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VLBI observations of 6 GHz OH masers in three ultra-compact H II regions

J.F. Desmurs[1,2,3] **and A. Baudry**[2]

[1] Observatoire de l'Université de Bordeaux 1, BP 89, F-33270 Floirac, France
[2] Observatorio Astronómico Nacional, Apartado 1143, E-28800 Alcalá de Henares, Spain
[3] Joint Institute for VLBI in Europe, Postbus 2, 7990 AA Dwingeloo, The Netherlands

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Abstract. Following our successful analysis of VLBI observations of the $^2\Pi_{\frac{3}{2}}, J=\frac{5}{2}, F=3-3$ and $F=2-2$ excited OH emission at 6035 and 6031 MHz in W3(OH), we have analyzed the same transitions in three other ultra-compact HII regions, M17, ON1, and W51. The restoring beams were in the range 6 to 30 milliarc sec. The $F=3-3$ and $2-2$ hyperfine transitions of OH were both mapped in ON1. Seven 6035 MHz LCP or RCP maser components were identified in ON1. They are distributed over a region whose diameter is similar to that of the compact HII region, namely $\approx 0.4-0.5$ arc sec. In contrast with the $F=3-3$ line emission, the $F=2-2$ transition at 6031 MHz is nearly an order of magnitude weaker than the peak 6035 MHz emission. In M17, we observed fringes only in the 6035 MHz line. The detected OH components appear to be projected on to the compact HII region. We report also on weak VLBI detection of the 6035 MHz emission from W51. This emission seems to be located between two active ultra-compact HII regions in a complex area which deserves further investigation. The 5 cm OH minimum brightness temperatures range from about 3 10^7 K in W51 to 8 10^9 K in ON1. Variability of the 6035 or 6031 MHz emission is well established and suggests that the 5 cm OH masers are not fully saturated.

The high spectral and spatial resolutions achieved in this work allowed us to identify Zeeman pairs and hence to derive the magnetic field strength. In ON1 and W51 the field lies in the range 4 to 6 mG with a trend for higher field at 6031 MHz than at 6035 MHz in ON1. In M17 no Zeeman splitting was observed and the magnetic field appears to be weaker than 1 mG.

Key words: masers – techniques: interferometric – ISM: magnetic fields – ISM: individual objects: M17 – ISM: individual objects: ON1 – ISM: individual objects: W51

1. Introduction

One of the main properties of the OH radical in space is that it gives rise to several maser hyperfine transitions resulting from strong deviations from thermal equilibrium throughout the $\Lambda-$doublet energy levels. These transitions highlight dense regions of the molecular gas and are used to trace the gas dynamics in star-forming regions or in the envelopes of late-type stars. The hyperfine transitions of OH are especially strong in the star-forming region W3(OH), and several of them have been observed with VLBI techniques up to the $^2\Pi_{\frac{3}{2}}, J=\frac{7}{2}$ state (Baudry and Diamond 1998). Recently, we used the new capabilities of the European VLBI Network (EVN) in the $6-7$ GHz band ($5-4.3$ cm band) to conduct a study of the $^2\Pi_{\frac{3}{2}}, J=\frac{5}{2}$ state of OH in the two main hyperfine transitions of this state at 6035.092 MHz ($F=3-3$) and 6030.747 MHz ($F=2-2$). We mapped these two transitions in W3(OH) and discussed extensively our results (Desmurs et al. 1998). The EVN 5 cm OH data acquired in three other ultra-compact HII regions, M17, ON1 and W51, in which massive stars are hidden, are analyzed in this paper. A preliminary account of this work was given in Desmurs et al. (1997).

Because the $J=\frac{5}{2}$ state lies immediately above the ground-state of OH, observations of the 5 cm OH hyperfine transitions are important (e.g. Baudry et al. 1997). Such observations constrain any prediction of the excitation of the four $J=\frac{5}{2}$ hyperfine transitions which, despite the accurate OH-H_2 collision rates derived by Offer et al. (1994), cannot be modeled precisely (see Pavlakis and Kylafis 1996, who mention potential difficulties in modeling highly excited OH states). On the other hand, the 5 cm OH spectra are much simpler than the ground-state spectra and, accordingly, Zeeman pairs may be identified with better confidence than at 18 cm, provided that enough spectral resolution is achieved at 5 cm. VLBI observations of the generally simple 5 cm OH spectra allow us to derive the strength and direction of the magnetic field which we need to know to better understand its role during the early stages of star-formation (see e.g. Heiles et al. 1993, McKee et al. 1993, or Pudritz and Norman 1986 for hydrodynamic modeling of disks around protostellar objects). The very high spatial resolution achieved in VLBI is indispensable for firmly identifying that two spectral components with opposite senses of circular polarization To coincide (Zeeman pair). This method proved to be successful in the $J=\frac{5}{2}$ state (Moran et al. 1978, Desmurs et al. 1998) as well as in the $J=\frac{7}{2}$ state (Baudry and Diamond 1998). In Sect. 2 we describe the observations and give details of data reduc-

Send offprint requests to: desmurs@oan.es

Table 1. Coordinates used at the correlator and center velocity.

Source	RA (J2000) ($h\,m\,s$)	Dec(J2000) ($\circ\,'\,''$)	V_{LSR} (km s^{-1})
M17	18 20 24.75	-16 11 34.94	$+22.0$
W51	19 23 43.97	$+14$ 30 30.26	$+55.0$
ON1	20 10 09.04	$+31$ 31 36.32	$+14.0$

tion. In Sect. 3 the results obtained in M17, ON1, and W51 are discussed, and in Sect. 4 some conclusions are given.

2. Observations and data reduction

Our 5 cm OH data were acquired with three antennas of the EVN, Effelsberg, Jodrell Bank-MkII and Medicina, in late May 1994. (It is interesting to note that Torun and Onsala would be available now in the array; more antennas could be included in a near future.) The 6035 and 6031 MHz line data were simultaneously recorded with MKIII terminals (mode C) in dual circular polarization. We used 250 kHz filters thus achieving a total velocity coverage of about 12 km s^{-1} and a separation between channels of 0.11 km s^{-1} at 6035/6031 MHz. We observed 6 ultra-compact HII regions, W3(OH), M17, W51, ON1, W75N and NGC7538 which are known for their strong 5 cm OH peak or integrated flux density (Baudry et al. 1997). Data reduction and our W3(OH) results were discussed in detail in Desmurs et al. (1998). For W75N and NGC7538 fringes have been detected but the data are of insufficient quality to warrant further analysis. We concentrate the present analysis on M17, ON1 and W51 which were observed 4, 5.5, and 5 hours, respectively; towards W51 and ON1 the observations covered a broad period of time in order to improve the uv coverage. The correlation task was performed at the EVN correlator in Bonn, and we used the NRAO's AIPS package for data analysis. The source coordinates used at the correlator and the center velocity are given in Table 1.

Our 5 cm OH maps were produced for both left and right circular polarizations (LCP and RCP) and for all three sources after applying all phase corrections, including the phase shift correction between polarizations. We searched for maser features in the various maps using the following criteria: (i) one feature must be detected in at least two adjacent channels at the same position (i.e. there must be coincidence within one synthesized beam), and (ii) the minimum detection level is $5\times\sigma$.

Examples of visibility plots are given for the 6035 MHz reference channel at 14.3 km s^{-1} in ON1 (Fig. 1).

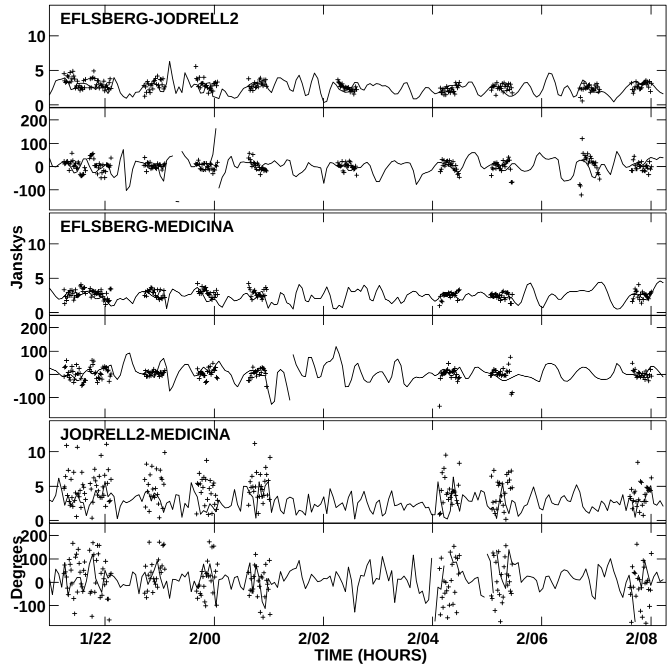

Fig. 1. Example of amplitude and phase plots for the three baselines of our EVN array. Data are for the reference channel in ON1 (RCP component A at (0,0) in Table 2). The continuous line shows the adopted complex gain model.

3. Results and discussion

3.1. General properties

The strongest 5 cm OH transition ($F = 3-3$ at 6035 MHz) was mapped in all three sources. The restoring beams were, in mas, 28×6 (PA = $25^{\rm o}$), 6.2×4.8 (PA = $-76^{\rm o}$), and 56×13 (PA = $-29^{\rm o}$) for M17, ON1 and W51, respectively. Only ON1 showed fringes in both main hyperfine transitions at 6035 and 6031MHz. However, only one weak VLBI feature was detected at 6031 MHz in each sense of polarization. The 6031 MHz line thus appears to be less frequently excited and weaker than the 6035 MHz transition. This fact confirms our previous results acquired both in VLBI towards W3(OH) (Desmurs et al. 1998) and in our single dish survey of star-forming regions (Baudry et al. 1997). The line parameters of each detected LCP or RCP feature were determined from our own routines developed in the GILDAS package (for more details see Desmurs 1996). The line parameters are given in Table 2. Peak fluxes range from about 0.5 to 7 Jy/beam, our detection limit being close to 0.4 Jy/beam. With the above synthesized beams the minimum brightness temperatures are of order $T_B \geq 5-10\;10^8$ K, $\geq 0.6-8\;10^9$ K and $\geq 3\;10^7$ K for M17, ON1, and W51, respectively. The lower brightness limit in W51 corresponds to weaker emission and to more extended synthesized beam than for M17 and ON1. All of these limits are below the $10^{11}-10^{12}$ K measured in the ground-state by García-Barreto et al. (1988) and in the $J=\frac{7}{2}$ excited-state at 13.44 GHz by Baudry and Diamond (1998).

3.2. M17 (G15.03-0.68)

The radio source observed here is an ultra-compact HII region located within the southern radio free-free emission 'bar' mapped by Felli et al. (1984). It exhibits a shell structure with a diameter of 0.4 arc sec or nearly 10^{16} cm at the 2.2 kpc distance of M17 (Chini et al. 1980). The radio continuum and infrared

Table 2. $^2\Pi_{\frac{3}{2}}, J = 5/2$, 6035 and 6031 MHz hyperfine components and magnetic field strength in M17, ON1 and W51.

Source	Component	Polzn.	$\Delta\Theta_x$ ^{a} mas	$\Delta\Theta_y$ ^{a} mas	V_{rad} ^{b} km s^{-1}	ΔV_{rad} ^{c} km s^{-1}	S_ν ^{d} Jy/beam	H ^{e} mG
M17								
6035	A	RCP	0	0	22.50	0.20	3.72	< 1
		LCP	0	0	22.55	0.20	4.65	
	B	RCP	-33	-140	21.45	0.15	3.83	<1
		LCP	-30	-143	21.45	0.14	2.22	
ON1								
6035	A	RCP	0	0	14.3	0.17	1.5	-3.6
		LCP	0	1	14.5	0.17	2.5	
	B	RCP	-156	7	14.35	0.18	7.1	
	C	RCP	-406	109	15.1	0.23	1.1	-5.3
		LCP	-408	110	15.4	0.23	0.7	
	D	RCP	-125	538	13.6	0.19	2.4	-3.6
		LCP	-125	539	13.8	0.22	1.1	
6031	A'	RCP	0	0	13.7	0.18	0.7	-6.3
		LCP	0	0	14.2	0.19	0.5	
W51								
6035	A	RCP	0	0	57.4	0.28	0.6	3.6
		LCP	0	0	57.2	0.33	0.75	

Table 2. a) Position offsets relative to the $(0, 0)$ reference feature. The (0,0) reference positions at 6035 and 6031 MHz in ON1 do not necessarily have identical absolute positions (see text). b), c), d) The center velocity, FWHM and peak flux density of each feature were determined from Gaussian fits. The weakest features we accepted were about 0.4 Jy/beam. e) The magnetic field intensity is derived from the velocity difference between the paired RCP and LCP components.

spectra of this ultra-compact HII region are consistent with those expected from an embedded B0$-$B0.5 ZAMS star (Felli et al. 1984). M17 (G15.03-0.68) lies between the ionized arc feature mapped by Felli et al. and the massive molecular cloud located to the SW; this suggests that the hidden main sequence star could have been formed from shock-induced processes. The J2000 coordinates of the ultra-compact HII region studied by Felli et al., $\alpha = 18^h\,20^m\,24.^s82, \delta = -16^o\,11'\,34.''9$, are similar, within the position uncertainties, with those used in this work (Table 1); our coordinates were taken from the VLA observations of the 1665 MHz OH source (Forster and Caswell 1989) and precessed to J2000. We observed strong 5 cm OH VLBI fringes near $21.50 - 22.55$ and 21.45 km s^{-1} (Table 2) where strong emission is observed with single aperture antennas (e.g. Baudry et al. 1997). The VLBI components A and B in Table 2 are separated by about 0.14 arc sec and appear to be projected on to the ultra-compact HII region. (The A-B spatial separation measured here is in excellent agreement with the observations of Caswell 1997 made for the same features.)

Variability of 5 cm OH sources was well observed in the works of Caswell and Vaile (1995) and Baudry et al. (1997). This also applies to M17. Comparison of the 6035 MHz spectra obtained in late March 1994 (Caswell and Vaile 1995), late May 1994 (see our autocorrelation spectrum in Fig 2), and July 1995 (Baudry et al. 1997) shows that two main features dominate the spectrum in both polarizations at all epochs and that the single polarization peak flux densities may vary by a factor of 2 approximately. Although the flux calibration procedures and spectral resolution are not identical in all of these works short term variability on time scales of about two months seems to be present in M17. This would imply 6035 MHz emission within a region less than $l = c \times t = 1.6 \times 10^{17}$ cm in size. This size, however, does not constrain the individual maser spot size since the diameter of the compact HII region is 0.4 arc sec or 10^{16} cm. We note that long term variability is present in M17 because one of the two 6035 MHz components observed in 1975 by Knowles et al. (1976) is clearly weaker than the other in contrast with the spectrum in Fig 2.

The 6031 MHz line was not detected with the 100-m telescope in 1995 July although we quote a possible weak 0.1 Jy feature in one channel only (see Table 2 in Baudry et al. 1997). No VLBI fringes were detected at 6031 MHz towards M17 in the present work. However, the 6031 MHz line was well detected in our Effelsberg autocorrelation spectrum of 1994 May 20. Thus the weaker 6031 MHz line, as the 6035 MHz line, seems to be variable. A similar result was observed in some other HII regions (Baudry et al. 1997). In conclusion, time variability suggests that the 5 cm OH masers in M17 are not strongly saturated.

3.3. ON1 (G69.54-0.98)

This isolated ultra-compact HII region was discovered by Winnberg et al. (1973). It exhibits a shell-like radio structure (Turner and Matthews 1984) with a diameter of about 0.5 arc sec. ON1 is totally obscured and located in the densest part of an extended molecular cloud (Israel and Wootten 1983). The kinematic distance ranges from about 1 to 6 kpc but Israel and

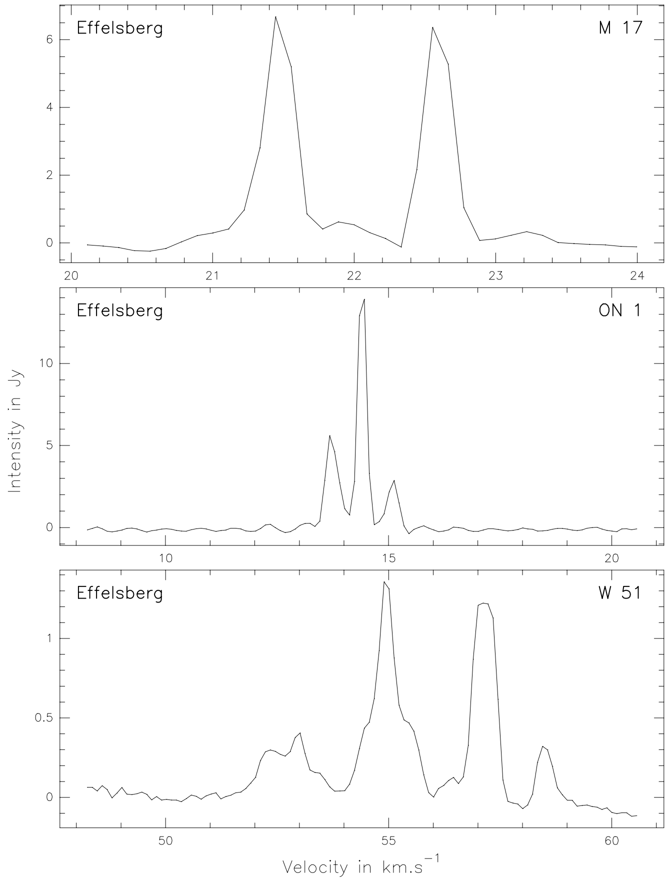

Fig. 2. Effelsberg's autocorrelation spectra of M17, ON1 and W51 observed at 6035 MHz (right circular polariztion) on 1994 May 20. The intensities are in Jy and the spectral resolution is 0.11 km s^{-1}.

Wootten give arguments in favour of a 1.4 kpc distance to ON1; this would imply a diameter of about 10^{16} cm for the ionized radio source. Strong 5, 6 and 18 cm OH emission and H_2O emission are observed towards ON1. The H_2O and 18 cm OH sources (Forster et al. 1978 and Ho et al. 1983) are closely associated with ON1 although they tend to be located at the edge of the compact HII region.

We have observed in the direction of the centroid of the ionized shell strong 6035 MHz fringes (Table 1). The four components called A, B, C, and D in Table 2, have been detected at velocities in excellent agreement with our single dish observations (Baudry et al. 1997). (However, the low velocity features detected by us with the 100-m around -0.5 km s^{-1} were not investigated in this VLBI experiment.) Components A to D are distributed over an area 0.5 arc sec in size. This size is similar to that of the compact HII region and the 6035 MHz features could thus be located at the periphery of and/or be projected on to the HII region. VLBI fringes were detected at 6031 MHz in ON1 (component A' in Table 2). Because the absolute positions of the 6035 and 6031 MHz sources are not known with enough accuracy in this work, the (0,0) positions at 6035 and 6031 MHz (components A and A') do not necessarily coincide; however, the component A and A' velocities are similar.

The correlated flux density in component B is the strongest detected in this work. With a synthesized beam of about 5.5 mas for ON1 it corresponds to the minimum brightness temperature $T_B \geq 8\ 10^9$ K. The other features detected in ON1 give minimum brightness temperatures in the range $0.8 - 3\ 10^9$ K at 6035 MHz and around $0.6 - 0.8\ 10^9$ K at 6031 MHz. These limits are well below those derived at 18 cm or at 13.44 GHz (see discussion in Sect. 3.1). It is interesting to note that components A and B are close in velocity to the 14.5 km s^{-1} VLBI feature which was detected at 4765 MHz ($J = 1/2$ state) in the other energy ladder of OH (Baudry and Diamond 1991). The minimum 4765 OH brightness emission in ON1 was roughly estimated to be 10^7 K (Baudry and Diamond 1991).

Our 6035 MHz autocorrelation spectrum (Fig. 2) and the spectra obtained by Baudry et al. (1997) show very similar relative spectral intensities among the three main features. On the other hand, comparison of the peak flux densities of these spectra both obtained by late May 1994 suggests rapid time variability. If this short term variability would be confirmed the light travel time would be less than 10^{16} cm i.e. less than the apparent diameter of the compact HII region placed at 1.4 kpc. In any case a clear intensity change was observed over a one year time-scale in our single dish 6035 MHz data (Baudry et al. 1997). As for M17, variability, together with rather low limits in the 5 cm OH brightness temperatures, suggest that the 5 cm OH masers in ON1 are not fully saturated.

3.4. W51 (G49.49-0.39)

W51 is a huge and complex HII region roughly 7 kpc away from us. It contains several compact HII regions and many strong OH and H_2O maser sources. The coordinates used here to correlate our 5 cm OH data correspond to the VLA 1665 MHz OH position of Forster and Caswell (1989). This position is nearly 4 arc sec away from the center of the compact continuum source W51$-e1$ and lies close to the 18 cm OH complex studied by Gaume and Mutel (1987). Another compact, and most active HII region, W51$-e2$, lies some 8 arc sec to the north of W51$-e1$. It is associated with strong 18 cm OH sources (Gaume and Mutel 1987) and with the strong water maser W51$-Main$ studied by Genzel et al. (1981). All of these sources lie within the primary beam of our VLBI array and the present 5 cm OH study is only preliminary. In fact, the W51 position given in Table 1 lies at the edge of a newly discovered compact 3.6 cm continuum component labeled W51$-e4$ in Gaume et al. (1993). Among the 4 main 6035 MHz features visible in Fig. 2 only the $57.2-57.4$ km s^{-1} component gave fringes. More investigation is needed to know whether the other velocity components would give fringes and would be located near W51$-e1$, $e2$ or $e4$. As in M17 and ON1 variability was observed in W51 at 6035 MHz (Caswell and Vaile 1995).

3.5. Magnetic field strength

The maser features meeting the spectral, spatial and sensitivity criteria given at the end of Sect. 2 are listed in Table 2.

All features, except one, can be paired as spatially coinciding components (within a small fraction of the synthesized beam) with opposite circular polarization and nearby velocities. We identify these components as Zeeman pairs and we derive from the velocity differences the field strength (last column in Table 2). The present work and our results for W3(OH) (Desmurs et al. 1998) prove that, in contrast with the ground-state, Zeeman pairs are frequent in the $J = \frac{5}{2}$ state. The same remark applies to observations of W3(OH) in the $J = \frac{7}{2}$ state (Baudry and Diamond 1998). This is due to the fact that the frequency splitting resulting from the Zeeman effect in the $J = \frac{5}{2}$ and $\frac{7}{2}$ states is comparable to the OH linewidths. On the other hand, this splitting is greater at 18 cm than in the excited-states of OH so that the OH velocity fields tend to be more 'decorrelated' for the narrow LCP and RCP 18 cm OH components resulting in less frequent Zeeman pairs. In W3(OH) García-Barreto et al. (1988) identified only a few 18 cm OH Zeeman pairs whereas we identified in the $J = \frac{5}{2}$ state 28 and 9 Zeeman pairs out of 61 and 21 maser features detected at 6035 and 6031 MHz, respectively (Desmurs et al. 1998) .

The field strength given in Table 2 ranges from about 3.5 to 5.5 mG at 6035 MHz. This is comparable to the 2 to 10 mG determined at 6035 MHz from the same VLBI experiment in W3(OH) by Desmurs et al. (1998). However, stronger magnetic fields, from 6 to 15 mG, were observed at 6031 MHz in some areas of W3(OH). The same trend seems to be observed here for ON1 (see below); this perhaps indicates that the two main hyperfine transitions are not excited in the same layers. It is important to note that with fields of order a few mG the net magnetic pressure, M, cannot be neglected with respect to the total kinetic energy of the gas, T. In a region with volumic density $n(H_2)$ we derive, using McKee et al. (1993), $M/T \approx 0.016$ B^2 / $(n(H_2) \times m(H_2) \times \sigma^2)$, where σ is the velocity dispersion. In the dense regions of the molecular gas highlighted by OH masers we expect $n(H_2) \approx 10^7$ cm^{-3} and we obtain $M/T \approx 0.05 - 5$ for fields in the range 1 to 10 mG and $\sigma \approx$ 1 km/s. The impact of magnetic pressure on the dynamics of dense gas regions was clearly demonstrated for the molecular outflow of Cepheus A observed in the 18 cm lines of OH (Cohen et al. 1990), and, in W3(OH), a relationship of the magnetic field gradient with the velocity field was observed along the arc-like structure mapped in the $J = \frac{7}{2}$ state of OH by Baudry and Diamond (1998).

Some details concerning the individual sources are discussed below.

In M17 the maser linewidths are greater than the frequency shift between both polarizations. Therefore, the strength of the magnetic field appears to be less than 1 mG. In fact, due to limited spectral resolution, our field detection limit is roughly 2 mG. We note that this is consistent with the results of Brogan et al. (1997) who detected a field weaker than 1 mG in the direction of the M17 dense molecular cloud through the Zeeman effect in the 21 cm HI absorption line; however their VLA observations were acquired with lower spatial resolution than in this work.

In ON1 the four identified pairs give consistent values of the field around -4 to -6 mG with no reversal of the field direction. This is also consistent with the -3 to -6 mG measured with the 100-m telescope at 6035/6031 MHz (Baudry et al. 1997). Apart from W3(OH), ON1 is the only source where we have identified a 6031 MHz Zeeman pair. The magnetic field is around -6 mG and is stronger than the -4 mG average field of the three pairs identified at 6035 MHz. Magnetic fields stronger at 6031 than at 6035 MHz were clearly observed in W3(OH) (Desmurs et al. 1998).

In W51 we identified only one Zeeman pair and derived a field strength of $+3.6$ mG for a region located between W51$-e1$ and $e2$. Because only one pair was identified here and because the uv coverage should be improved more observations of this source are needed. However, this field is comparable to the 6035 MHz non interferometric determinations of Caswell and Vaile (1995) and Baudry et al. (1997) giving $+4.7$ and $+3.9$ respectively. The VLA observations of Gaume and Mutel (1987) gave several possible Zeeman pairs in W51$-e1$ and $e2$ at 1665, 1667 or 1720 MHz; the field is in the range $+6$ to $+10$ mG.

4. Conclusions

This VLBI test experiment proved that the properties of 5 cm OH masers and of the magnetic field can be investigated in ultra-compact HII regions weaker than the exceptional W3(OH) region. Our new results as well as those acquired in W3(OH) demonstrate the close association of excited OH sources with ultra-compact HII regions powered by obscured O or B ZAMS stars. In M17 and ON1 the 5 cm OH masers appear to be projected on to, or to be located at the edge of the ionized compact region. In W51 the emission is also associated with a compact HII region but the W51 complex harboring several ultra-compact HII regions deserves further study. We derived minimum brightness temperatures in the range $T_B \geq 3\ 10^7$ K to $8\ 10^9$ K. These temperatures weaker than in the ground-state, together with short-term or long-term flux density variability, suggest that all 5 cm OH masers are not fully saturated. As in W3(OH) the 6031 MHz emission is less frequently excited and weaker than the 6035 MHz emission. Several Zeeman pairs were identified and gave field strengths in the range 4 to 6 mG. The 6031 MHz line seems to give higher field strength than at 6035 MHz, thus confirming the trend previously observed by us in W3(OH).

Finally, we note that with the present and foreseen developments of the EVN in the 5 cm band the sensitivity will be enhanced, and better uv coverage will become possible in several galactic sources of interest.

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