Polarimetric observations of OH masers in proto-planetary nebulae

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Abstract. The 1612 and 1667 MHz OH maser lines have been measured in all four Stokes parameters in 47 proto-planetary nebula (PPN) candidates. Out of 42 objects detected, 40 and 34 are 1612 and 1667 MHz emitters, respectively. The spectral extent of the 1667 MHz line overshoots that of the 1612 MHz line in about 80% of the targets. 52% and 26% of the 1612 and 1667 MHz sources, respectively, show linear polarization in at least some features. Circular polarization is more frequent, occurring in 78% and 32% of sources of the respective OH lines. The percentage polarization is usually small (<15%) reaching up to 50–80% in a few sources. Features of linearly polarized emission are usually weak (0.5–4 Jy) and narrow (0.3–0.5 km s⁻¹).

The 1612 and 1667 MHz OH maser lines have been measured in all four Stokes parameters in 47 proto-planetary nebula (PPN) candidates. Out of 42 objects detected, 40 and 34 are 1612 and 1667 MHz emitters, respectively. The spectral extent of the 1667 MHz line overshoots that of the 1612 MHz line in about 80% of the targets. 52% and 26% of the 1612 and 1667 MHz sources, respectively, show linear polarization in at least some features. Circular polarization is more frequent, occurring in 78% and 32% of sources of the respective OH lines. The percentage polarization is usually small (<15%) reaching up to 50–80% in a few sources. Features of linearly polarized emission are usually weak (0.5–4 Jy) and narrow (0.3–0.5 km s⁻¹).

The role of the magnetic field in the shaping of PPN has recently received a considerable attention. Chevalier & Luo (1994) proposed the magnetized wind-blown bubble model in which initially weak toroidal magnetic fields carried in a fast wind are strengthened and produce prolate and bipolar structures (e.g. Garcia-Segura et al. 1999; Matt et al. 2000). Soker (2002) argued that the magnetic field does not play a global role in the shaping of PPN but that the locally strong magnetic field may facilitate the maser amplification.

The presence of magnetic fields around AGB and late type stars has been proved by maser polarization studies (e.g. Kemball & Diamond 1997; Szymczak & Cohen 1997; Szymczak et al. 1998, 2001; Bains et al. 2003a). OH maser emission appears to be the best tracer of magnetic fields in the outer circumstellar regions providing information on the direction, strength and orientation of the fields.

OH masers have been found in several PPN candidates during the surveys of very cold IRAS sources (Likkel 1989; te Lintel Hekkert 1991; Hu et al. 1992; te Lintel Hekkert & Chapman 1996) and of radio continuum sources or young PNe (Zijlstra et al. 1989). Some PPN candidates with OH emission were identified on the basis of their irregular spectra with a velocity range over 50 km s⁻¹ (Zijlstra et al. 2004). Polarization properties of OH masers associated with PPNs are poorly...
known. Zijlstra et al. (1989) measured the circular polarization in 5 objects and a high percentage polarization (>80%) was found in IRAS17150–3754 at 1612 MHz. Another object with strongly circularly polarized emission in all OH lines was IRAS16342–3814 (te Lintel Hekkert & Chapman 1996). Miranda et al. (2001) reported that the PPN K3–35 shows strong circular polarization at 1667 MHz. However, nothing is known about the linear polarization of OH masers in PPNe.

In this study we describe the results of a full polarization survey of OH masers in 47 PPN candidates. With the full polarization data we wish to better understand the properties of the circumstellar material of PPNe and to see if there is evidence that the magnetic field can facilitate the development of axisymmetric morphology. Our data should help to choose the best candidates for mapping the magnetic fields with the aperture synthesis technique. This paper provides the first evidence for the dominance of the magnetic field components perpendicular to the long axis of proto-planetary nebula.

2. Observations

The 1612 and 1667 MHz lines of OH were observed with the upgraded Nançay Radio Telescope (NRT) (van Driel et al. 1996) in a series of observing runs between February 2002 and June 2003. At the OH frequencies, the half-power beamwidth of the telescope is 3.5' in the E–W direction and 19' in the N–S direction. At $\delta = 0^\circ$, the beam efficiency is 0.65 and the point source efficiency is 1.4 K Jy$^{-1}$. The system temperature is about 35 K.

The new focal system of the NRT consists of a dual-reflector offset Gregorian configuration fed by a corrugated horn. The horn itself is 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 from $-90^\circ$ to $+90^\circ$ from a rest position of $0^\circ$ (where the position angles of the electric vectors are 45° and 135°). The maximum level of the cross-polarization lobe is −22 dB. The linearly polarized signals are then up-converted, equalized in amplitude and phase and combined in a 7 GHz hybrid to yield right hand (RHC) and left hand (LHC) circularly polarized signals. The isolation of opposite circular polarizations is better than 20 dB. The signals of the four RF channels (the two linear polarizations without hybridization and the two circular polarizations) are then down converted and the four IF channels 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 readily obtained by rotating the feed box by 45° as is apparent from equations (2) and (3) below.

The gain of each polarization channel was measured with a noise diode at the beginning of each 3 min integration scan to $\pm 5\%$ in absolute value and to within $\pm 1\%$ in relative value.

A 8192 channel autocorrelator configured into eight banks of 1024 channels was used as spectrometer. The two OH transitions were simultaneously observed with a spectral resolution of 0.07 or 0.14 km s$^{-1}$. For a few sources, with an OH maser spectral extent greater than 60 km s$^{-1}$, the data were taken with a resolution of 0.28 km s$^{-1}$. The radial velocities were measured with respect to the local standard of rest. The two orthogonal linear polarizations and two opposite circular polarizations of each OH line were observed at feed box positions of 0 and 45°.

The typical integration time for each feed box position was about 20 min. The calibration of the instrumental polarization and of the polarization position angle was verified with regular observations of W3OH and OH17.7–2.0. The polarization characteristics of those secondary calibrators are known from interferometric observations (Garcia-Barreto et al. 1988). Bains et al. 2003). Moreover, the percentage of linear polarization and the position angle (PA, measured eastward from north) of the electric vector of the continuum source 3C286 were measured at 1400 MHz and found to be $8.5\pm0.5\%$ and $33\pm0\'$, respectively (Colom, private communication), in good agreement with published values (Brindle et al. 1972).

The four Stokes parameters were calculated for each velocity channel using the following equations:

$$I = S(0) + S(90) = S(RHC) + S(LHC)$$

$$Q = S(0) - S(90)$$

$$V = S(RHC) - S(LHC),$$

where $S(0)$, $S(90)$, $S(45)$ and $S(-45)$ are the line flux density at PAs of $0^\circ$, $90^\circ$, $45^\circ$ and $-45^\circ$, respectively. S(RHC) and S(LHC) are the line flux densities for right and left circularly polarizations, respectively. The linearly polarized flux density $p = \sqrt{Q^2 + U^2}$, fractional linear polarization $m_L = p/I$, fractional circular polarization $m_C = V/I$ and polarization position angle $\chi = 0.5\tan^{-1}(U/Q)$ were derived from the Stokes spectra. The uncertainties in the fractional linear polarization and the polarization position angle (McIntosh & Predmore 1993) are

$$\sigma_{m_L} = \frac{\sqrt{\sigma_I^2 + \sigma_Q^2}}{I}$$

and

$$\sigma_{\chi} = \frac{\sigma_Q}{\sqrt{2}p},$$

where $\sigma_I$, $\sigma_Q$ and $\sigma_p$ are the rms noises of the $I$, $Q$ and $p$ spectra, respectively. As discussed by Wardle and Kronberg (1974), the non-Gaussian probability distribution of the polarized electric vector may lead to systematic errors when the signal-to-noise ratio (SNR) is small. We have neglected this effect since we only considered emission features with a SNR greater than 5.

A typical $\sigma_I$ was about 35 mJy for 0.14 km s$^{-1}$ spectral resolution. Baseline subtraction was done by frequency switching. This mode introduces an error of less than 0.6% in the polarization parameters, as compared to the position switching mode. No correction for ionospheric Faraday rotation was applied to the data. The absolute uncertainty of the OH polarization measurements is less than 7%.

Each target was observed 3–5 times on an irregular basis to check the quality of polarization data rather than to study the
variability which is beyond the scope of the paper. Consistent polarization parameter measurements were obtained for all objects at epochs spanning 3-15 months. Data for one epoch are presented and analyzed here with the exception of section 5.3 where data from 2–5 observations are used to derive the polarization position angles. This procedure is of special value for sources with weak $p$ flux to improve the accuracy of polarization position angle estimates.

3. The sample

We selected 47 target sources from several surveys of OH masers of IRAS sources with dust temperatures between $\sim100$ K and $\sim200$ K. This range is typical for late AGB stars and early post-AGB heavily obscured by thick circumstellar envelopes only detectable in the infrared, as well as for post-AGB and young PN still associated with the infrared emission but with optically visible central stars of spectral types from M to B (Likkel 1989; Zijlstra et al. 1989; te Lintel Hekkert 1991; Hu et al. 1994; te Lintel Hekkert & Chapman 1996; Zijlstra et al. 2001). OH maser emission from those objects at one or more transitions is usually over 50 km s$^{-1}$ wide and significantly different from the conventional standard twin-peak AGB star OH 1612-MHz maser profile. Sometimes the red-shifted peaks are weak or absent. Some objects with a moderate OH velocity range of 20-30 km s$^{-1}$ are included because they have been revealed as bipolar nebulae by radio observations (e.g. W43A, K3-35). Our sample also contains some objects detected as OH masers during the surveys of known young PN or radio continuum sources (Zijlstra et al. 1989). We did not include PPN candidates lying in the directions of strong background OH confusion where the genuine OH emission of the source cannot be unambiguously resolved with the telescope beam. The well known OH supergiant stars with high outflow velocities are excluded from our list. The sample is confined to the objects with $\delta > -39^\circ$.

4. Results

Table 1 lists the objects observed and contains velocity ranges ($\Delta V$) and integrated flux densities ($S_i$) at 1612 and 1667 MHz. For sources with only the blue- or red-shifted emission detected the measured values of $\Delta V$ are denoted by asterisks while the presumed values of $\Delta V$, discussed below in section 4.6, are given in italics. For the non-detections we list the $3\sigma$ noise levels.

Figure 1 shows the 1612 MHz polarization spectra of OH17.7$-2.0$. Circularly and linearly polarized emission was detected in the blue- and red-shifted parts of the spectrum. The percentage of linear and circular polarization was generally lower than 8% and $\pm15\%$, respectively. We note that changes in the PA of linear polarization across the spectrum closely follow the pattern observed with MERLIN (Bains et al. 2003a). This result demonstrates that the NRT spectrum provides a reliable measure of the magnetic field orientation in this circumstellar envelope the structure of which was resolved with a $0.2^\prime$ beam. Furthermore, it suggests that the field orientation is stable over a period of about 2.5 years. Because our data were taken with a spectral resolution of a factor of 2.6 higher than that of MERLIN but with a sensitivity about a factor of 4.5 lower, the PA profile is noisier than that deduced from Bains et al. (2003a). The polarization spectra for the remaining sources for which the $p$ spectra contain at least one feature with SNR>5 are shown in Fig. A1.

4.1. Polarization statistics

Among the 42 objects detected, there are 32 objects with polarized (circular and/or linear) emission in at least one OH transition (Table 2). 23 sources show linearly polarized emission in either or both of the OH lines. Linearly polarized emission is always associated with circularly polarized emission. 10 out of 31 polarized objects at 1612 MHz show only circular polarization (Table 2). There is a higher probability of detecting linear polarization in the 1612 MHz line (21/40) than in the 1667 MHz line (9/34) (Tables 1 and 2).

The distribution of source counts versus integrated flux density (Fig. 2) demonstrates that polarized emission preferentially occurs in objects with strong emission; at 1612 MHz the average values of $S_i$ in polarized and non-polarized sources are 19.4 and 2.3 Jy km s$^{-1}$, respectively, whereas at 1667 MHz the corresponding values are 16.7 and 1.1 Jy km s$^{-1}$. Plot of $|V|$ and $p$ fluxes versus the total flux $I$ of the strongest peak for the whole sample (Fig.3) clearly shows that only one source with flux less than 0.8 Jy had detectable polarization. Below a flux density of about 2 Jy the polarized source counts are likely to be incomplete.
Table 1. The sample of OH PPN candidates.

| IRAS name | Other name | Epoch (JD−2450000) | Spectral resolution (km s\(^{-1}\)) | 1612 MHz | 1667 MHz |
|-----------|------------|---------------------|-----------------------------------|----------|----------|
|           |            |                     | \(\Delta V\) (km s\(^{-1}\)) | \(S_1\) (Jy km s\(^{-1}\)) | \(\Delta V\) (km s\(^{-1}\)) | \(S_1\) (Jy km s\(^{-1}\)) |
| 06530−0213 |            | 2411                | 0.14                              | <0.06    | <0.05    |
| 07331+0021 |            | 2461                | 0.07                              | 10.2     | 11.6     |
| 07399−1435 | OH231.8+4.2 | 2442                | 0.28                              | 106.0    | 3.0      |
| 08005−2356 |            | 2410                | 0.28                              | 32.0     | 3.2      |
| 16342−3814 | OH344.1+5.8 | 2758                | 0.14                              | 132.0    | 33.6     |
| 16559−2957 |            | 2432                | 0.14                              | <0.14    | <0.09    |
| 17079−3844 |            | 2502                | 0.07                              | <0.13    | <0.11    |
| 17103−3702 | NGC6302    | 2602                | 0.14                              | 210\(^{+}\) 5.6 | 10.0\(^{-1}\) 0.5 |
| 17150−3754 | OH349.4+0.2 | 2769                | 0.14                              | 2.8\(^{+}\)  (28.5) 4.2 | 31.5 53.9 |
| 17333+0151 | OH0.1+5.1  | 2495                | 0.14                              | 17.7     | 7.3      |
| 17253−2831 |            | 2370                | 0.14                              | 31.8     | 11.6     |
| 17347−3139 |            | 2314                | 0.14                              | 127.0    | 5.1      |
| 17371−2747 |            | 2502                | 0.14                              | 18.2\(^{+}\) 11.6 | 10.0\(^{-1}\) 0.3 |
| 17375−2759 |            | 2818                | 0.14                              | 15.6\(^{+}\) 5.7 | 13.8\(^{+}\) 1.4 |
| 17393−3000 |            | 2602                | 0.14                              | 44.4     | 11.6     |
| 17385−3332 | OH355.6−1.7 | 2530                | 0.28                              | 25.7     | 18.5     |
| 17393−2727 | OH0.9+1.3  | 2672                | 0.07                              | 32.1     | 199.2    |
| 17393−3004 |            | 2821                | 0.07                              | 62.5     | 30.7     |
| 17404−2713 | OH1.2+1.3  | 2672                | 0.14                              | 29.2     | 24.8     |
| 17423−1755 | HEN3-1475  | 2327                | 0.28                              | (24.3)   | 0.2      |
| 17433−1750 |            | 2628                | 0.28                              | 32.0     | 3.4      |
| 17436+5003 | HD161796   | 2383                | 0.07                              | <0.12    | <0.10    |
| 17443−2949 |            | 2820                | 0.14                              | 24.8\(^{+}\) 3.5 | 31.5\(^{+}\) 3.9 |
| 17516−2525 |            | 2432                | 0.14                              | 37.2     | 9.4      |
| 17579−3121 |            | 2683                | 0.14                              | 24.1     | 47.6     |
| 18016−2743 |            | 2419                | 0.14                              | 24.8     | 3.5      |
| 18025−3906 |            | 2558                | 0.14                              | 51.6     | 41.0     |
| 18052−2016 | OH10.1−0.1 | 2434                | 0.14                              | 63.0     | 17.0     |
| 18071−1727 | OH12.8+0.9 | 2421                | 0.14                              | 22.3     | 8.1      |
| 18091−1815 |            | 2436                | 0.28                              | 32.9     | 16.8     |
| 18095+2704 | OH53.8+20.2 | 2440                | 0.14                              | 20.8     | 0.4      |
| 18105−1935 |            | 2442                | 0.14                              | 21.8     | 8.5      |
| 18135−1456 | OH15.7+0.8 | 2694                | 0.07                              | 31.3     | 156.6    |
| 18266−1239 | OH19.2−1.0 | 2499                | 0.14                              | 37.7     | 76.2     |
| 18276−1431 | OH17.7−2.0 | 2326                | 0.14                              | 28.0     | 299.2    |
| 18450−0148 | W43A       | 2777                | 0.14                              | 16.2     | 37.9     |
| 18491−0207 |            | 2421                | 0.28                              | <0.20    | 132.0    |
| 18596−0315 | OH37.1−0.8 | 2430                | 0.14                              | 30.1     | 39.0     |
| 19067+0811 | OH42.3−0.1 | 2694                | 0.14                              | 35.3     | 74.3     |
| 19114+0002 | HD179821   | 2809                | 0.28                              | 55.3     | 297.5    |
| 19127−1717 |            | 2438                | 0.14                              | <0.17    | <0.12    |
| 19219+0947 | VY2-2      | 2775                | 0.07                              | 8.5\(^{+}\) 19.5 | 19.5 0.10 |
| 19255+2123 | K3-35      | 2420                | 0.07                              | 25.4     | 3.4      |
| 19343+2926 | M1-92      | 2421                | 0.14                              | 4.0\(^{+}\) (45.6) 0.4 | 46.0 7.9 |
| 22036+5306 |            | 2335                | 0.28                              | 60.7     | 14.7     |
| 23321+6545 |            | 2447                | 0.14                              | <0.14    | 20.7     |

\(^{1}\) width of single feature or complex; Absorption features: \(^{2}\)−0.1 Jy at \(-37.8\text{ km s}^{-1}\), \(^{3}\)−0.2 Jy at \(-7.2\text{ km s}^{-1}\), \(^{4}\)−0.4 Jy at \(1.2\text{ km s}^{-1}\), \(^{5}\)−0.1 Jy at \(4.8\text{ km s}^{-1}\), \(^{6}\)−0.1 Jy at \(30.7\text{ km s}^{-1}\).

4.2. Strongly polarized sources

There are 7 OH PPN candidates in the sample with strongly polarized features (Table 2 and Fig. A1). The most prominent is IRAS16342−3814 containing, in the blue-shifted part of the 1612 MHz spectrum, several polarized features with \(|m_c|>70\%\) and \(m_L=14\%\). The 1612 MHz features of IRAS19255+2123 have even higher polarization percentages (\(|m_c|>80\%, m_L=40\%)\. IRAS08005−2356 shows considerable polarization at 1612 MHz (\(|m_c|=37\%, m_L=51\%) near \(-0.3\text{ km s}^{-1}\). In the 1612 MHz line strong circular polariz-
4.3. Evidence for complex magnetic fields

The data for OH17.7−2.0 (Fig.1) indicate that the measurements of the position angles of polarization vectors are fully consistent with those obtained using an interferometric array. In this source, a large-scale regular magnetic field structure was revealed by Bains et al. ([2003a]). It is possible that sources with considerable changes in \( \chi \) across the \( p \) profile have structured magnetic fields. In our sample the source IRAS17393−2727 appears as the best candidate to map a complex magnetic field; a \( p \) flux density higher than 1 Jy is seen over a velocity extent of greater than 6 km s\(^{-1}\), \( \chi \) varies in a characteristic way from \(-90^\circ\) to \(90^\circ\) (Fig. A1). Two further objects, IRAS07399−1435 at 1667 MHz and IRAS19067+0811 at 1612 MHz, with linearly polarized flux densities of about 1 Jy, could also have structured fields. Evidence for large variations in the PA of polarization vectors across the \( p \) profile is seen for IRAS16342−3814, IRAS17150−3224 and IRAS1404−2713 at 1612 MHz. In these targets, however, the linearly polarized flux is quite weak (usually less than 0.5 Jy) and the width of \( p \) features is as narrow as 0.3 km s\(^{-1}\).

4.4. Zeeman splitting

At 1612 MHz we found S-shaped features in the \( V \) spectra of IRAS07331+0021 and IRAS18266−1239 (Fig. 4). It is possible that they arise due to the Zeeman effect, which could be confirmed by high angular resolution observations. Assuming that for the \( \sigma \) components an average velocity splitting of 0.236 km s\(^{-1}\) is produced by a magnetic field of strength of 1 mG, the corresponding strength of magnetic field along the line of sight is \(-1.07\pm0.24\) mG for IRAS07331+0021 and \(-2.57\pm0.14\) mG for IRAS18266−1239. A negative sign indicates a field pointing towards the observer. These estimates are consistent with the field strengths measured in AGB stars and other PPN candidates (Szymczak et al. [1998] Bains et al. [2003a]).

4.5. Depolarization

A reduced degree of polarization for bright \( I \) features is seen in some objects in the sample. Figure 5 shows the percentage linear polarization as a function of the normalized total flux density for 6 objects with \( p \) flux seen in at least 35 spectral channels at 1612 MHz. Decreasing trends are clearly visible for IRAS17393−2727, IRAS18276−1431 and IRAS19067+0811. The depolarization effect can be described by a power law of the form \( m_L = A\tau^\alpha \) where \( \alpha = -0.57 \pm 0.05 \) effectively characterizes all the data for these three sources. This trend cannot be accounted for by the uncertainties in the fractional polarization. Observations of these sources with different spectral resolutions (usually 0.07 or 0.14 km s\(^{-1}\)) have no significant influence on the decreasing trend. Sources IRAS07331+0021, IRAS18135−1456
Table 2. The strongest polarized OH features in PPN candidates.

| IRAS name          | Line (MHz) | $V_\perp$ (km s$^{-1}$) | $m_C(\sigma)$ (%) | $V_\parallel$ (km s$^{-1}$) | $m_L(\sigma)$ (%) | $\chi(\sigma)$ |
|--------------------|------------|--------------------------|--------------------|-----------------------------|--------------------|---------------|
| 07331+0021         | 1612       | 32.3                     | 5.0(1.1)           | 32.5                        | 12.3(0.4)          | -31.6(1.6)    |
| 07399−1435         | 1667       | 19.0                     | 2.7(0.2)           | 20.4                        | 10.7(0.4)          | 54.2(2.4)     |
| 08005−2356         | 1612       | -0.3                     | -37.0(1.5)         | -0.4                        | 51.3(5.1)          | 30.5(5.7)     |
| 16342−3814         | 1612       | -7.3                     | -70.8(2.1)         | -7.5                        | 14.2(1.9)          | -43.8(10.7)   |
| 1667               | 9.8        | 13.8(1.6)                | -4.2              | 26.5(4.0)                   | -61.8(13.0)        |
| 17150−3754         | 1612       | -125.3                   | -84.2(6.3)         |                             |                   |               |
| 17150−3224         | 1612       | 25.0                     | -5.2(0.8)          | 24.9                        | 9.0(1.0)           | 79.8(2.4)     |
| 1667               | 26.0       | 8.6(1.4)                 | 25.9              | 4.2(0.4)                    | -68.2(5.6)         |
| 17253−2831         | 1612       | -71.6                    | -2.9(0.3)          |                             |                   |               |
| 17347−3139         | 1612       | -23.1                    | 11.9(2.4)          |                             |                   |               |
| 17375−2759         | 1612       | 22.2                     | -7.1(2.6)          | 23.8                        | 16.1(2.0)          | -17.5(8.3)    |
| 17375−3000         | 1612       | -35.6                    | -9.5(1.2)          |                             |                   |               |
| 17385−3332         | 1612       | -245.6                   | -7.0(2.3)          | -242.3                      | 4.1(1.1)           | 19.6(12.1)    |
| 17393−2727         | 1612       | -120.5                   | 12.9(0.8)          | -123.5                      | 4.2(0.2)           | -60.8(3.3)    |
| 17393−3004         | 1612       | -124.5                   | -13.5(3.2)         | -124.5                      | 24.3(4.3)          | 6.6(13.8)     |
| 17404−2713         | 1612       | 16.1                     | -29.6(2.6)         | -27.4                       | 11.4(0.5)          | -23.3(5.5)    |
| 17443−2949         | 1612       | -15.4                    | -12.8(1.0)         |                             |                   |               |
| 17579−3121         | 1612       | -0.2                     | -9.3(1.1)          | 22.3                        | 3.0(0.1)           | -34.5(5.5)    |
| 18016−2743         | 1612       | 61.4                     | 12.0(2.8)          | 61.4                        | 15.9(2.7)          | 0.2(10.6)     |
| 18025−3906         | 1612       | -129.1                   | 23.1(3.0)          |                             |                   |               |
| 18052−2016         | 1612       | 79.5                     | 5.7(0.4)           |                             |                   |               |
| 18071−1727         | 1612       | 17.6                     | 17.0(0.7)          |                             |                   |               |
| 18091−1815         | 1612       | 10.6                     | -5.4(7.0)          |                             |                   |               |
| 18105−1935         | 1612       | 8.5                      | -7.0(0.4)          |                             |                   |               |
| 18135−1456         | 1612       | 13.5                     | 3.8(0.2)           | 13.1                        | 5.1(0.2)           | -21.2(3.8)    |
| 18266−1239         | 1612       | 13.9                     | -7.6(0.6)          |                             |                   |               |
| 18276−1431         | 1612       | 57.5                     | -2.6(0.5)          | 57.8                        | 5.6(0.5)           | 71.9(4.3)     |
| 1667               | 74.3       | -15.4(1.3)               | 72.6              | 72.0(9.0)                   | 80.4(7.0)          |
| 18450−0148         | 1612       | 40.5                     | 11.3(1.8)          | 40.3                        | 2.4(0.2)           | 63.3(5.2)     |
| 18596+0315         | 1612       | 40.6                     | 21.1(1.2)          | 26.4                        | 19.0(2.4)          | 77.4(6.2)     |
| 19067+0811         | 1612       | 99.4                     | -11.0(2.4)         | 76.9                        | 4.7(0.5)           | -3.1(4.4)     |
| 19114+0002         | 1612       | 75.6                     | 2.1(0.6)           | 76.5                        | 69.9(18.9)         | 87.9(4.3)     |
| 19219+0947         | 1612       | 123.8                    | -6.5(0.2)          | 123.7                       | 7.5(0.1)           | -88.4(0.5)    |
| 19255+1213         | 1612       | 124.9                    | -8.6(0.1)          | 124.9                       | 1.8(0.1)           | -86.9(2.6)    |
| 22036+5306         | 1612       | -61.9                    | 6.6(0.8)           | -62.1                       | 4.0(0.4)           | 3.9(10.0)     |
| and IRAS19114+0002  |           |                          |                   |                             |                   |               |

In looking for possible causes of depolarization it is worth noting that the extremely low dispersion ($18.1 - 2.3^\circ$) in the position angle of polarization vectors among the sources which do not show the depolarization effect, compared with $4.3 - 12.5^\circ$ dispersion among the objects with depolarization (Fig. A1). This suggests that the depolarization effect depends on the global magnetic field structure in the envelope; the directions of the projected field in the sources without depolarization are well aligned along specific PAs, whereas in the sources with depolarization the field geometry appears to be much more complex.

In the case of circularly polarized emission we note strong depolarization in IRAS17393−2727 and IRAS19067−0811. No depolarization is seen in IRAS18276−1431 and in the other three sources not showing linear depolarization. This suggests that mechanisms for depolarization may be common to linear and circular emission.
4.6. Overshoot of 1667 MHz spectral extent

There are 20 objects with well detected blue- and red-shifted parts of spectra at 1612 and 1667 MHz (Table 1) and in 15 of them the spectral extent of the 1667 MHz line is by at least 0.2 km s$^{-1}$ larger than that of the 1612 MHz line. All 7 objects with only the blue-shifted or red-shifted emission at one maser line (estimates of the presumed spectral extent are given in Table 1 as italic) but with the complete profile at other maser line also exhibit the overshoot of the 1667 MHz line relative to the 1612 MHz maser extent. The absolute value of overshoot usually ranges from 0.2 to 6 km s$^{-1}$. The distribution of the ratio of the velocity extent at 1612 and 1667 MHz is shown in Figure 6. The overshoot effect is seen in 81% (22/27) of the objects in the sample.

The overshoot phenomenon is less prominent and less frequent (27–29%) in OH/IR objects (Dickinson & Turner 1997; Sivagnanam et al. 1989). Although there is no unique mechanism for overshoot (Sivagnanam & David 1999) a departure from spherical symmetry in the envelope is a plausible cause; most PPNe candidates observed at high angular resolution show non-spherical geometry (Zijlstra et al. 2001).

4.7. Absorption features

We found 5 objects with absorption features, usually at 1667 MHz (Table 1). All these are inner Galaxy low latitude sources (349° < l < 13°, |b| < 1.1°). In IRAS17347−3139, IRAS17393−3004 and IRAS17443−2949 the velocities close to zero of the absorption features strongly suggest that they are interstellar in nature. OH maps by Boyce & Cohen (1997) confirm this unambiguously for the latter two objects. The absorption feature of IRAS18091−1815 near 30.7 km s$^{-1}$ appears in the red-shifted part of the OH spectrum and is possibly not related to the source. In IRAS17103−3702 the 1667 MHz absorption near −37.8 km s$^{-1}$ (see also Payne et al. 1988 and Zijlstra et al. 1989) coincides in velocity with the edge of the 1612 MHz maser emission. As only the blue-shifted emission is observed it is likely that the absorption arises in front of the ionized region of the nebula. This OH PPNe object possibly represents an older phase of evolution. We conclude that in the studied sources, the OH absorption features are generally interstellar in origin.

5. Discussion

The present systematic data reveal an OH polarization pattern in PPNe candidates which is quite different from that described in the literature for late-type stars. Out of 40 targets detected at 1612 MHz, 21 and 31 were found to show linearly and circularly polarized features, respectively. Early observations did not provide evidence for polarization in many PPNe, with the exception of a few stars during flare activities, (Cohen 1989, for a review). Considerable circular polarization was found in supergiants (Cohen et al. 1987) and OH/IR stars (Zell & Fix 1991) when observed with high sensitivity and spectral resolution. Zijlstra et al. (1989) measured circular polarization in 5 PPNe candidates and polarized emission was detected in IRAS17150−3754 and IRAS17393−2727.

Out of 34 1667 MHz objects, 9 exhibited linearly polarized emission. This detection ratio is about 2.5 times higher than that reported for Mira-type stars (Olson et al. 1980; Claussen & Fix 1982). Because linearly polarized features are generally weak (0.5−4 Jy) and narrow (0.3−0.5 km s$^{-1}$) their only occasional detection in the past seems to be partly an effect of insufficient sensitivity and spectral resolution.

We note that at the two OH frequencies studied, linearly polarized features are always associated with circularly polarized features, but circular polarization can be present without associated linear polarization. A similar correlation has been reported for AGB stars (Claussen & Fix 1982). Appearance of circular polarization alone suggests that the effect of magnetic beaming (Gray & Field 1995) can work in the PPNe objects.
5.1. Upper limit for electron density

In IRAS18276−1431 and IRAS19114+0002 linearly polarized features in the red-shifted parts of spectra at the two transitions were observed at the same velocities (Fig. 1 and Fig. A1). Strong enough features (>0.5 Jy) at 1612 and 1667 MHz were identified in IRAS18276−1431 near 72.8 and 74.4 km s\(^{-1}\) and in IRAS19114+0002 near 124.9 km s\(^{-1}\). Assuming that both lines emerge in the same volume of gas, any difference in \(\chi\) between the two lines would probably be due to Faraday rotation over the envelope path length. No significant differences in PA exist within errors of 9\(^\circ\)9 and 12\(^\circ\)4 for IRAS18276−1431 and IRAS19114+0002, respectively. As the radii of OH envelopes at the transitions of interest were determined in both targets (Bains et al. 2003a; Gledhill et al. 2001) and the strength of the magnetic field along the line of sight was measured in the first object (4.6 mG) we can estimate an upper limit of the mean electron density in the envelope from the expression for Faraday rotation (García-Barreto et al. 1988):

\[
\phi = 0.5n_e B_\| L \lambda^2, \tag{7}
\]

where \(n_e\) is the electron density in cm\(^{-3}\), \(B_\|\) is the strength of magnetic field along the line of sight in mG, \(L\) is the depth of the maser region in units of 10\(^{15}\) cm and \(\lambda\) is the wavelength of the transition in units 18 cm. For an adopted distance of 2 kpc to OH17.7−2.0 (IRAS18276−1431) the depth of the maser region is comparable with the diameter of the envelope of 5.1×10\(^{16}\) cm (Bains et al. 2003a). The radiation comes from the far side of the envelope. The above observational parameters of OH17.7−2.0 imply an upper limit for \(n_e\) of 1.2 cm\(^{-3}\). Such a low value suggests largely neutral matter in the envelope.

5.2. Magnetic fields in PPNe

Our polarimetric observations revealed a great variety of polarization properties of OH maser lines in PPNe. IRAS19255+2123 is a good example to illustrate the diversity of polarization properties. The 1612 MHz emission is largely unpolarized with the exception of the feature near 21.2 km s\(^{-1}\) which shows elliptical polarization \((m_C = -83\%, m_L = 40\%)\). We failed to detect any polarized emission at 1667 MHz. Considerable circular polarization at 1665 MHz was reported by Miranda et al. 2001. As the emission from both main lines is located in different parts of the envelope from the 1612-MHz emission it is likely that their polarization parameters are due to the local magnetic field strength and orientation. The 1612 MHz data imply that the PA of the projected magnetic field differs by 53\(^\circ\) from the PA of the bipolar lobes observed in radio continuum (Miranda et al. 2001). This result partly supports the theoretical models of outflows in PNe collimated by toroidal magnetic fields (García-Segura et al. 1999; Matt et al. 2000). However, the small number of polarized OH features in this source prevents the study of the magnetic field orientation with high angular resolution in order to verify the existence of a magnetized torus postulated by Miranda et al. 2001.

Although the magnetic field of 1-2 mG tentatively found in two PPN objects needs further confirmation by high angular resolution studies, its strength is consistent with that measured with MERLIN in IRAS18276−1431 (Bains et al. 2003a) as well as in AGB stars (Szymczak et al. 1998). A simple consideration suggests that the magnetic field of the order of a few mG can shape the outflow in this object (Bains et al. 2003a). They document how IRAS18276−1431 has a magnetic field with large-scale well ordered structure, the geometry of which is consistent with a stretched dipole. The signature of a structured field is seen in the polarization vector PA profile (Fig. 1). Several sources in our sample, most prominently IRAS17393−2727, show clear evidence for a more complex magnetic field. Among the promising candidates is IRAS19114+0002 which shows broad linearly polarized features at red-shifted velocities at both lines and much weaker blue-shifted features at 1612 MHz. The strongest linearly polarized features, near 124 km s\(^{-1}\), are 2 and 7% of the total peak flux densities at 1667 and 1612 MHz, respectively. MERLIN observations of both lines failed to detect any polarized emission above the noise level (Gledhill et al. 2001) possibly due to insufficient spectral resolution. Our data show very small and smooth changes of the polarization position angles for the two lines, suggesting a magnetic field aligned along PA≈5\(^\circ\). The distribution of the 1667 MHz emission is elongated along PA=15\(^\circ\) (Gledhill et al. 2001), suggesting that the magnetic field is well aligned approximately parallel to the possible outflow direction.

Three targets (including IRAS19114+0002) possess OH spectra which are rich in linearly polarized features and do not exhibit the depolarization effect (shown by small symbols in Fig. 5). All these objects have highly aligned fields, as judged from the polarization position angle profiles. In contrast, the three sources with prominent depolarization (open symbols in Fig. 5) exhibit greater deviations in their linear polarization PAs across their velocity profiles. We suggest that they have structured magnetic fields of geometry similar to that observed in IRAS18276−1431. We speculate that the weakly polarized emission from these bright sources is intrinsically polarized but has been depolarized in regions of complex magnetic field. Alternatively, intrinsically weakly or unpolarized emission due to the relationship between our viewing angle and the source magnetic field configuration and maser beaming effects (Gray & Field 1993; Elitzur 1996, 1998) becomes polarized with the PA varying steeply as a function of angular position and apparent velocity. As pointed out in section 5.1 the Faraday rotation in these objects is probably too small to affect the detectability of linear polarization.

5.3. Prevalence of orthogonal fields

These single dish measurements of the polarization position angle of OH masers provide useful information on the orientation of the magnetic field in the maser region. It has been commonly argued that features with linear polarization are \(\sigma\) components of the Zeeman pattern (García-Barreto et al. 1988; Gray & Field 1993; Szymczak et al. 1998), implying that the projected angle of the magnetic field on the plane of the sky is perpendicular to the polarization position angle. Several ob-
5.4. Disappearance of OH masers

No OH emission was detected in 5 targets (Table 1). In IRAS06530−0213 weak 1667 MHz emission (0.22 and 0.16 Jy) at 27.8 and 29.8 km s\(^{-1}\) was observed in 1986 and 1987 (Likkel \[1989\]). No 1612 MHz emission was detected (Likkel \[1989\], Hu et al. \[1994\]). The source was classified recently as a carbon-rich PPN (Hrivnak & Bacham \[2003\]). IRAS16559−2957 was detected at 1612 MHz in 1986 with a 0.58 Jy peak near 56.2 km s\(^{-1}\) (Likkel \[1989\]). At a similar epoch te Lintel Hekkert et al. \[1991\] observed the blue-shifted emission at 57.0 km s\(^{-1}\) (0.43 Jy) and red-shifted emission at 86.5 km s\(^{-1}\) (0.15 Jy), while in 1991 Hu et al. \[1994\] found a 0.30 Jy peak near about 70 km s\(^{-1}\) at 1612 and 1665 MHz. In IRAS17079−3844 a 1612 MHz multi-peak profile was seen in 1987 (te Lintel Hekkert et al. \[1991\]). The 1667 MHz maser from IRAS17436+5003 was found by Likkel \[1989\] in 1986 and 1987 near a velocity of −26 km s\(^{-1}\). Recent observations by Bains et al. \[2003\] suggest that the disappearance of OH maser in this source can be permanent. In IRAS19127+1717, 1667 MHz emission was detected at 15.6 km s\(^{-1}\) (0.24 Jy) in 1987 (Likkel \[1989\]). She suggested that the emission is probably not related to the nebula.

We point out that all 5 targets not detected in the survey were known as weak (0.2–0.4 Jy) OH emitters about 15–17 years ago. Their emission has dropped below ~0.1 Jy. These objects need further observations to decide whether the emission disappeared temporarily or permanently.

One of the most interesting objects in the sample IRAS17393−2727 (OH0.9+1.3) continues a growth of the blue-shifted emission at a rate of about 1 Jy yr\(^{-1}\) (Shepherd et al. \[1990\]), whereas its red-shifted emission near −93.5 km s\(^{-1}\) appears to be constant, within a 0.2 Jy accuracy, as compared to Shepherd’s data taken about 14 yrs ago.

6. Conclusions

High sensitivity observations of the 1612 and 1667 MHz OH masers from a sample of 47 proto-planetary nebula candidates have provided new information on the polarization pattern.

A large fraction (55%) of the sources exhibit linearly polarized features in one or both OH lines. Circularly polarized features are present in 76% of the sources. Generally the maser features are elliptically polarized; the degrees of linear and circular polarization are usually low (<15%), but in some features this is as high as 50–80%. The linearly polarized features are usually narrow (<0.5 km s\(^{-1}\)) and weak (<4 Jy).

There are several sources with a large velocity extent (>4 km s\(^{-1}\)) of linearly polarized flux for which a diversity of variations of polarization position angle \(\chi\) across the profile is observed. The sources with large changes in \(\chi\) are very likely to have structured magnetic fields, as recently revealed for OH17.7−2.0. They also exhibit depolarization of linearly polarized emission. The sources with nearly constant values of \(\chi\) possibly have magnetic fields highly aligned with specific directions and do not show depolarization effects. Both types of objects appear to be good candidates for future mapping of magnetic fields with high angular and spectral resolutions.
Table 3. The $p$-flux-weighted average polarization angle of the linearly polarized OH maser emission at 1612 MHz and/or 1667 MHz (PA$_{1612}$, PA$_{1667}$) and the position angle of nebula long axis (PA$_{axis}$) taken from optical and/or infrared or radio images.

| IRAS name    | Type | N  | PA$_{1612}$ | $\sigma_{PA_{1612}}$ | PA$_{1667}$ | $\sigma_{PA_{1667}}$ | PA$_{axis}$ | $\sigma_{PA_{axis}}$ | Refs |
|--------------|------|----|------------|---------------------|------------|---------------------|------------|---------------------|------|
| 07331+0021   | d    | 3  | -32.3      | 4.7                 |            |                     | 89(30)     |                     | 1    |
| 07399-1435   | c    | 4  | -48.0      | 6.7                 | 23(5)      |                     | 1.2        |                     |      |
| 08005-2356   | s    | 2  | 22.1       | 4.4                 | -47(5)     |                     | 3          |                     |      |
| 16342-3814   | d,d  | 4  | -54.8      | 8.4                 | -51.6      | 5.6                 | 69(3)      |                     | 3    |
| 17150-3224   | s,c  | 5  | -72.2      | 32.9                | -37.2      | 17.2                | -33(3)     |                     | 3    |
| 17393-3004   | s    | 2  | -23.0      | 6.5                 |            |                     | 13(3)      |                     | 4    |
| 18266-1239   | c    | 2  | 50.6       | 7.2                 |            |                     | 66(30)     |                     | 5    |
| 18276-1431   | c,c  | 1  | 47.0       | 5.0                 | 77.0       | 14.8                | 20(3)      |                     | 6    |
| 18450-0148   | c,s  | 3  | 82.1       | 18.5                | 75.3       | 3.8                 | 63(2)      |                     | 7    |
| 19114-0002   | c,c  | 2  | -84.8      | 8.4                 | -84.0      | 7.3                 | 21(3)      |                     | 3    |
| 19219+0947   | c    | 2  | -0.7       | 4.5                 |            |                     | 34(5)      |                     | 8    |
| 19255+2123   | s    | 5  | 64.5       | 2.5                 |            |                     | 27(5)      |                     | 9,10 |
| 22036+5306   | c    | 3  | -73.8      | 5.3                 |            |                     | 66(2)      |                     | 11   |

Type of spectrum: s - single peak, d - two features, c - complex; N: number of observations used to derive PA$_{1612}$ and PA$_{1667}$;
References for PA$_{axis}$: (1) Meixner et al. 1999; (2) Kastner et al. 1998; (3) Ueta et al. 2000; (4) Philipp et al. 1999; (5) Chapman 1988; (6) Bains et al. 2003a; (7) Imai et al. 2002; (8) Seaquist & Davis 1985; (9) Miranda et al. 2000; (10) Miranda et al. 2001; (11) Sahai et al. 2003

For the subset of PPNe with optical images showing asymmetric morphology we found a dominance of magnetic field components misaligned by $> 60^\circ$ with the long axis of the nebulae. This finding lends support to the theoretical model of magnetic collimation of bipolar lobes in planetary nebulae.

The magnetic field strength inferred from likely Zeeman split 1667 MHz line implies a largely neutral envelope.

The overshoot of the 1667 MHz velocity extent relative to the 1612 MHz velocity extent is common (81%) in the studied sources. This effect, rarely seen in AGB stars, can be related to changes in the source geometry and excitation conditions in the envelopes during the transition from AGB to PN phase.

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