	1665	1.00	0.59	1.46	0.40	0.09	
		1667	0.71	0.75	0.68	-0.07	0.18	
G23.39+0.19	07/04	1665	0.23	0.0	0.48	0.24	0.0	
		1667	0.17	0.06	0.28	0.11	0.07	
G23.44-0.18	04/03	1665	11.70	7.79	20.74	4.46	0.66	
		1667	5.36	4.38	6.68	0.90	0.05	^b
G23.49+0.08	08/05	1665	0.09	0.17	0.0	-0.07	0.0	
		1667	0.94	1.84	0.05	-0.89	0.14	
G23.97-0.11	09/05	1665	0.61	0.81	0.44	-0.20	0.0	
		1667	0.58	0.73	0.41	-0.16	0.36	
G24.15-0.01	10/05	1665	1.32	1.97	0.69	-0.64	0.0	
G24.51-0.05	04/03	1665	0.86	0.80	0.93	-0.10	0.0	
		1667	1.82	1.45	2.18	-0.35	0.0	

Table A.1. continued.

Source	Epoch (mm/yy)	Line (MHz)	$S_i(I)$ (Jy km s ⁻¹)	$S_i(\text{LHC})$ (Jy km s ⁻¹)	$S_i(\text{RHC})$ (Jy km s ⁻¹)	$S_i(V)$ (Jy km s ⁻¹)	$S_i(p)$ (Jy km s ⁻¹)	Note
G24.79+0.09	04/03	1665	8.79	4.90	12.61	3.76	2.19	
		1667	2.13	2.16	2.03	0.41	0.0	<i>b</i>
G25.71+0.04	06/04	1665	8.86	10.72	6.94	-1.95	1.16	
		1667	1.99	2.59	1.41	-0.54	0.10	
G25.83-0.18	09/07	1667	0.29	0.15	0.48	0.18	0.16	
G27.22+0.14	09/04	1665	1.48	0.46	2.51	1.02	0.48	
		1667	0.23	0.23	0.22	0.0	0.0	
G28.15+0.00	10/05	1665	3.34	4.40	2.31	-1.02	0.27	
		1667	0.09	0.07	0.10	0.04	0.0	
G28.199-0.048	05/03	1665	38.89	37.85	39.92	1.04	0.69	
		1667	6.92	6.12	7.67	0.80	0.05:	
G28.40+0.07	12/05	1665	1.03	1.10	0.92	-0.17	0.0	
		1667	0.07	0.0	0.15	0.08	0.0	
G28.82-0.25	09/04	1665	9.37	7.47	11.32	1.90	1.15	
		1667	7.34	5.09	9.46	2.27	0.64	
G28.82+0.37	09/05	1665	0.40	0.69	0.05	-0.33	0.03	
G29.86-0.05	11/05	1665	2.53	2.66	3.52	0.38	1.15	<i>b</i>
G30.20-0.17	06/03	1665	1.10	1.00	1.35	0.16	0.15	
		1667	0.90	1.17	0.61	-0.27	0.00	
G30.589-0.044	05/03	1665	18.58	17.84	19.35	0.66	0.31	
		1667	12.15	11.80	12.48	0.32	0.41	
G30.703-0.069	05/03	1665	7.95	5.03	12.79	3.04	1.60	<i>b</i>
		1667	10.95	11.07	11.83	0.06	2.99	<i>b</i>
G30.79+0.20	09/05	1665	1.14	1.02	1.22	0.04	0.00	
		1667	0.35	0.26	0.37	0.13	0.0	<i>b</i>
G30.82-0.05	06/03	1665	5.20	6.77	3.48	-1.57	0.34	
		1667	1.75	2.48	0.73	-0.84	0.12	<i>b</i>
G30.82+0.27	06/03	1665	10.20	6.93	13.47	3.27	0.88	
		1667	2.86	2.32	3.30	0.55	0.0	
G30.89+0.17	09/05	1665	0.76	0.87	0.15	-0.39	0.0	
		1667	0.27	0.27	0.28	0.02	0.0	
G31.06+0.09	09/05	1665	3.28	3.43	3.52	0.20	0.21	
		1667	3.86	3.46	4.00	0.25	0.0	
G31.27+0.06	09/05	1665	1.81	3.12	0.64	-1.33	0.28	
		1667	1.00	1.71	0.39	-0.74	0.0	
G31.41+0.31	09/04	1665	7.36	7.60	7.12	-0.16	0.84	
		1667	31.33	30.07	32.60	1.26	2.02	
G32.05+0.06	06/03	1665	3.00	2.16	3.88	0.86	0.0	
		1667	0.75	0.95	0.48	-0.14:	0.0	
G32.74-0.08	04/05	1665	5.95	7.04	4.85	-1.17	0.38	
		1667	2.75	2.95	2.56	-0.16	0.30	
G32.98+0.04	04/05	1665	1.04	0.66	1.38	0.32	0.0	
		1667	0.81	0.51	1.07	0.50	0.05	
G33.13-0.09	07/04	1665	19.29	24.57	13.96	-5.33	1.63	
		1667	2.23	2.36	2.12	-0.12	0.0	
G33.39+0.03	10/05	1665	0.69	1.05	0.34	-0.36	0.0	
G33.64-0.21	04/05	1665	4.77	3.37	6.10	1.32	2.13	
		1667	1.64	0.78	2.50	0.86	0.36	
G34.25+0.16	03/03	1665	50.75	33.75	68.04	17.02	10.72	
		1667	64.60	87.83	41.71	-23.94	29.03	<i>b</i>
G35.02+0.35	03/03	1665	20.28	14.95	25.50	5.31	6.37	
		1667	1.05	0.95	1.17	0.10	0.0	<i>b</i>
G35.197-0.743	05/03	1665	13.71	11.35	16.11	2.37	2.74	
		1667	1.36	1.36	1.33	0.03	0.27	
G35.200-1.736	05/03	1665	9.19	13.47	5.36	-3.97	1.15	<i>b</i>
		1667	4.08	7.99	3.11	-3.49	0.58	<i>b</i>
G35.79-0.17	07/04	1665	0.68	0.66	0.59	-0.08	0.0	
		1667	0.42	0.70	0.11	-0.25	0.06	
G37.55+0.19	04/03	1665	1.32	1.82	0.82	-0.56	0.0	
		1667	2.26	2.67	1.86	-0.36	0.0:	
G38.03-0.30	03/03	1665	0.36	0.31	0.46	0.10	0.22	<i>a</i> , <i>b</i>
G40.42+0.70	10/05	1665	6.74	3.40	10.08	3.33	0.28	
		1667	0.19	0.15	0.21	0.15	0.0	
G40.62-0.14	09/04	1665	70.91	82.32	59.43	-11.37	45.21	
		1667	14.52	17.43	11.64	-2.88	2.10	

Table A.1. continued.

Source	Epoch (mm/yy)	Line (MHz)	$S_i(I)$ (Jy km s ⁻¹)	$S_i(\text{LHC})$ (Jy km s ⁻¹)	$S_i(\text{RHC})$ (Jy km s ⁻¹)	$S_i(V)$ (Jy km s ⁻¹)	$S_i(p)$ (Jy km s ⁻¹)	Note
G43.03-0.45	03/05	1665	3.08	2.77	3.32	0.23	1.33	
		1667	2.34	2.71	1.98	-0.37	0.10	
G43.165-0.028	09/05	1665	497.7	593.5	409.6	-69.46	21.63	^b
		1667	108.0	138.0	79.0	-31.74	9.49	^b
G43.796-0.127	06/03	1665	86.65	81.56	91.62	5.31	23.57	
		1667	5.21	5.62	4.76	-0.40	0.46	
G43.89-0.78	08/05	1665	0.26	0.12	0.45	0.25	0.0	
		1667	0.71	1.17	0.22	-0.45	0.0	
G45.071+0.134	06/03	1665	75.07	52.48	97.67	22.56	8.99	
		1667	12.18	14.93	9.20	-2.92	0.71	
G45.465+0.047	05/03	1665	34.13	48.81	19.63	-14.56	4.27	
		1667	3.59	3.03	3.94	0.37	0.31	^b
G45.472+0.134	05/03	1665	12.03	22.58	1.67	-10.56	1.58	^b
		1667	2.67	3.13	0.87	-1.59	0.34	^b
G49.488-0.387	04/03	1665	207.9	144.5	275.1	66.10	3.75	^{b, c}
G53.14+0.07	08/05	1665	0.41	0.0	0.81	0.39	0.0	
G59.78+0.06	08/05	1665	0.81	0.73	0.87	0.07	0.50	
G60.57-0.19	04/03	1665	0.82	1.08	0.52	-0.28	0.0	
G69.54-0.98	03/03	1665	31.21	29.52	32.90	1.68	7.56	
		1667	1.41	1.24	1.57	0.14	0.21	
G70.293+1.601	04/03	1665	32.47	40.54	24.46	-7.97	0.88	
		1667	5.37	7.31	3.96	-2.20	0.59	^b
G71.52-0.38	03/03	1665	0.32	0.0	0.54	0.27	0.0	
		1667	0.16	0.0	0.31	0.16	0.0	
G75.77+0.34	08/05	1665	97.50	58.33	136.7	39.26	9.92	
		1667	74.36	43.32	104.4	30.61	9.57	^b
G78.12+3.64	06/04	1665	1.94	0.79	2.78	0.84	0.12	
G80.87+0.42	03/03	1665	8.83	8.36	9.28	0.45	1.22	^a
G81.87+0.78	02/06	1665	965.8	1462.	469.7	-495.9	759.1	
		1667	8.76	8.60	9.16	0.42	0.58	
G90.92+1.51	09/05	1665	0.79	0.48	1.10	0.31	0.46	
		1667	0.08	0.17	0.0	-0.09	0.0	
G98.04+1.45	08/05	1665	4.01	1.91	6.06	2.12	0.35	
		1667	0.13	0.05	0.22	0.07	0.0	
G109.87+2.12	09/04	1665	31.15	45.32	16.96	-14.20	3.51	
		1667	9.55	14.92	4.16	-5.37	1.13	
G111.53+0.76	02/05	1665	12.87	14.93	11.27	-1.79	2.86	
		1667	3.37	3.17	3.26	0.04	0.10	^b
G133.95+1.06	01/04	1665	477.8	513.3	442.2	-35.60	134.4	
		1667	36.71	49.14	24.32	-12.41	10.74	
G173.48+2.43	02/05	1665	1.70	2.37	0.90	-0.75	0.12	
		1667	0.40	0.52	0.27	-0.13	0.0	
G174.20-0.08	05/05	1665	0.61	0.41	0.67	0.18	0.0	^a
G183.35-0.58	09/05	1665	0.59	0.13	1.12	0.52	0.03	
		1667	0.26	0.08	0.44	0.13	0.0	
G188.95+0.89	06/05	1665	0.83	0.48	1.13	0.31	0.12	
		1667	0.37	0.21	0.58	0.22	0.05	
G196.454-1.677	04/04	1665	4.62	6.83	2.38	-2.22	0.44	^a
G213.71-12.60	02/05	1665	10.64	5.30	16.04	5.37	0.39	^b
		1667	2.21	2.34	3.07	0.08	0.0	^b
G232.62+1.00	04/04	1665	2.86	3.23	2.46	-0.38	1.88	
		1667	0.10	0.12	0.08	-0.02	0.05	

^a Weak emission (≤ 0.3 Jy at peak) at 1667 MHz; ^b values derived may be uncertain by 10–20% due to poor baseline; ^c 1667 MHz line heavily blended.

Appendix B: Table B.1**Table B.1.** Sources with highly linearly polarized features.

Source	Line (MHz)	V_p (km s ⁻¹)	S_L (Jy)	m_L (%)	χ (deg)	m_C (%)	m_T (%)	References
G9.622+0.195	1667	1.04	1.44	72.7	-25.2	3.3	72.8	1
		6.05	0.57	67.3	58.6	-53.4	85.9	
		7.14	2.95	56.4	-38.3	-65.8	86.7	
G10.624-0.385	1665	-2.24	27.6	74.0	64.3	53.2	91.2	1
	1667	-1.96	12.2	50.4	86.5	80.1	94.6	
G12.21-0.09	1665	22.16	0.60	58.9	-86.6	58.8	83.2	
G12.890+0.488	1665	31.59	0.53	87.3	-63.9	-14.6	88.5	
		32.76	4.96	76.7	88.2	-8.9	77.2	
G12.908-0.259	1665	40.64	9.97	60.1	-7.7	28.3	66.4	
G13.72-0.52	1665	48.39	14.9	92.7	24.0	11.4	93.4	
G19.49+0.14	1665	20.38	2.93	62.9	74.3	7.1	63.2	
G19.61-0.13	1665	54.56	0.53	69.4	47.0	12.5	70.5	
		55.04	0.89	71.3	-10.5	-15.6	73.0	
G20.24+0.07	1665	73.10	0.95	62.2	-62.7	23.7	66.6	
G22.45-0.17	1665	25.08	1.56	51.8	79.3	-28.1	58.9	
G23.26-0.24	1667	55.08	0.66	85.4	-76.7	-10.3	86.0	
G23.44-0.18	1665	100.87	0.53	69.7	-18.0	20.1	72.5	
G23.97-0.11	1667	65.65	0.51	95.7	-19.9	-21.4	98.1	
G24.79+0.09	1665	109.39	0.78	95.9	-12.1	-2.6	95.9	
		110.97	4.34	57.2	57.4	56.3	80.2	
G25.71+0.04	1665	98.50	1.54	78.7	86.3	44.9	90.6	
G25.83-0.18	1667	92.96	0.70	60.5	-49.5	78.1	98.8	
G28.82-0.25	1665	83.89	1.05	65.6	-73.8	18.3	68.1	
G30.703-0.069	1665	90.96	2.90	57.1	69.9	68.0	88.8	
		85.40	1.37	87.0	-50.1	19.6	89.2	
		96.38	0.56	55.6	-77.2	-39.8	68.4	
		96.99	0.59	79.7	28.9	-61.4	100.6	
		106.91	0.52	62.4	35.2	-46.2	77.6	
G31.41+0.31	1665	94.90	1.33	74.9	13.6	50.6	90.4	
G33.64-0.21	1665	60.07	2.18	77.2	30.9	-14.1	78.5	
		60.48	3.33	69.3	-80.6	13.9	70.7	
G34.25+0.16	1667	60.41	0.79	50.2	-79.2	34.7	61.0	1, 5
	1665	58.68	3.75	56.6	58.3	6.9	57.0	
		60.61	1.16	67.2	-76.9	0.9	67.2	
	1667	57.59	5.10	52.9	58.8	-4.9	53.1	
		58.62	71.8	59.9	42.3	-36.5	70.1	
		25.01	0.73	90.9	77.1	-43.0	100.5	
G35.197-0.743	1665	26.04	1.51	76.1	-1.4	-34.4	83.5	6
		29.21	0.74	53.4	9.8	9.9	54.3	
G35.200-1.736	1665	41.90	1.32	51.9	82.1	26.3	58.2	
G40.62-0.14	1665	32.37	29.2	73.9	-1.7	-11.9	74.8	1
		32.65	130.7	74.0	-77.9	-26.1	78.5	
	1667	30.86	1.88	62.5	87.6	0.9	62.5	
		58.02	2.77	77.4	19.5	45.1	89.6	
G43.796-0.127	1665	44.37	20.7	79.0	63.8	-17.4	80.9	1
		44.99	2.54	87.3	-69.9	-45.6	98.5	
G45.472+0.134	1667	58.72	0.91	79.7	64.0	-34.7	86.9	
G59.78+0.06	1665	20.43	1.12	87.9	-48.9	11.0	88.6	
G69.54-0.98	1665	14.27	13.95	55.5	-38.5	25.1	60.9	1
G75.77+0.34	1665	-1.49	3.93	66.5	-83.2	12.3	67.6	1
G81.87+0.78	1665	0.26	1147.5	78.3	48.1	-62.3	100.1	1, 3, 7
		2.05	142.3	86.4	56.6	-23.8	89.6	
		11.32	14.3	68.8	-25.3	15.9	70.6	

Table B.1. continued.

Source	Line (MHz)	V_p (km s ⁻¹)	S_L (Jy)	m_L (%)	χ (deg)	m_C (%)	m_T (%)	References
G90.92+1.51	1665	-76.52	0.60	88.8	-48.2	-35.1	95.5	
G109.87+2.12	1665	-6.91	3.21	75.6	-78.0	-6.7	75.9	1, 4
G111.53+0.76	1665	-60.63	1.28	81.9	-60.6	49.3	95.6	1, 8
		-57.74	1.19	74.7	-7.4	3.0	74.8	
G133.95+1.06	1665	-47.41	135.9	98.9	65.4	-15.4	100.1	2, 9
	1667	-47.75	2.30	75.5	-47.7	-63.4	98.6	
		-44.26	16.9	65.6	-88.5	22.0	69.2	
G232.62+1.00	1665	21.63	4.81	90.3	-77.8	-8.5	90.7	
		22.17	1.14	53.2	-6.9	2.2	53.2	

References: for VLBI observations – (1) Fish et al. (2005); (2) Garcia-Barreto et al. (1988); (3) Slysh et al. (2002); for MERLIN observations – (4) Bartkiewicz et al. (2005); (5) Gasiprongs et al. (2002); (6) Hutawarakorn & Cohen (1999); (7) Hutawarakorn et al. (2002); (8) Hutawarakorn & Cohen (2003); (9) Wright et al. (2004a).

Appendix C: Figure C.1. Atlas of the Stokes parameters for OH spectra

Fig. C.1. Polarization spectra.

Fig. C.1. continued.

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Fig. C.1. continued.

Fig. C.1. continued.

Appendix D: Figure D.1. Highly variable OH sources

Fig. D.1. Variations of polarization spectra of the 1665 MHz maser in W75N. The $\sqrt{Q^2 + U^2}$ spectrum taken on 14/08/2005 is enlarged by a factor 400 (dashed line).