A MERLIN Study of 6-GHz excited-state OH and 6.7-GHz methanol masers in ON1

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ABSTRACT
Multi-Element Radio Linked Interferometer Network (MERLIN) observations of 6.668-GHz methanol and both 6.031- and 6.035-GHz hydroxyl (OH) emission from the massive star formation region ON1 are presented. These are the first methanol observations made in full polarization using five antennas of MERLIN, giving high resolution and sensitivity to extended emission. Maser features are found to lie at the southern edge of the ultracompact H II region, following the known distribution of ground-state OH masers. The masers cover a region ∼1 arcsec in extent, lying perpendicular to the H 13CO + bipolar outflow. Excited-state OH emission demonstrates consistent polarization angles across the strongest linearly polarized features which are parallel to the overall distribution. The linear polarizations vary between 10.0 and 18.5 per cent, with an average polarization angle of −60° ± 28°. The strongest 6.668-GHz methanol features provide an upper limit to linear polarization of ∼1 per cent. Zeeman splitting of OH shows magnetic fields between −1.1 and −5.8 mG, and a tentative methanol magnetic field strength of −18 mG is measured.

Key words: masers – polarization – stars: formation – ISM: individual: ON1.

1 INTRODUCTION
High-mass star formation regions have been observed to demonstrate maser emission from a wide variety of molecules, including both methanol and hydroxyl (OH). One such region, ON1, is an ultracompact H II region (UCHII) contained within the Onsala molecular cloud. The region was first observed by Eldér, Rönnäng & Winnberg (1969) through its OH maser emission, before it was observed in CO, H₂CO and HCO + in 1983 by Israel and Wootten and shown to be part of an extended molecular cloud complex. NH₃ and H76α recombination line observations led Zheng et al. (1985) to identify ON1 as a rapidly rotating condensation, but Kumar, Tafalla & Bachiller (2004) later identified two H13CO + outflows, demonstrating a resolved bipolar structure with a velocity gradient of ∼30 km s⁻¹ pc⁻¹. ON1 is associated with the IRAS source 20081+3122. It is believed that ON1 contains a central binary massive protostar of type B0.3 surrounded by a young stellar cluster (Israel & Wootten 1983; Macleod et al. 1998; Kumar et al. 2004).

The kinematic distance estimate to ON1 is between ∼1.4 and 8 kpc depending on the model used for the Galactic rotation (Israel & Wootten 1983; Macleod et al. 1998). The currently favoured distance is the near kinematic distance of 1.8 kpc, as derived by Macleod et al. (1998), using the Wouterloot & Brand (1989) rotation curve. Macleod et al. (1998) estimate the age of ON1 to be 0.5 × 10⁵ yr.

The 6.7-GHz methanol maser has an intrinsic relationship with high-mass star formation, having to date been observed in exclusive association with known massive star formation regions (Minier et al. 2003). Methanol maser emission at 6668.512 MHz was first observed in ON1 with the 43-m Greenbank telescope in 1991 by Menten, who detected a feature with a peak flux density of 91 Jy at +15.1 km s⁻¹. This was later observed by Szymczak, Hrynek & Kus (2000) and found to have a peak flux density of 109 Jy. The spectrum of this observation is given in Fig. 1, and reveals a weak feature at around 0 km s⁻¹ in addition to the peak feature at +15.1 km s⁻¹.

6.7-GHz methanol maser polarization has only been studied twice previously, Ellingsen (2002) found fractional polarizations between a few and 10 per cent in NGC 6334F, whilst Vlemmings, Harvey-Smith & Cohen (2006a) found approximately 2 per cent, with levels up to 8 per cent, in W3(OH). The methanol molecule is diamagnetic and as such has low magnetic permeability and a small magnetic dipole moment and so methanol masers in the presence of an external magnetic field are not expected to demonstrate strong linear polarization, nor to show large fractional circular polarization.

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As the OH molecule is paramagnetic, OH masers are good tracers of the magnetic field. Ground-state OH towards ON1 was observed with Multi-Element Radio Linked Interferometer Network (MERLIN) by Nammahachak et al. (2006). The 6-GHz excited state of OH is also particularly effective for measuring the Zeeman effect (Caswell & Valie 1995). Desmurs & Baudry (1998) conducted VLBI observations of 6.035-GHz OH in ON1 in 1994, finding four right-hand circularly polarized (RHC) features and three left-hand circularly polarized (LHC) features, with flux densities ranging from 0.7 to 7.1 Jy beam$^{-1}$. The local standard of rest (LSR) velocities of these features range from 13.8 to 15.4 km s$^{-1}$.

This paper represents the first high-resolution observations of 6.668-GHz methanol maser emission in ON1 combined with the first detailed studies of the polarization properties of both the 6.668-GHz methanol and 6.031-/6.035-GHz excited-state OH in ON1. Unfortunately, the MERLIN results presented here did not have a wide enough bandwidth both to give adequate spectral resolution and to cover both features, so they were centred near the main peak shown in Fig. 1.

2 OBSERVATIONS

ON1 was observed using the MERLIN on 2005 January 12 and 16. These were the first data taken with new broad-band 4–8 GHz e-MERLIN receivers on five telescopes (the MKII, Darnhall, Tabbey, Knockin and Cambridge), enough for full synthesis imaging, completely dominating the array (http://www.merlin.ac.uk/userguide/). The relative positional errors for all components, determined from 2013+340 were then applied to ON1, including phase and amplitude solutions derived from 2013+340.

Using local MERLIN software, the flux density of 3C84 was established to be 15.5 Jy with respect to the primary amplitude calibration source, 3C286. The data were converted to FITS files, using 3C84 to apply a preliminary bandpass scaling to all data. All further processing was performed using the Astronomical Image Processing Software (AIPS), see the MERLIN User Guide (Diamond et al. 2003) for details. A small percentage of the data had anomalous phase and amplitude and was edited accordingly. Phase self-calibration was performed for all the calibration sources and 3C84 was used to derive the instrumental phase offset between the continuum and spectral configurations. Amplitude self-calibration was performed on 3C84 and this source was used to derive bandpass correction tables and also to measure the polarization leakage. Systematic leakage was calibrated and there was found to be a residual leakage of $\leq 0.5$ per cent Stokes $I$ in Stokes $Q$ and $U$ and $\leq 0.25$ per cent in Stokes $V$. 3C286 was used to derive the polarization angle correction. The various corrections appropriate for each frequency were then applied to ON1, including phase and amplitude solutions derived from 2013+340.

Inspection of the spectra of each of the ON1 lines in LHC and RHC enabled the selection of the brightest channel in a single hand of circular polarization, this was imaged to obtain an accurate reference position. The systematic position errors are $\sim 12$ mas at 6–7 GHz due to uncertainty in the phase calibration, telescope positions and atmospheric variation (Etoka, Cohen & Gray 2005). The clean components of each reference image were then used as a model for phase and amplitude self-calibration and the solutions applied to all channels and both polarizations of that line. Finally, the brightest channel in the weaker hand of polarization for each line was selected and self-calibrated, applying the solutions to that hand of polarization only. In this way, good calibration was achieved without compromising the absolute position accuracy or the polarized phases and amplitudes.

When all calibration was complete, the contributions of the antennas were reweighted according to their sensitivity, their individual efficiency and to avoid baselines to a single antenna completely dominating the array (http://www.merlin.ac.uk/userguide/). This allowed preparation of clean image data cubes for each line in all four Stokes parameters ($I$, $Q$, $U$ and $V$) and in RHC and LHC. A circular restoring beam of 50-mas full width at half-maximum (FWHM) was used with a pixel size of 12 mas, giving in total an image field of view of 12 arcsec. The Stokes $I$ images had a $\sigma_{\text{rms}}$ noise level of 25 and 15 mJy beam$^{-1}$ for methanol and OH, respectively, except in the brightest total intensity channels, which were dynamic range limited with a noise level of up to 0.5 per cent of the peak. The LHC and RHC images had noise levels of 35, 20 and 25 mJy beam$^{-1}$ for the methanol, 6.031- and 6.035-GHz OH lines, respectively.

Elliptical Gaussian components were fitted to each patch of emission above $\sigma_{\text{rms}}$ in each Stokes $I$, LHC and RHC channel and the position, deconvolved size, peak and total intensities, and the uncertainties were all measured. Any components not found at similar positions in a series of five or more consecutive channels were discarded. The relative positional errors for all components, determined from the errors in the peak position of the Gaussian fits, were 2 mas or better (for the accuracy of Gaussian component fitting see Condon 1997; Condon et al. 1998; Richards, Yates & Cohen 1999). The uncertainty in component size is the square root of 2 multiplied by the position uncertainty, which enables brighter component sizes to be determined with meaningful accuracy. The position and intensity of emission in the $Q$, $U$ and $V$ channel maps were measured at the position of each Stokes $I$ component for that line and channel.
Table 1. Properties for the 6.7-GHz methanol features in the ON1 star-forming region. Positions relative to RA (J2000) = 20h10m29s23628, Dec. (J2000) = 31°36′37.84″. Features A and B have relative positions accurate to ±0.01 arcsec or better, whilst C and D have an accuracy of ±0.002 arcsec. As the velocities are taken as the mid-points of channels there is an error of ±0.5 channels (corresponding to ~0.02 km s⁻¹).

| Features | ΔRA (arcsec) | ΔDec. (arcsec) | V₁₀₀₃ (km s⁻¹) | ΔV₁₂ (km s⁻¹) | Peak T₀ (K) |
|----------|--------------|---------------|----------------|---------------|------------|
| A        | -2.459       | -1.184        | 15.57          | 0.21          | ≥1.99 × 10³ |
| B        | -2.342       | -1.353        | 15.13          | 0.28          | ≥1.83 × 10³ |
| C        | -2.413       | -1.307        | 14.62          | 0.27          | ≥8.97 × 10² |
| D        | -2.005       | -1.438        | 14.46          | 0.27          | ≥3.43 × 10³ |

3 RESULTS

3.1 6.7-GHz methanol

51 individual channel Stokes I components were detected in the 6.667-GHz methanol transition. These individual channel components were grouped into features as described in Section 2 and the flux-density-weighted mean properties for each feature are given in Tables 1 and 2. Four methanol features were observed with peak velocities between 14.46 and 15.57 km s⁻¹. The positions and velocities of the 6.7-GHz methanol features are given in Table 1 and the Stokes I spectrum and channel-averaged map are shown in Fig. 2. Features show typical FWHM linewidths of between 0.21 and 0.28 km s⁻¹. Peak flux densities of the individual features varied between 0.48 and 73.62 Jy beam⁻¹. Estimates of the deconvolved component sizes from the Gaussian fitting ranged from 16 to 52 mas (equivalent to 29–94 au at the assumed distance of 1.8 kpc). Combined with the peak flux densities these allow lower limits to the peak brightness temperatures to be determined (ranging between 1.99 × 10⁷ and 8.97 × 10⁸ K).

No previous high-resolution observations of 6.7-GHz methanol are available in the literature for comparison. A larger restoring beam of 100 mas was used to search for extended emission, similar to that seen in W3(OH) by Harvey-Smith & Cohen (2005), but none was found. It is difficult to speculate how much of the single dish flux density is recovered by the current observations as the previous single-dish observations were taken in 1999 (Szymczak et al. 2000) and showed possible variability in comparison to the previous observations in 1991 (Menten 1991). The two flux densities recorded were, as noted in Section 1, 109 and 91 Jy, respectively, taken with the 32-m Torun and the 43-m Greenbank telescope. The errors in the absolute flux-density calibrations for the two observations were ±15 and ±10 per cent, respectively, so the two measurements could be consistent to within the errors. However, there have been a number of studies into the variability of 6.7-GHz methanol masers, most recently by Goedhart, Gaylard & van der Walt (2005), and these have served to show that 6.7-GHz methanol masers are generally variable on time-scales of years, but the nature of their variability is wide ranging from periodic/quasi-periodic through monotonic increases/decreases to sporadic behaviour, and so with just two previous epochs it is impossible to judge the nature of the possible increased flux density in 1999. Given there is a lack of extended emission from the 100 mas restoring beam and if minimal variability is assumed, then comparison with the spectrum of Szymczak et al. (2000) implies the flux density recovered is likely to be over 80 per cent.

3.2 6-GHz excited-state OH

14 individual channel Stokes I components were detected in the 6.031-GHz OH transition, and 63 for that at 6.035-GHz OH. Nine individual channel LHC and eight RHC components were detected for 6.031-GHz OH, whilst 53 individual channel LHC components and 50 RHC, were found for 6.035-GHz OH. These individual channel components were grouped into features as described in Section 2 and the flux-density-weighted mean properties for each feature are given in Tables 3 and 4. A single OH LHC feature and a single OH RHC feature were found at 6.031 GHz with peak velocities of 14.19 and 13.87 km s⁻¹, respectively. Six OH LHC and five OH RHC features were found at 6.035 GHz with peak velocities between 13.76 and 15.50 km s⁻¹. The positions and velocities of these OH features are given in Table 3, with the corresponding Stokes I feature details in Table 4. The RHC and LHC spectra and Stokes I channel-averaged maps are shown in Fig. 2. Linewidths vary between 0.15 and 0.34 km s⁻¹. The peak flux densities varied between 0.35 and 15.72 Jy beam⁻¹. Estimates of the deconvolved component sizes from the Gaussian fitting ranged from 13 to 38 mas (equivalent to 23–68 au at the assumed distance of 1.8 kpc). Combined with the peak flux densities these allowed lower limits to the peak brightness temperatures to be determined (ranging between 1.02 × 10⁷ and 2.71 × 10⁸ K).

The overall shape of the 6.035-GHz OH emission spectrum is consistent with the VLBI spectrum of Desmurs & Baudry (1998) and the single-dish spectrum of Baudry et al. (1997), with peaks at similar velocities and similar relative intensities between the spectral features. However, the overall flux density in the current observations is greater. Baudry et al. (1997) established from two epochs, separated by a year, that there is rapid time variability of the source, and hence over the 10 yr between those observations and the current, significant flux-density variation could have occurred and, similar to the methanol, any derivation of the recovered flux density would lack significant accuracy.

Comparison between the features found by Desmurs & Baudry (1998) and the current observations is also difficult, again due to the variability, but also due to the error in absolute position of the previous observations (between 0.2 and 0.5 arcsec). However, the
OH and methanol masers in ON1

Figure 2. From left- to right-hand side: Stokes I 6.668-GHz methanol emission and map, RHC and LHC (dotted and solid lines, respectively) 6.031-GHz OH emission and Stokes I map, RHC and LHC 6.035-GHz OH emission and Stokes I map. Maps show emission integrated over all channels, with contour levels at 10–100 per cent of the peak flux density for the 6.667-GHz methanol and 6.035-GHz OH emission and 40–100 per cent for the 6.031-GHz OH emission. The peaks are 72.76, 7.87 and 1.71 Jy beam\(^{-1}\), respectively.

Table 3. Hydroxyl maser features for the ON1 star-forming region. Positions relative to RA (J2000) = 20\(^h\)10\(^m\)09\(^s\), Dec. (J2000) = +31\(^\circ\)31\(^\prime\)36\(^\prime\)3784. All relative positions are accurate to ±0.001 arcsec or better, with the exception of feature B which is ±0.002 arcsec. Velocities are accurate to ±0.02 km s\(^{-1}\). Peak flux density is accurate to ∼0.02 Jy beam\(^{-1}\). The magnetic field strengths are accurate to 0.4 mG.

| Transition | Features | Stokes I no. | ΔRA (arcsec) | ΔDec. (arcsec) | \(V_{\text{LSR}}\) (km s\(^{-1}\)) | \(\Delta V_{1/2}\) (km s\(^{-1}\)) | Peak flux density (Jy beam\(^{-1}\)) | Peak \(T_B\) (K) | Comment |
|------------|----------|-------------|-------------|-------------|-----------------|-----------------|-----------------|-----------|---------|
| 6031-LHC   | A        | 1           | -2.886      | -0.739      | 14.19           | 0.27            | 2.34            | ≥9.45 \times 10^8 | \(Z_1\) -3.9 mG |
|            | a        | 1           | -2.885      | -0.739      | 13.87           | 0.25            | 3.46            | ≥1.29 \times 10^9 | \(Z_1\) |
| 6031-RHC   | A        | 1           | -2.280      | -1.339      | 15.50           | 0.24            | 3.33            | ≥3.83 \times 10^8 | \(Z_2\) -4.6 mG |
|            | b        | 1           | -2.234      | -1.352      | 15.06           | 0.15            | 0.35            | ≥1.02 \times 10^7 |       |
| 6035-LHC   | A        | 1           | -2.028      | -1.440      | 14.89           | 0.29            | 0.51            | ≥3.04 \times 10^7 | \(Z_1\) -5.8 mG |
|            | B        | 2           | -2.884      | -0.744      | 14.16           | 0.34            | 2.23            | ≥4.56 \times 10^8 | \(Z_2\) -4.2 mG |
|            | C        | 3           | -1.871      | -1.446      | 14.57           | 0.23            | 3.71            | ≥4.58 \times 10^8 | \(Z_3\) -1.1 mG |
|            | D        | 4           | -1.996      | -0.907      | 13.85           | 0.32            | 1.89            | ≥1.67 \times 10^8 | \(Z_4\) -1.6 mG |
|            | E        | 5           | -2.208      | -1.441      | 14.56           | 0.23            | 15.72           | ≥2.71 \times 10^9 | \(Z_5\) |
|            | F        | 6           | -1.872      | -1.446      | 14.51           | 0.22            | 3.86            | ≥4.53 \times 10^8 | \(Z_6\) |
| 6035-RHC   | a        | 1           | -2.280      | -1.339      | 15.25           | 0.26            | 2.99            | ≥4.97 \times 10^8 | \(Z_7\) |
|            | b        | 2           | -2.028      | -1.441      | 14.56           | 0.23            | 15.72           | ≥2.71 \times 10^9 | \(Z_8\) |
|            | c        | 3           | -1.872      | -1.446      | 14.51           | 0.22            | 3.86            | ≥4.53 \times 10^8 | \(Z_9\) |
|            | d        | 4           | -2.884      | -0.744      | 13.92           | 0.30            | 3.34            | ≥1.12 \times 10^9 | \(Z_{10}\) |
|            | e        | 5           | -1.996      | -0.908      | 13.76           | 0.24            | 3.66            | ≥3.64 \times 10^8 | \(Z_{11}\) |

range of velocities of the features between 13.6 and 15.4 km s\(^{-1}\) is similar, as are the relative positions of the 6.035- and 6.031-GHz OH emission (described in Section 4 and seen in Fig. 3). Specifically at 6.031-GHz OH, Fish et al. (2006) and Desmurs & Baudry (1998) found one LHC and one RHC feature at velocities of 14.2 and 13.8 km s\(^{-1}\), respectively, which are also found in the current observations. For the 6.035-GHz OH, the current observations fail to detect the LHC features at 5.47, 7.74 and 12.59 km s\(^{-1}\) seen by Fish et al., but do detect two previously unseen LHC features. The current study also fails to detect the RHC feature at 5.53 km s\(^{-1}\), but otherwise recovers the RHC features seen by Fish et al. and Desmurs and Baudry and finds one further feature.

3.3 Linear polarization

Two of the four 6.7-GHz methanol features demonstrate, in terms of random noise, statistically significant (>3\(\sigma\)) Stokes \(Q\) and \(U\) flux densities, resulting in linear polarizations of 0.2 and 1.3 per cent. However, analysis of the bandpass calibrator 3C84 showed a residual polarization leakage of ≤0.5 per cent, reducing the significance.
of the measurements to an upper limit. The 6.031-GHz OH Stokes I feature had significant $Q$ and $U$ flux density giving 12 per cent linear polarization. Of the five 6.035-GHz OH Stokes I features, two had significant $Q$ and $U$ flux density giving linear polarizations of 19 and 10 per cent. The three features that had statistically significant linear polarization showed reasonably consistent polarization angles of $-6^\circ \pm 28^\circ$. The upper limit of $\sim 1$ per cent linear polarization in methanol is consistent with that found in W3(OH) by Vlemmings et al. (2006a) and in NGC 6334F by Ellingsen (2002), where both had the majority of features displaying less than 5 per cent linear polarization. Linear polarization of excited-state OH in ON1 has not been studied before. The polarization vectors of the statistically significant OH results are plotted in Fig. 4 together with the upper limits of methanol polarization.

The two methanol features with tentative linear polarization have a $90^\circ$ difference in polarization angle. As shown in the case of SiO and $H_2$O masers, which are also diamagnetic, such a $90^\circ$ flip can be caused by a difference in the angle $\theta$ between the maser line of sight and the magnetic field. When $\theta$ is larger than the critical angle $\theta_{\text{crit}} \approx 55^\circ$, the linear polarization direction is perpendicular to the magnetic field, whilst when $\theta < \theta_{\text{crit}}$, the linear polarization is parallel. Furthermore, as the fractional linear polarization also decreases close to the critical angle, this could explain why the strongest methanol maser feature has the lowest significant linear polarization fraction (Vlemmings & Diamond 2006; Vlemmings et al. 2006b, and references therein).

### 3.4 Circular polarization and magnetic fields

In order to investigate the degree of circular polarization within methanol the cross-correlation method of Modjaz et al. (2005) was employed. This method estimates Zeeman splitting via the cross-correlation of the RR and LL spectra and as such is independent of any polarization leakage that may affect the Stokes V spectrum. Also, assuming the magnetic field strength is similar across the blended maser features, it allows for a determination of Zeeman...
splitting when spectral blending makes a measurement using the $V$ spectrum impossible. The rms of the cross-correlation method is a function of the spectral channel width and the rms noise on the RR and LL spectra. The method was shown by Modjaz et al. (2005), via Monte Carlo simulations, to have a sensitivity equivalent to the standard S-curve method. Through this method, methanol feature D is seen to have a Zeeman splitting of $0.0009 \pm 0.0003 \text{ km s}^{-1}$. Compared with OH, methanol is believed to have a much lower Zeeman splitting coefficient, but a precise value has never clearly been defined. Using the only currently available value of the methanol $g$-Landé factor, determined by Jen (1951) from 25 GHz methanol maser lines, the Zeeman splitting coefficient of the 6.7-GHz methanol maser transition is calculated to be $0.0493 \text{ km s}^{-1} \text{ G}^{-1}$ (Vlemmings et al. 2006a). Consequently the Zeeman splitting of feature D corresponds to a field strength of $-18 \pm 6 \text{ mG}$. This represents the first tentative detection of Zeeman splitting in 6.7-GHz methanol. As the noise is limited by the dynamic range, the noise increases in the peak channels to $\sim 60 \text{ mJy}$, and therefore means the field strength is at $\sim 3\sigma$ (rather than $>5\sigma$, as it would have been without the dynamic range limitation). In terms of fractional circular polarization, statistically significant results could not be determined due to the residual leakage, but the feature demonstrating the Zeeman splitting had a circular polarization of 0.65 per cent at $2.5\sigma$.

In total six excited-state OH Zeeman pairs were found, five at 6.035 GHz and one at 6.031 GHz, with the LHC and RHC features in each pair having a spatial association to within 1 mas. Splitting factors of 0.0564 and 0.0790 km s$^{-1}$ mG$^{-1}$, respectively, were assumed (Yen et al. 1969). This implies a magnetic field strength ranging from $-1.1$ to $-5.8 \text{ mG}$ for the pairs at 6.035 GHz and $-3.9 \text{ mG}$ for the single pair at 6.031 GHz. All the magnetic fields are directed towards us and concur in magnitude and direction with those found previously by Desmurs & Baudry (1998), which varied between $-3.6$ and $-6.3 \text{ mG}$, and the single-dish measurements of Fish et al. (2006) of between $-0.8$ and $-5.0 \text{ mG}$. Furthermore the fields seen in ON1 appear to be typical for excited-state OH in star formation regions in general, which have been observed to vary between $+9.1$ and $-13.5 \text{ mG}$ (Fish et al. 2006). Fig. 4 shows the location of the measured field strengths. Overall the fields compare favourably with the field strengths found for the ground-state OH by Nammahachak et al. (2006), which varied between $-0.4$ and $-4.6 \text{ mG}$.

4 DISCUSSION

4.1 Distribution and coincidences

The methanol features lie in a roughly linear south-east to north-west distribution, covering about 0.6 arcsec ($\sim 1080 \text{ au}$ at 1.8 kpc). The excited-state OH features meanwhile show a wider spread of about 1.2 arcsec ($\sim 2160 \text{ au}$), with one feature offset from the linear distribution by about 0.5 arcsec ($\sim 900 \text{ au}$). The linear distribution of both the 6.7-GHz methanol and the 6-GHz excited-state OH is parallel to the mainline ground-state OH distribution of Nammahachak et al. (2006), with the methanol consistently offset by on average $\sim 70 \text{ mas}$ (130 au). The three 6.035-GHz features towards the centre of the distribution, seen in Fig. 3, are systematically offset from the ground-state 1665-MHz OH features by an average of $\sim 57 \text{ mas}$ (100 au).

It is worth considering if proper motion of the maser features between the observations of Nammahachak et al. observed in 1996 and the current observations in 2005 could explain the observed spatial offset between the ground-state OH and the methanol and excited-state OH maser features (both sets of observations used the same extragalactic phase reference source). The systematic offset between the 6.035-GHz OH and 1665-MHz OH of 100 au would require a motion over $\sim 1.5 \times 10^{10} \text{ km in 9 yr}$, which is $\sim 50 \text{ km s}^{-1}$. Both internal and external proper motion should be examined. Work by Bloemhof, Reid & Moran (1992) looked at the internal proper motion of the 1665-MHz OH masers in the W3(OH) region, which is located at a similar distance, and found very few motions greater than 5 mas over the 7.5 yr period they studied (velocities were typically a few km s$^{-1}$). This implies that internal proper motion is unlikely to account for the separation seen. It is also likely that any internal proper motion of the ground-state OH masers would also affect the excited-state masers, as their masing gas clouds are likely to share a bulk proper motion. In terms of external proper motion it is possible to examine the effect of Galactic rotation on the region over the 9-yr separation. Adopting the rotation curve of Brand & Blitz (1993) leads to an external east to west motion of $\sim 45 \text{ km s}^{-1}$ for the region, which would amount to $\sim 45 \text{ mas}$ over 9 yr. This would result in a separation of $\sim 10 \text{ mas}$ between the overall line of ground- and excited-state OH masers and $\sim 25 \text{ mas}$ between the ground-state OH and the methanol. Coupled with the uncertainties in these calculations, possible peculiar motion and the absolute positional errors of the two sets of data (20 and 15 mas, respectively), it is possible that proper motion may account for the spatial separation seen. An accurate determination of these offsets requires near simultaneous observations of both frequency regimes, but this is beyond the scope of the current paper.

However, if this apparent lack of spatial coincidence is demonstrated it could be the result of differences in the specific column densities of the two species, as modelling of OH and methanol masers by Cragg, Sobolev & Godfrey (2002) showed that both OH and methanol require very similar high-density, low-temperature regimes (dust temperatures exceeding 100 K, gas temperatures <100 K, and densities in the range $10^5 < n_H < 10^8 \text{ cm}^{-3}$). On the other hand, subtle variations in the above parameters could pick out the exact conditions required for each species of maser. A plot of

![Figure 4. Linear polarization properties for the statistically significant 6.031- and 6.035-GHz OH and the upper limits of the 6.668-GHz methanol features. Numbers indicate the magnetic field strengths deduced from Zeeman splitting, with blue representing 6.035-GHz OH, the $-3.9 \text{ mG}$ in red is the 6.031-GHz field and the $-18 \text{ mG}$ in red italics is the tentative 6.667-GHz methanol detection. Positions are given relative to RA (J2000) = 20°10′09″23628, Dec. (J2000) = 31°31′36″3784.](image-url)
the approximate regions for maser emission for a dust temperature of 175 K is given in Fig. 5.

For the excited-state OH and methanol frequencies of the current observations, based on a combination of the absolute and relative positional errors as per Etoka et al. (2005), 15 mas can be taken as the distance for association, within which it is not possible to determine if individual methanol and excited-state OH features are spatially separate and hence may indicate coincidence and/or co-propagation. In the current study, there is no association between the 6.7-GHz methanol and the 6-GHz excited-state OH (the closest emission peaks are separated by ~23 mas, even taking into account the deconvolved component sizes there is still distinct separation). The two transitions also display significantly different magnetic field strengths as described in Section 4.3. The RHC and LHC Zeeman pair at 6.031 GHz coincides with a 6.035-GHz OH Zeeman pair to <5.5 mas spatially and <0.049 km s\(^{-1}\) in velocity, implying co-propagation. This is a confirmation of the suspected coincidence which was identified in Desmurs & Baudry (1998) to within their accuracy of ~200 mas. Gray, Field & Doel (1992) show that for the two transitions to be coincident, if the dust temperature is ~50 K and assuming a hydrogen number density of 2.5 \(\times\) 10\(^7\) cm\(^{-3}\), then the kinetic temperature must be ~75 K. However, the results of Cragg et al. (2002), using a more extensive model and a dust temperature of 175 K, allow for a range of kinetic temperatures (as shown in Fig. 5). The 100 per cent association of 6.031-GHz emission with 6.035 GHz is consistent with previous results, such as by Etoka et al. (2005). The fact that there is only one case of coincidence of all the features shows the physical conditions of the main group of maser spots must vary from the offset coincident pair.

At face value the data sets we have show that the individual 6-GHz excited-state OH features do not appear to show any spatial coincidence with ground-state OH to within 20 mas (the closest separation of peak emission is ~28 mas). There is one exception, a satellite line feature at 1612 MHz. There are only two 1612-MHz OH features in the region, one is separated by 34 mas from 6.035-GHz emission, the other has just a 7-mas separation. As mentioned earlier this may be accounted for by proper motion of the region, but if not then it may imply, contrary to previous models, that there might be an overlap in the conditions for maser emission between the 1612-MHz transition and the 6.035-GHz transition, which is not present for the other ground-state OH transitions. On the other hand the two transitions could be tracing higher density gas, but not be spatially coincident, and so exist in different temperature regions. Gray et al. (1992) suggest the 1612-MHz transition requires kinetic gas temperatures of \(\geq 150\) K and hydrogen number densities around \(6 \times 10^6\) cm\(^{-3}\). Fig. 5 also implies that a higher density is required for both to be present, but if the dust temperature is consistent, the kinetic temperature regimes vary (but as noted in the caption to the Figure other factors may allow for the two to be coincident).

It is also possible to conclude that the possible spatial separation between the ground- and excited-state OH (with the exception of the one 1612-MHz feature), could mean we see the very highest density of OH in the excited-state regions, as the conditions for excited-state OH maser emission extend to higher densities than the ground state (Fig. 5). As the methanol lies in the same, slightly offset, region of 6.035-GHz emission it too perhaps is in a similarly high-density regime. However of course if both the gas density and temperature are high, then the collision rate will be increased and both species of maser are likely to be quenched. Combined with the 1612-MHz distribution, this would lead to the assumption the excited-state OH traces the slightly cooler, dense gas, the 6.668-GHz methanol the hotter dense gas and the 1612-MHz tracing possibly the hottest dense gas (although the abundances of the molecular species and the dust temperature may also vary). The higher density region could be indicative of a shock front, propagating away from the UCHII.

Velocities of the maser features suggest a positional gradient, with three of the four methanol features showing a north-west to south-east gradient, which is also seen in the excited-state OH at 6.035 GHz in three of the five features. If a gradient does exist this would concur with the ground-state OH picture and the possibility that the masers are tracing an outflow or disc. Interestingly two of the methanol features and one of the 6.035-GHz OH features also demonstrate tentative velocity gradients within their individual channel components. The two methanol features’ internal gradients lie on a north-east to south-west direction, i.e. perpendicular to the overall velocity gradient across the features, and may suggest the masers are tracing a planar shock (Elitzur, Hollenbach & McKee 1992; Dodson, Ojha & Ellingsen 2004). The 6.035-GHz OH feature’s internal gradient, meanwhile, lies parallel to the main distribution.

For comparison W3(OH) represents a star formation region at a similar distance to ON1, which has been studied at high resolution for multiple transitions of masers (Menten et al. 1992; Sutton et al. 2004; Wright et al. 2004; Etoka et al. 2005; Harvey-Smith & Cohen 2005; Harvey-Smith & Cohen 2006). The region has far more maser features across the transitions and there is far more ‘intermingling’ between the species and transitions, without the possible separation that is seen in ON1. Within 15 mas in W3(OH) there is a high percentage of associations between the excited-state OH and the mainline ground-state OH (Etoka et al. 2005), which may not be the case for ON1. Both regions show a lack of association on the smallest scales between 6-GHz OH and 1720-MHz OH sources, but unlike W3(OH), ON1 demonstrates possible association of 6-GHz OH with 1612-MHz OH. W3(OH) shows 27 per cent of 6.7-GHz methanol masers had associated 6-GHz OH maser emission, whilst in ON1 there is no association to 15 mas. Some of these differences could be accounted for by a difference in the orientation of the regions and also the same caveat of internal and external proper
motions may affect the W3(OH) results (in so far as the comparison of Etoka et al. 2005 compares data for mainline OH observed in 1996, 4.7-GHz OH observed in 1993 and excited-state OH and 6.7-GHz methanol seen in 2001).

4.2 Extended emission

The current observations did not detect any extended emission above the 3σ limit of 1.75 mJy beam$^{-1}$ at 100 mas resolution. This contrasts with the detection in the W3(OH) star formation region (Harvey-Smith & Cohen 2006) at a well-established distance of 1.95 kpc (Xu et al. 2006). If ON1 is at a similar distance, it lacks diffuse methanol emission; however, if it is at the far-kinematic distance, it might just be undetectable at present. Further study would be required, both to determine whether extended emission is prevalent in methanol maser sources, and thus expected to be seen, and better determination of the distance to ON1 (perhaps through maser astrometry as per Xu et al. 2006).

4.3 Magnetic field strength and alignment

The average polarization angle of $-60^\circ \pm 28^\circ$ is consistent with the line of maser distribution, which is itself perpendicular to the known H$^{13}$CO$^+$ outflow with a position angle of 44$^\circ$ (Kumar et al. 2004). This suggests the emission could be a propagating shock front, which agrees with the excited-state OH and methanol lying in a potentially higher density region, as identified in the previous section. Faraday rotation is inversely proportional to the square of the frequency and as such will strongly affect the ground-state OH transitions. Nammahachak et al. (2006) estimate the external rotation measure for ON1 to exceed $-100$ rad m$^{-2}$, more than enough to disrupt any pattern present. For the excited-state OH at 6 GHz and methanol at 6.7 GHz internal Faraday rotation is minimal. External Faraday rotation, which is calculated from the standard Faraday rotation equation using typical values for interstellar electron density and magnetic field as per Vlemmings et al. (2006a), but adjusted for the distance of 1.8 kpc, is of the order of 12$^\circ$ and 11$^\circ$ for the 6-GHz OH and 6.7-GHz methanol, respectively.

The coincident 6.031- and 6.035-GHz Zeeman pairs (Z$_{2}$ and Z$_{4}$) show the same field strength to within the errors, which concurs with the possibility of co-propagation mentioned previously. However, as this is the only coincidence of the two transitions, and there is a similar sized field at 6.035 GHz for Z$_{2}$, the magnetic field strength may not be intrinsically linked to the conditions necessary for maser co-propagation. The similarity of the 6.031- and 6.035-GHz fields for Z$_{2}$ are in contrast to that found by Desmurs & Baudry (1998), where the 6031-GHz transition was seen to have stronger fields compared to the 6035-GHz transition.

The tentative magnetic field strength of $-18 \pm 6$ mG derived from methanol for the current observations is larger than that of both the excited-state OH and the ground-state OH, although it is within the established upper limit for the field strength derived through methanol observations of W3(OH) of $-22$ mG (Vlemmings et al. 2006a). The measured field strength implies the methanol may be tracing a localized increase in density compared to the OH. If the standard scaling law of B$^{1.5}$ of Crutcher (1991) is applied, which has been found to be valid up to the highest maser densities such as those probed by H$_{2}$O masers (Vlemmings et al. 2006b), then the implication is that the methanol masers occur in gas denser by a factor of 5–10 compared to the OH maser gas at hydrogen densities of $\sim 10^{8}$. However, caution must still prevail as the magnetic field detection is only marginal. If further study demonstrated the presence of a stronger magnetic field in the regions of methanol maser emission, this could well lead to a better determination on the exact criteria for the 6.7-GHz emission or indeed the star formation stage it traces.

Comparison with the ground-state OH magnetic field strengths measured by Nammahachak et al. (2006) highlight several similarities. The field strength of the 6.035-GHz OH seen towards the middle of the linear distribution, that of Zeeman pair Z$_{2}$, is comparable to the field strength of the nearby (~60 mas separation) 1665-MHz OH, both giving 4.6 mG directed towards us. The field detected at the south-east end of the distribution, for the 6.035-GHz OH Zeeman pair Z$_{4}$, is comparable to the 1720-MHz OH (~26 mas separation) of 1.0 mG. However, located between these two sets of similar fields, the field strengths found for the methanol Zeeman splitting and the 6.035-GHz OH Zeeman pair Z$_{4}$ are both larger than the 1665-MHz OH field (1.5 mG), although in this case there is a larger separation of ~190 mas.

5 CONCLUSIONS

New high-resolution MERLIN data demonstrate for the first time the distribution and possible polarization properties of 6.7-GHz methanol maser emission in the ON1 star-forming region. When combined with new excited-state OH observations and existing ground-state OH data, and correcting for the effects of Galactic motion, we see all transitions lie in a similar region. We see the structure of ON1 to be that of two parallel, possibly offset, elongated distributions, one in ground-state OH, one in interwoven excited-state OH and 6.7-GHz methanol. The 6.031-GHz transition of excited-state OH shows a linear polarization of 12 per cent, whilst the 6.035-GHz OH transition shows linear polarization varying between 10 and 19 per cent. In comparison the methanol, as expected, demonstrates a lower value of ~1 per cent. Consistent magnetic field strengths were observed across the region for the excited-state OH, with a slight tendency for smaller field strengths towards the south-east of the distribution, which is in agreement with the known ground-state OH magnetic field strengths. Zeeman splitting was detected for the first time in the 6.7-GHz methanol maser emission, demonstrating a possible magnetic field strength of $-18 \pm 6$ mG.

A Zeeman pair at 6.031 GHz is seen in coincidence with a 6.035-GHz OH Zeeman pair, with both having matching magnetic fields within the errors. This coincidence represented 100 per cent association to ~5 mas for the 6.031-GHz OH with the 6.035-GHz OH emission, but only a 20 per cent association of 6.035 GHz with 6.031-GHz OH. To the same level of spatial separation there is no coincidence between the methanol and excited-state OH transitions.

The observed interweaving of excited-state OH and methanol maser features along the elongated distribution, together with the separation of these masers from the ground-state OH is in agreement with the postulation of Caswell (1997), that the two species delineate similar or complimentary regions. The separation of the individual methanol and excited-state OH features on the scales afforded by high-resolution observations, could just be due to variations in the relative abundances of the species, or it could be that the methanol is tracing a slightly higher gas temperature or even denser regions and thus a different component of the region surrounding the evolving massive star. This is complimented by the significantly higher magnetic field strength suggested for the 6.7-GHz methanol maser.

Whether the maser features show a velocity gradient, and thus possibly trace a disc, is not possible to judge as the number of
features are too few to draw statistically sound conclusions. However, the consistent polarization angles and offset nature of denser gas imply the masers trace a shock front, possibly in the form of a torus or ring around a young stellar object. This is also highlighted by possible orthogonal velocity gradients across the individual components of the methanol maser features. The shock front hypothesis concurs with the previous study of the ground-state transitions of OH of Nammahachak et al. (2006). The potential shock front lies orthogonal to the known H$^{13}$CO$^+$ outflow and future proper motion studies of the masers may be able to determine if they are moving in synchronization with the outflow.

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