THE OH (1720 MHz) SUPERNova REMNANT MASERS IN W28: MERLIN AND VLBA POLARIZATION OBSERVATIONS

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ABSTRACT

Full-polarization MERLIN and VLBA observations of the 1720 MHz maser emission from the OH molecule in the supernova remnant W28 are presented. Zeeman splitting ($|B| \approx 0.75$ mG) has been directly resolved between right- and left-circularly polarized spectra for the first time. Linear polarization position angles and circular polarization Zeeman splitting observed in the maser emission permit interpretation of a comprehensive picture of the magnetic field at the supernova/molecular cloud interface marked by the masers. We find the post–SNR shock magnetic field to be well ordered over the ~1 pc covered by the maser region (compared with the approximately 30 pc diameter of the entire SNR) and well aligned with the shock front that is traced by synchrotron radiation and molecular emission. Based on MERLIN data having a resolution of 200 mas and VLBA data with a resolution of 15 mas, the masers are measured to have deconvolved angular sizes of 90–350 mas (225–875 AU) with compact cores 20 mas (50 AU) in size, consistent with theoretical expectations and previous observations.

Subject headings: ISM: individual (W28) — masers — supernova remnants

1. INTRODUCTION

Spectral line emission from the OH (1720 MHz) satellite transition ($2^3\Pi_{3/2}, J = 3/2, F = 2 \rightarrow 1$) in supernova remnants (SNRs) was first observed by Goss (1968) toward W28. The maser nature of the emission was noted shortly thereafter, along with the recognition that the 1720 MHz line emission, when observed in association with absorption in the other ground-state OH lines, requires a pump mechanism different than that used to explain H ii region OH masers (Goss & Robinson 1968; Ball & Staelin 1968; Turner 1969; Robinson et al. 1970). Much later, observations of W28 by Frail et al. (1994) renewed the interest in the SNR masers while also recognizing (1) the astrophysical diagnostic value of the masers’ association with molecular clouds and (2) the viability of the collisional pump suggested by Elitzur (1976) to explain the level population inversion. Subsequent studies and surveys (Yusef-Zadeh et al. 1996, 1999, 2000; Koralesky et al. 1998; Green et al. 1997; Frail et al. 1996) have since observed approximately 200 Galactic SNRs and found 22 remnants with associated OH (1720 MHz) maser emission.

Observations support the premise that OH (1720 MHz) SNR masers occur where the shock front from a supernova explosion encounters a molecular cloud (e.g., W28, Frail et al. 1994; Kes 78, Koralesky et al. 1998; 3C 391, Frail et al. 1996; W44, Wootten 1977). In such interactions, a C-type (nondissociative) shock can produce the relatively rare conditions ($n \approx 10^5$ cm$^{-3}$, $T \approx 90$ K, $N_{OH} \sim 10^{16}–10^{17}$ cm$^{-2}$) needed for the collisionally pumped OH (1720 MHz) masers (Elitzur 1976; Wardle 1999; Lockett et al. 1999; see also Draine & McKee 1993). The suggested temperature, density, and OH column of the OH (1720 MHz) collisional pump are consistent with those determined from observation (e.g., Claussen et al. 1997, hereafter C97; Hoffman et al. 2003a, hereafter H03). Furthermore, OH (1720 MHz) SNR masers are observed at the SNR/molecular cloud interface where the shock front is edge-on, moving transversely across the plane of the sky (e.g., Reynoso & Mangum 2000). Frail & Mitchell (1998) and Arikawa et al. (1999) have examined the postshock gas in W28 using observations of shocked CO ($J = 3 \rightarrow 2$) using the James Clerk Maxwell Telescope. Figure 1 shows the good positional agreement between the OH masers, the shocked gas, and the limb of the synchrotron emission from the SNR (this agreement is discussed in § 4.4).

The intrinsic, transverse sizes of the masers have been the subject of several recent studies. Indeed, the narrowband maser emission does not permit simple multiwavelength fitting of the scattering properties to the $j^2$ wavelength dependence expected of scattering owing to the ionized interstellar medium at radio frequencies. Claussen et al. (2002) suggest that the angular scatter broadening of the maser images in W28 is not significant based on studies of the angular scattering of an adjacent extragalactic source and the temporal broadening of a background pulsar. Hoffman et al. (H03) observed the OH (1720 MHz) SNR masers in IC 443 near the Galactic anticenter where interstellar scatter broadening is expected to be negligible. Conversely, Yusef-Zadeh et al. (1999) find the OH (1720 MHz) SNR masers in the direction of the Galactic center to be appreciably scatter broadened. Both Claussen et al. (2002) and H03 find that the...
observed sizes of the masers are consistent with those predicted from collisional pump theory ($\sim 10^{15}$ cm; Lockett et al. 1999). However, OH (1720 MHz) SNR maser observations using the VLBA and MERLIN (H03; Brogan et al. 2002; Claussen et al. 1999, hereafter C99) are not sensitive to the very extended (60º), “face-on” maser emission observed in W28 using the VLA (Yusef-Zadeh et al. 2003; 60º $\approx 10^{18}$ cm projected linear size for a distance of 2.5 kpc to the SNR; Velázquez et al. 2002). The current study examines only the approximately 40 individual maser “spots” observed by C97 (using the VLA) at the location where the shock front of W28 is viewed edge-on (moving transversely across the sky). The maser region observed for this paper is about 1 pc in diameter compared with the approximately 30 pc diameter of the W28 SNR (Fig. 1).

The intrinsic angular size of OH (1720 MHz) SNR maser spots (on the order of 100 mas) is a relatively problematic angular scale for observation with most existing instruments. Radio interferometers with baselines on the order of 10 km in length do not resolve the maser emission and, furthermore, typically convolve several maser spots together within a large beam (on the order of 1º). This “spatial blending” confuses both the angular and spectral character of the individual masers, preventing a determination of intrinsic emission properties. Past high angular resolution studies have employed VLBI baseline lengths on the order of 1000 km (fringe spacings of approximately 30 mas). Although OH (1720 MHz) SNR masers are known to have a compact core component (C99; H03), VLBI experiments typically “resolve out” most maser spots (i.e., the observations are not sensitive to emission on 100 mas angular scales owing to low correlated fringe visibility). However, the angular sensitivity of the MERLIN array (baselines on the order of 100 km in length) is well matched to the angular scale of the masers. The minimum angular resolution of observations using MERLIN (approximately 100 mas) is sufficient to alleviate spatial blending. The largest angular scale sampled in observations using MERLIN (approximately 3º) is sufficient to recover all of the flux density of the masers.

Since the OH radical is paramagnetic, the polarization state of OH emission is strongly affected by the magnetic field in the maser gas (compared with nonparamagnetic molecules such as H$_2$CO). Indeed, circular polarization studies of the Zeeman splitting of OH spectral lines are a significant source of information about the interstellar magnetic field (e.g., Caswell 2004). Zeeman observations of the OH (1720 MHz) maser emission in SNRs have provided estimates of the magnitude of the magnetic fields in supernova/molecular cloud interactions ($\mathbf{B} \approx 0.5$ mG; C99; Brogan et al. 2000, hereafter B00). In addition, observations of the linear polarization of the maser radiation can yield the orientation of the post–SNR shock magnetic field. However, the suggested theoretical conversion from observational parameters to the three-dimensional magnetic field geometry responsible for the observed maser polarization is not straightforward (e.g., Elitzur 1998; Watson & Wyld 2001, hereafter WW01; Gray 2003). Nevertheless, measurement of the following three observational polarization parameters is a necessary step toward understanding the physics of the maser emission: (1) the magnitude of the level splitting due to the Zeeman effect, (2) the position angle $\chi$ of the linear polarization, and (3) the fractional linear polarization $q \equiv (Q^2 + U^2)^{1/2}/I$ of the maser radiation (where $Q$, $U$, and $I$ are Stokes parameters).

To date, all of the full-polarization studies of OH (1720 MHz) SNR masers were completed by C97 and B00 using the VLA. Since much of the prevailing theory pertinent to these masers was published after the C97 paper (Elitzur 1998; Lockett et al. 1999; Wardle 1999), B00 contains a thorough discussion of the theories and their implications for both the C97 and B00 data. The interpretation of many of the results of the current paper also relies on B00. However, because of the insufficient spectral and angular resolution of the VLA observations presented in C97 and B00, the theoretical suggestions presented by B00 could not be confidently constrained using the data available at the time. Indeed, the observational hurdle currently confronting OH (1720 MHz) SNR maser studies is the acquisition of full linear and circular polarimetry of resolved maser sources. The purpose of the current study is to observe a large sample of OH (1720 MHz) SNR masers with spectral and angular resolution sufficient to apply more definitively the wealth of maser polarization theory discussed by B00. The W28 SNR is chosen for this purpose because of the large number of masers (approximately 40).

This paper presents full-polarization observations of the OH (1720 MHz) masers in W28 made using the Multielement Radio-linked Interferometry Network$^1$ (MERLIN) and the Very Long Baseline Array (VLBA).
Long Baseline Array (VLBA) of the NRAO. This paper uses the source numbering convention of C97 (Table 1).

2. OBSERVATIONS AND DATA REDUCTION

2.1. MERLIN+ Lovell

The W28 masers were observed on 2002 January 29 and 31 using the MERLIN radio telescope of Jodrell Bank Observatory for a total of approximately 8 hr. The observations were centered on a Doppler velocity of \(v_{\text{LSR}} = 11\) km s\(^{-1}\) for a line rest frequency of 1720.52998 MHz. Seven antennas were used: the Mark II and Lovell telescopes at Jodrell Bank, the 32 m antenna at Cambridge, and the 25 m dishes at Knockin, Darnhall, Tabley, and Delford. The very short (<500 m) Mark II–Lovell baseline is not used. The baseline lengths of MERLIN range from 11 to 217 km; the array is not sensitive to angular scales larger than 3.3°. The antennas have right- (R) and left-circularly (L) polarized feeds from which RR, LL, RL, and LR cross-correlations were formed. The correlator produced 256 spectral channels across 250 kHz (44 km s\(^{-1}\)). The spectra were Hanning-smoothed off-line, yielding a velocity resolution of 0.36 km s\(^{-1}\). The visibilities were integrated for 8.0 s.

The absolute amplitude calibration is based on observations of 3C 286. The bandpasses were calibrated based on observations of 3C 84. The phases were calibrated using frequent on-line integration (''time smearing;'’ see Thompson et al. 2003). The visibility phases and amplitudes were then (self-)calibrated using images of the bright (approximately 70 Jy) F39 maser (C97). Source 3C 84 was observed at both 14 MHz and 256 kHz bandwidth allowing bandwidth-dependent calibration to be transferred. The position angle of the linear polarization response of the antennas was determined from the observations of 3C 286 and 1748–253. The rms noise in the final single-channel images is 8 mJy beam\(^{-1}\), in agreement with expected instrumental behavior. The FWHM synthesized beam of the images is 550 x 100 mas at a position angle of 9°.

The tracking position during the observations was the position of the F39 maser determined from VLBA observations by C97 (\(\alpha_{2000.0} = 18^h01^m52.7054, \delta_{2000.0} = -23^\circ19'24".641\)). Since the primary beam of the largest MERLIN antenna (the 76 m Lovell) is approximately 10′, only the E and F region masers are within the primary beam of the array and the amplitude of the A, B, C, and D region masers are attenuated (the A region lies in a sidelobe of the primary beam of the Lovell antenna). In addition, the relatively large angular distance from the phase-tracking center to the outlying maser regions resulted in decreased amplitude due to decoherent fringe visibility averaging during on-line integration (‘‘time smearing;’’ see Thompson 1999). These amplitude degradations have been corrected for the few masers detected in the outlying regions.

2.2. VLBA+ Y1

We also observed the W28 OH (1720 MHz) masers on 2002 September 26 and October 7 and 14 and 2003 February 24 and March 14 and 24 with the 10 antennas of the VLBA plus one antenna of the VLA (Y1) for approximately 30 hr. The antennas have right- (R) and left-circularly (L) polarized feeds from which RR, LL, RL, and LR cross-correlations were formed. The correlator produced 128 spectral channels across a 62.5 kHz (11 km s\(^{-1}\)) band yielding a 0.09 km s\(^{-1}\) velocity channel spacing. The spectra were off-line Hanning-smoothed, yielding a velocity resolution of 0.18 km s\(^{-1}\). Two overlapping observing bands were used, centered on \(v_{\text{LSR}} = 13\) and 8 km s\(^{-1}\) in order to cover the 16 km s\(^{-1}\) range over which the masers are observed. The visibilities were integrated for 4.7 s.

The absolute amplitude scale is set using on-line system temperature monitoring and a priori antenna gain measurements. Bandpass responses and station delays were found from observations of 3C 345. The visibility phases and amplitudes were then (self-)calibrated using images of the bright (approximately 70 Jy) F39 maser (C97). The position angle of the linear polarization response of the antennas is determined from observations of 3C 286 and J1751+0939.

The baseline lengths of the VLBA+Y1 array range from 52 to 8611 km; the array is not sensitive to angular scales larger than 0.70. The correlated field of view with respect to the phase-tracking position is 30′. Thus, in order to observe all of the W28 masers, two array-pointing positions and eight correlator-tracking positions were used, listed in Table 1. The synthesized beam of the resulting images is 25 x 9 mas at a position angle of 10°. The rms noise in the final single-channel images is 30 mJy beam\(^{-1}\), in agreement with expected values.

3. RESULTS

3.1. Angular Structure and Position

All data reduction and imaging were performed with the AIPS\(^3\) software package. Figures 2, 3, and 4 show the line-integrated (zeroth-moment) MERLIN images of 19 of the masers. The majority of maser detections are in the E and F maser regions; the MERLIN observations contain only three detections outside of regions E and F, and the VLBA observations contain no detections outside of regions E and F. These detection rates are consistent with expectations based on previous observations. Of the 41 maser spots detected in W28 by C97 using the VLA, 23 were observed to have intensities greater than 1 Jy beam\(^{-1}\). The MERLIN observations contain

\(^{2}\) The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

\(^{3}\) The Astronomical Image Processing System (AIPS) is documented at http://www.nrao.edu/aips.
detections of 21 of these 23 masers; the only exceptions are the A2 and E32 masers. Even though the A maser region lies in a sidelobe of the Lovell primary beam, the A3 maser was detected. However, since its amplitude is very uncertain, we do not discuss it further. In addition, the MERLIN observations indicate that there are multiple angular components in the F20 maser region (Figs. 2 and 3). Figures 5 and 6 show the peak-channel images of the F39A and F39C masers from the VLBA+Y1 observations.

Tables 2 and 3 list the deconvolved angular sizes and total flux densities observed using MERLIN and the VLBA. The F40 maser is detected on only the Y1-PT baseline (VLA–Pie Town, 52 km station separation, 700 mas fringe spacing) and Y1-LA baseline (VLA–Los Alamos, 226 km, 150 mas) in the VLBA+Y1 observations and was not imaged. The observed size of the F40 maser in the VLBA data set is estimated to be 350±50 mas from the two fringe visibilities. Four of the 28 masers detected using MERLIN are detected using the VLBA+Y1 (E24, F39A, F39C, and F40) for a detection rate of approximately 15%. Using the VLBA+Y1, H03 were able to image one of the five masers in IC 443 that are detected using MERLIN for a comparable detection rate of approximately 20%.

The deconvolved sizes of the MERLIN maser images are in the range 90–350 mas (225–875 AU projected linear size). Compact cores with deconvolved sizes of 20 mas (50 AU) are apparent in the VLBA images. These findings are consistent with theoretical expectations (Lockett et al. 1999; Wardle 1999) and previous observations (C99; H03). In addition, the total...
flux density of the masers as measured from the MERLIN images is in good agreement with the VLA data of C97, indicating that none of the maser emission is resolved out using MERLIN. The VLBA images of the F39A and F39C maser emission cores contain approximately 75% of the flux density detected in observations using the VLA and MERLIN, consistent with previous observations (C99; H03).

The absolute positions in the current VLBA data have a 3σ uncertainty of about 100 mas since the observations did not include an astrometric-quality phase calibrator (e.g., Reid 1999). However, the current MERLIN observations were phase-referenced to the calibrator 1748–253 and have a 1σ absolute position uncertainty of about 5 mas. The VLBA observations of C99 were also phase-referenced to 1748–253 and have a 1σ absolute position uncertainty of 3 mas. The current maser positions measured using MERLIN are consistent with the positions measured by C99. For a distance to the masers of 2.5 kpc (Velázquez et al. 2002), the agreement between the C99 observations in 1997 May and the current MERLIN observations in 2002 January implies a 3σ upper limit of 60 km s⁻¹ on the velocity of the masers. The absolute positions in the current VLBA data have a 3σ uncertainty of about 100 mas since the observations did not include an astrometric-quality phase calibrator (e.g., Reid 1999). However, the current MERLIN observations were phase-referenced to the calibrator 1748–253 and have a 1σ absolute position uncertainty of about 5 mas. The VLBA observations of C99 were also phase-referenced to 1748–253 and have a 1σ absolute position uncertainty of 3 mas. The current maser positions measured using MERLIN are consistent with the positions measured by C99. For a distance to the masers of 2.5 kpc (Velázquez et al. 2002), the agreement between the C99 observations in 1997 May and the current MERLIN observations in 2002 January implies a 3σ upper limit of 60 km s⁻¹ on the velocity of the masers.

Fig. 4.—Line-integrated (zeroth-moment) contour and gray-scale image of part of the W28 E maser region from the MERLIN observations. The contours are 15, 30, 60, and 90 times 180 Hz Jy beam⁻¹. The beam, plotted in the lower right corner, is 550×90 mas at a position angle of 9°.

Fig. 5.—Contour and gray-scale image of the F39A maser region using the velocity channel from the VLBA observations. The contour levels are −15, 15, 30, 45, 60, and 75 times the image rms noise level of 30 mJy beam⁻¹ (no negative contours appear). The beam, plotted in the lower left corner, is 25×9 mas at a position angle of 10°. The three image features are labeled (Table 5).

Fig. 6.—Contour and gray-scale image of the F39C maser region using the velocity channel from the VLBA observations. The contour levels are −14, 14, 28, and 42 times the image rms noise level of 30 mJy beam⁻¹ (no negative contours appear). The beam, plotted in the lower left corner, is 25×9 mas at a position angle of 10°. The two image features are labeled (Table 5).
transverse speed of the masers. Draine et al. (1983) suggest speeds in the range 10–50 km s⁻¹ (3–16 mas yr⁻¹) for the shocks in which OH (1720 MHz) SNR masers occur (see H03 for a complete discussion of the potential for proper motion in OH SNR masers). Since the current observations are not sensitive to the proper motions that may have occurred since the C99 observations, we adopt the C99 position for the F39A maser in this paper.

The relative positions of the masers to the F39A maser are limited only by the signal-to-noise ratio and the angular resolution of the observations, not by the initial phase calibration. For example, the current VLBA observation of the F39C maser (40:1 signal-to-noise, 15 mas beam) has a 1σ relative position uncertainty of <1 mas with respect to the F39A maser position. Furthermore, the relative separation of the two main peaks in the current VLBA images of the F39A (27 mas, 70 AU) and F39C (40 mas, 100 AU) masers is consistent with the VLBA observations by C99, indicating a 1σ upper limit on the relative motion among the multiple maser emission cores of less than 1 mas (2.5 AU; a relative transverse velocity <2 km s⁻¹).

### 3.2. Line Profiles

Tables 4 and 5 list the fitted positions and deconvolved spectral profile properties of the maser lines from the MERLIN and VLBA observations. All line profiles were fitted using the GIPSY software package. Typical line widths are slightly less than 1 km s⁻¹, with values measured using the VLBA being smaller (narrower) than values measured using MERLIN (the trend of observed line width decreasing with beam size is observed for many maser species; e.g., OH [4765 MHz], Palmer et al. 2003; H₂CO [4830 MHz], Hoffman et al. 2003b). This difference in line width between the MERLIN and VLBA data is also observed for the OH (1720 MHz) masers in IC 443 (H03). However, unlike the IC 443 observations, none of the line widths observed in W28 are below the Doppler line width of 0.5 km s⁻¹ [i.e., in the current data Δv/Δν > (2c)/(2kT ln 2/m²); where c is the speed of light, k is Boltzmann’s constant, m is the mass of the OH molecule, and T is the kinetic temperature of the maser gas, which we assume to be 90 K, as suggested in §1]. Also listed in the tables are the brightness temperatures T_b of the masers, derived using the relation T_b = (0.565Δν²S)/(kθₑθₑ), where S is the flux density of the maser (W m⁻² Hz⁻¹), Δν is the wavelength of the radiation (m), k is Boltzmann’s constant, and θₑ and θₑ are the major and minor axes, respectively, of the synthesized beam (rad; e.g., Rybicki & Lightman 1979).

#### 3.3. Zeeman Circular Polarization

##### 3.3.1. Resolved Splitting

The OH (1720 MHz) SNR masers in W28 were imaged separately in right-circular polarization (RCP, using RR cross-correlations) and left-circular polarization (LCP, using LL cross-correlations). Although the RCP and LCP images of a given maser are coincident in sky position and spectral channel (the instrumental channel separation is approximately 0.2 km s⁻¹; §2), the Gaussians fitted to the RCP and LCP line profiles have different center velocities (separated by approximately 0.07 km s⁻¹). We assume that the relative displacement of the RCP and LCP lines is due to Zeeman level splitting of the maser transition in a magnetic field. Both the MERLIN and VLBA observations indicate resolved Zeeman splitting in this manner.

The spectral line observations of the masers in this data set have both high signal-to-noise ratio (~2500:1 for the F39A maser in the MERLIN data) and well-resolved spectral lines (the lines span about 15 spectral channels). For these relatively high confidence detections, the uncertainty in the measurement of the relative displacement of the fitted RCP and LCP line centers is approximately 10 m s⁻¹. In addition, the symmetric fit residuals discussed in §4.2 do not affect the confidence with which the central velocity is fitted.

The velocity difference is converted to magnetic field using the relationship $v_{\text{RCP}} - v_{\text{LCP}} = 2B_{\text{RL}}$, where $B_{\text{RL}}$ denotes the magnetic field measured using RCP and LCP line profiles and Z is the Zeeman splitting coefficient (e.g., Fish et al. 2003). The magnetic substates of the OH ground-state satellite lines have the ratio of intensities 6:3:1 (e.g., Davies 1974). For thermal emission and absorption, all of these substates contribute to the observed spectrum and the Zeeman splitting factor is their
weighted average $Z = 0.236 \text{ km s}^{-1} \text{ mG}^{-1}$ (1.35 Hz $\mu$G$^{-1}$). However, for maser amplification, the strongest of these substates is dominant (e.g., Gray et al. 1992; Caswell 2004). For the saturated OH satellite line masers in the current study, we adopt $Z = 0.114 \text{ km s}^{-1} \text{ mG}^{-1}$ (0.654 Hz $\mu$G$^{-1}$). (For an alternate viewpoint, compare the discussion in Fish et al. [2003] concerning their choice of $Z = 0.236 \text{ km s}^{-1} \text{ mG}^{-1}$.) Table 6 lists the velocity differences and corresponding magnetic fields for the masers in which the Zeeman splitting is resolved.

3.3.2. Stokes $V$ Fitting

The results presented in § 3.3.1 represent the first observation of resolved Zeeman splitting in OH (1720 MHz) masers. Although these resolved Zeeman splitting results already provide complete information about the magnetic field strength, we present the following Stokes $V$ fitting results as well since previous Zeeman analyses of OH (1720 MHz) SNR masers have employed the fitting method described in this section.

Zeeman analyses are based on the degree to which the Zeeman components have been separated in frequency from the resonance frequency of the line transition. The separation may be parameterized with $x_B \equiv \Delta \nu_B / \Delta \nu_D$, where $\Delta \nu_B$ is the Zeeman frequency separation of the split substates and $\Delta \nu_D$ is the Doppler-broadened width of the maser line, typically the same as the width of the saturated Stokes $I$ maser line profile (cf. H03; Watson & Wyld 2003). The Zeeman splitting in the current data set is $x_B \approx 0.1$ (Tables 4, 5, and 6). This degree of splitting may violate the assumption ($x_B \ll 1$) upon which most theoretical investigations are based (e.g., Goldreich et al. 1973), as is discussed in § 4.3.

| Feature | R.A. (J2000.0) | Decl. (J2000.0) | $I$ (mJy beam$^{-1}$) | $\Delta \nu$ (km s$^{-1}$) | $v_{\text{LSR}}$ (km s$^{-1}$) | $T_B$ ($10^3$ K) |
|---------|----------------|----------------|----------------------|----------------|----------------|----------------|
| B7      | 18 01 15.637   | $-23$ 16 36.67 | 150(50)$^a$          | 1.34(8)        | 5.22(3)        | 1.3            |
| D13     | 18 01 44.349   | $-23$ 16 21.24 | 270(50)$^a$          | 0.89(3)        | 13.96(1)       | 2.3            |
| F14     | 18 01 50.754   | $-23$ 18 20.76 | 1120                 | 1.04(1)        | 15.36(1)       | 9.5            |
| F16     | 18 01 50.977   | $-23$ 18 32.07 | 469                  | 0.85(2)        | 11.95(1)       | 4.0            |
| F19     | 18 01 51.210   | $-23$ 18 29.09 | 287                  | 0.67(2)        | 11.21(1)       | 2.4            |
| F20A    | 18 01 51.227   | $-23$ 18 33.85 | 712                  | 1.11(2)        | 9.27(1)        | 6.1            |
| F20B    | 18 01 51.229   | $-23$ 18 32.47 | 721                  | 0.96(2)        | 8.92(1)        | 6.1            |
| F21     | 18 01 51.238   | $-23$ 18 30.98 | 895                  | 0.89(2)        | 10.20(1)       | 7.6            |
| E22     | 18 01 51.269   | $-23$ 17 43.89 | 863                  | 1.00(2)        | 15.29(1)       | 7.6            |
| E23     | 18 01 51.341   | $-23$ 17 45.61 | 479                  | 0.96(3)        | 15.69(2)       | 4.1            |
| E24     | 18 01 51.350   | $-23$ 17 43.50 | 3214                 | 0.94(1)        | 13.10(1)       | 27.4           |
| E26     | 18 01 51.376   | $-23$ 17 51.95 | 167                  | 0.91(5)        | 11.21(2)       | 1.4            |
| E27     | 18 01 51.415   | $-23$ 17 47.56 | 191                  | 1.22(4)        | 12.70(2)       | 1.6            |
| E30     | 18 01 51.697   | $-23$ 17 54.89 | 1571                 | 0.78(1)        | 11.62(1)       | 13.4           |
| E31     | 18 01 51.755   | $-23$ 17 56.60 | 3003                 | 0.95(1)        | 11.68(1)       | 25.6           |
| E33     | 18 01 51.850   | $-23$ 18 08.46 | 585                  | 0.94(2)        | 9.37(1)        | 5.0            |
| E34     | 18 01 51.852   | $-23$ 18 07.00 | 398                  | 1.11(2)        | 11.23(1)       | 3.4            |
| E35     | 18 01 52.015   | $-23$ 17 11.16 | 232                  | 0.87(3)        | 11.92(1)       | 2.0            |
| E36     | 18 01 52.114   | $-23$ 17 09.17 | 869                  | 0.75(1)        | 11.56(1)       | 7.4            |
| F39A    | 18 01 52.707   | $-23$ 19 24.65 | 28890                | 0.70(1)        | 11.18(1)       | 246.0          |
| F39B    | 18 01 52.707   | $-23$ 19 25.55 | 1221                 | 0.73(2)        | 9.78(1)        | 10.4           |
| F39C    | 18 01 52.731   | $-23$ 19 24.20 | 19279                | 0.77(1)        | 9.75(1)        | 164.2          |
| F39D    | 18 01 52.736   | $-23$ 19 25.21 | 2579                 | 0.84(2)        | 10.79(1)       | 22.0           |
| F40     | 18 01 52.714   | $-23$ 19 15.94 | 604                  | 0.69(2)        | 8.96(1)        | 5.1            |
| F41     | 18 01 52.826   | $-23$ 19 19.18 | 1265                 | 0.76(1)        | 9.94(1)        | 10.8           |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ Corrected for beam attenuation and time smearing.
### TABLE 6
**Zeeman Results**

| FEATURE | $v_{\text{RCP}} - v_{\text{LCP}}$ (km s$^{-1}$) | $B_{\text{RL}}$ (mG) | $B_{\theta}$ (mG) | $v_{\text{RCP}} - v_{\text{LCP}}$ (km s$^{-1}$) | $B_{\text{RL}}$ (mG) | $B_{\theta}$ (mG) |
|---------|---------------------------------------------|---------------------|-----------------|---------------------------------------------|---------------------|-----------------|
| F14     | 0.029(12) 0.25 ± 0.10 0.22 ± 0.04 b b b |
| F16     | 0.082(17) 0.72 ± 0.15 0.66 ± 0.10 b b b |
| F19     | ... ... ... 0.34 ± 0.14 b b b |
| F20A    | 0.08(2) 0.70 ± 0.17 0.55 ± 0.07 b b b |
| F20B    | 0.070(17) 0.61 ± 0.15 0.58 ± 0.06 b b b |
| F21     | 0.058(14) 0.51 ± 0.12 0.53 ± 0.05 b b b |
| E22     | 0.09(2) 0.79 ± 0.17 0.80 ± 0.05 b b b |
| E23     | ... ... ... 0.27 ± 0.09 b b b |
| E24     | 0.062(6) 0.54 ± 0.05 0.63 ± 0.01 0.051(34) 0.45 ± 0.27 0.36 ± 0.14 |
| E26     | ... ... ... 1.15 ± 0.20 b b b |
| E27     | ... ... ... 0.84 ± 0.16 b b b |
| E30     | 0.049(10) 0.43 ± 0.09 0.40 ± 0.03 b b b |
| E31     | 0.043(8) 0.38 ± 0.07 0.34 ± 0.02 b b b |
| E33     | ... ... ... 0.53 ± 0.08 b b b |
| E35     | ... ... ... 0.65 ± 0.19 b b b |
| F39AI   | 0.060(1) 0.52 ± 0.01 0.581 ± 0.006 0.042(4) 0.37 ± 0.03 0.31 ± 0.02 |
| F39AII  | ... ... ... b b b |
| F39AIII | ... ... ... 0.064(9) 0.56 ± 0.08 0.37 ± 0.09 b b b |
| F39B    | 0.098(18) 0.86 ± 0.08 1.00 ± 0.04 b b b |
| F39C    | 0.079(5) 0.69 ± 0.04 0.70 ± 0.01 0.093(8) 0.82 ± 0.07 0.63 ± 0.08 |
| F39CII  | ... ... ... 0.075(9) 0.66 ± 0.08 0.50 ± 0.06 b b b |
| F39D    | 0.054(9) 0.47 ± 0.08 0.27 ± 0.02 b b b |
| F41     | 0.122(8) 1.07 ± 0.07 1.09 ± 0.04 b b b |

* The velocity difference between the centers of the Gaussians fitted to the RCP and LCP line profiles.

b Feature not detected.

### TABLE 7
**MERLIN Linear Polarization Results**

| Feature | $Q$ (mJy beam$^{-1}$) | $U$ (mJy beam$^{-1}$) | $\chi$ (deg) | $q$ (%) | $\partial\chi/\partial\nu$ (deg Hz$^{-1}$) |
|---------|----------------------|----------------------|------------|--------|---------------------------------|
| B7      | <10                  | <10                  | ...        | <70    | a                              |
| D13     | <10                  | <10                  | ...        | <40    | a                              |
| F14     | -17                  | 17                   | 68(12)     | 2(1)   | a                              |
| F16     | -15                  | -25                  | 60(12)     | 2(1)   | a                              |
| F19     | 39                   | 15                   | 76(10)     | 1(4)   | a                              |
| F20A    | -33                  | 25                   | 71(8)      | 6(1)   | -0.0023(10)                    |
| F20B    | 17                   | 30                   | 30(8)      | 5(1)   | -0.0043(20)                    |
| F21     | <10                  | 17                   | 45(9)      | 9(2)   | -0.0022(10)                    |
| E22     | <10                  | 24                   | 75(6)      | 5(1)   | 0.012(8)                       |
| E23     | <10                  | <10                  | ...        | <6     | a                              |
| E24     | <52                  | <10                  | 90(3)      | 2(1)   | a                              |
| E26     | -35                  | <10                  | 90(5)      | 22(5)  | a                              |
| E27     | <10                  | <10                  | <10        | <10    | a                              |
| E30     | -30                  | -15                  | 77(8)      | 2(1)   | a                              |
| E31     | -48                  | <10                  | 90(4)      | 2(1)   | a                              |
| E33     | -12                  | 12                   | 68(16)     | 2(1)   | a                              |
| E34     | -11                  | <10                  | 90(11)     | 4(1)   | a                              |
| E35     | <10                  | -10                  | 45(7)      | 12(2)  | a                              |
| E36     | -25                  | -8                   | 81(9)      | 3(1)   | a                              |
| F39A    | -1712                | -689                 | -79.0(13)  | 7(1)   | -0.00236(6)                    |
| F39B    | -109                 | -37                  | -81(3)     | 9(1)   | a                              |
| F39C    | -2159                | 214                  | 87.2(35)   | 11(1)  | 0.00076(9)                      |
| F39D    | -139                 | -11                  | -88(2)     | 5(1)   | -0.0053(11)                     |
| F40     | <10                  | 33                   | 45(5)      | 6(1)   | a                              |
| F41     | <10                  | 77                   | 45(3)      | 6(1)   | 0.0040(15)                      |

* Insufficient signal-to-noise ratio to constrain slope.
In the regime $x_B \ll 1$, the following equation relates the Stokes $I$ and Stokes $V$ profiles (e.g., Roberts et al. 1993; Sarma et al. 2001; B00):

$$V = b \frac{\partial I}{\partial \nu} + aI. \quad (1)$$

The Stokes $I$ and $V$ profiles of the maser lines from both the MERLIN and VLBA observations were fitted to equation (1). All fitting was performed with the MIRIAD\textsuperscript{5} software package.

The $aI$ term in equation (1) represents the symmetrical component of the Stokes $V$ profile. The fitted sign and magnitude of $a$ are consistent with instrumental “leakage” of Stokes $I$ into Stokes $V$ (e.g., Crutcher et al. 1975); in the current data $a$ does not represent an intrinsic property of the maser radiation. For example, the fits to the MERLIN data for the F39A and E24 masers yield $a = 0.4\%$ and $0.2\%$, respectively, consistent with the expected instrumental leakage (0.3\%) of the MERLIN array.\textsuperscript{6} However, we investigated whether $a$ may represent an intrinsic property of the maser emission. In the case of unsaturated amplification, a symmetric component of Stokes $V$ is expected (e.g., Vlemmings et al. 2002) but must be accompanied by a narrowing of $\partial I / \partial \nu$ with respect to Stokes $V$, an effect that is not observed in the current data (see also B00). Therefore, we have subtracted the $aI$ term from the data and do not consider it in the current analysis.

The conversion between the fit parameter $b$ and the magnetic field strength has differing theoretical interpretations, to be discussed in § 4.3. Since many of the relevant current theories suggest that $b$ depends on $\theta$, the angle between the line of sight and the magnetic field, we denote the magnetic field strength determined from equation (1) as $B_{\theta}$, to distinguish it from $B_{RL}$, which is measured as described in § 3.3.1. In this paper the values of the fitted parameter $b$ are related to the magnetic field $B_{\theta}$ using $b = ZB_{\theta}/2$. Note that the factor of $\frac{1}{2}$ is associated with the derivative of Stokes $I$ since $I = 2R$ or $2L$ (in the case of equal amplification of both polarizations) and $V = R - L$.

\textsuperscript{5} The Multichannel Image Reconstruction, Image Analysis and Display (MIRIAD) is documented at http://bima.astro.umd.edu/miriad.

\textsuperscript{6} See the MERLIN User Guide, http://www.merlin.ac.uk/user_guide/OnlineMUG.

**TABLE 8**  

| Feature       | $Q$ (mJy beam$^{-1}$) | $U$ (mJy beam$^{-1}$) | $\chi$ (deg) | $q$ (%) | $\partial \chi / \partial \nu$ (deg Hz$^{-1}$) |
|---------------|-----------------------|-----------------------|---------------|--------|----------------------------------|
| E24           | $<30$                 | $<30$                 | ...           | $<15$  | $^*$                                   |
| F39AI         | $-190$                | $-70$                 | $-81(6)$      | $8(1)$ | $-0.0038(14)$                          |
| F39AI         | $-170$                | $<30$                 | $90(8)$       | $9(1)$ | $^*$                                   |
| F39AI         | $<-30$                | $<30$                 | ...           | $<-6$  | $^*$                                   |
| F39CI         | $-300$                | 90                    | 82(7)         | 24(2)  | 0.0058(16)                            |
| F39CI         | $-280$                | 220                   | 71(8)         | 22(2)  | $^*$                                   |

* Insufficient signal-to-noise ratio to constrain slope.

Fig. 7.—Typical full-polarization spectra from the MERLIN observations for the (a) F39A and (b) E24 masers. The dashed lines are, from top to bottom, the best-fit Gaussian to Stokes $I$, the derivative of the best-fit Gaussian scaled with the fitted Zeeman magnetic field, and the best-fit Gaussian scaled with the Stokes $Q$ and $U$ amplitudes listed in Table 7.
Table 6 it is clear that the derived values of $B_{RL}$ and $B_{RL}/C_{18}$ are in good agreement. This correspondence is discussed further in § 4.3.

The improvement in the spectral and angular resolution from the C97 VLA observations to the MERLIN observations has allowed a more reliable determination of the polarization properties of the line profiles. For example, the F20B and E27 masers are shown to have multiple spectral components based on the MERLIN observations (Table 4). Furthermore, the C97 VLA experiment yielded only 11 Zeeman detections from 41 image features, while the current MERLIN observations yield 23 Zeeman detections from 28 image features (Table 6). Low signal-to-noise ratio, not confusion due to blending, prevented Zeeman fitting of 5 of the 28 masers observed using MERLIN.

We can directly compare the derived magnetic field strengths from this work with those of C99. Such a comparison shows that the field strengths reported in C99 are systematically higher by about a factor of 4. We do not understand this discrepancy. Indeed, we have reanalyzed the data of C99 in exactly the same manner as we analyzed the new data presented here. In doing so, we obtain comparable results for the strength of the magnetic field fitted to both the C99 data and the current data. For example, in our reanalysis, the magnetic field derived for the position marked F39B using the C99 data (which is labeled F39AI in Fig. 5) is $0.014\pm0.06$ mG. This compares favorably with the field determined from the current data as $0.031\pm0.02$ mG. Given the similar results from the reanalysis, we suggest that C99 had a conversion error in the calculation of their field strengths.

3.4. Linear Polarization

The linear polarization angles $\chi$ listed in Tables 7 and 8 are determined using the usual relation $\tan(2\chi) = (U/Q)$, where $Q$ and $U$ are Stokes parameters calculated from the RL and LR cross-correlations (§ 2). The polarization angles are in good agreement with those observed by C97 using the VLA. Figure 7 shows typical full-polarization profiles for two of the masers observed using MERLIN. The dotted lines in Figure 7 also show the results of our Stokes $I$ Gaussian analysis, the Stokes $V$ fit using equation (1), and the Stokes $I$ fit scaled to the appropriate value to match the amplitudes of $Q$ and $U$ listed in Table 7. Figure 8 shows two full-polarization spectra from the VLBA observations. The percentage of linear polarization found for the W28 OH (1720 MHz) masers ranges from approximately 5% to 20%. The exact values for each maser are also listed in Tables 7 (MERLIN) and 8 (VLBA).

For every pair of masers in the MERLIN observations, the difference in polarization angles $\Delta\chi$ has been plotted in Figure 9 as a function of the relative separation of the masers. The histogram in the figure indicates that the majority of the masers (approximately 55%) have $\Delta\chi\approx0^\circ$, with a secondary population (approximately 30%) near $\Delta\chi=45^\circ$. The dashed lines in Figure 9 have a slope of zero, indicating that the difference in polarization angles is predominantly independent of maser separation.
Thus, the masers have comparable polarization angles throughout the approximately 2° spanned by the E and F maser regions.

The value for $\chi_C^{23}$ listed in Tables 7 and 8 is the observed change in polarization angle across the maser line profile. Figures 10 and 11 show that $\chi_C^{23}$ is approximately linear. This result is discussed in §4.5. The values of $\chi_C$ listed in the tables and figures are the values at the center of the line.

4. DISCUSSION

As described in §1, previous OH (1720 MHz) SNR maser studies were based on arcsecond-resolution observations with instruments such as the VLA (e.g., B00). In the current paper we describe MERLIN and VLBA observations that have more favorable angular and spectral resolution. As expected, these new observations have sufficiently alleviated instrumental blending to permit reliable measurements of the intrinsic emission properties of the masers. However, in interpreting these results in this section of the paper, we must rely on the existing literature concerning theoretical investigations of the maser emission.

The theoretical investigations upon which our analyses are based may be grouped into three topics, listed here in order of decreasing consensus: (1) the population inversion of the 1720 MHz transition, (2) the degree of saturation of the maser gain process, and (3) the polarization of the maser emission due to the presence of a magnetic field in the maser gas.

In §4.1 we discuss the relative location, size, and brightness of the W28 masers. In the 10 years since the rediscovery of OH SNR masers (Frail et al. 1994), there has been a successful convergence between observation and theory concerning the expected size and excitation process of OH SNR masers (H03; Claussen et al. 2002; Lockett et al. 1999; Wardle 1999). In this paper we add further evidence of the agreement between theory and observation (§3.1) and describe some new results pertinent to the milliarcsecond scale of the current observations.

In §4.2 we discuss the degree to which the masers are saturated. Using two independent tests, we find that the masers must be at least partially saturated. However, many of the relevant maser polarization theories depend sensitively on the exact degree of maser saturation, which we are unable to accurately constrain.

In §§4.3, 4.4, and 4.5 we compare the observed polarization properties with existing maser theories, including new work since this topic was reviewed by B00 (e.g., WW01; Gray 2003). However, we emphasize that all of these theories employ two limits: either $x_B < 1$ (typical of the thermal Zeeman case) or $x_B > 1$ (fully resolved Zeeman splitting typical of masers found in star-forming regions), which may render them inapplicable to our specific case in which $x_B \approx 0.1$. For the time being we are stuck with this ambiguity but hope that these observational data will spark interest in a theoretical study appropriate to the SNR OH (1720 MHz) maser regime. Thus, the “$x_B$ limit” caveat imposed by the currently available theories should be kept in mind throughout these sections.

4.1. Angular Morphology

Observations that span a wide range of spatial scales suggest that the OH (1720 MHz) masers exhibit (1) a large region (500–1000 AU) of relatively weak emission surrounding, in some cases, (2) multiple, closely spaced (on the order of 100 AU), compact cores (50–100 AU) of emission (C99; H03). In general,
radio interferometers such as the VLA (baseline lengths on the order of 10 km), MERLIN (~100 km), and VLBA (~1000 km) are sensitive to different size-scale regimes of this emission morphology.

The W28 SNR, and OH (1720 MHz) SNRs in general, contain several physically distinct maser regions (discerned using differing velocities, polarization properties, etc.) separated by angular distances of a few hundred milliarcseconds to several arcminutes. Observations using the VLA (with beam sizes ~100 mas) yield images in which several emission regions are blended into single image spots. Observations using MERLIN (with beam sizes of approximately 100 mas) yield images in which every image feature represents a physically distinct region of maser emission (Tables 2, 4, and 7). For example, Figure 2 shows four masers in the F39 region with distinct velocities, Zeeman profiles, and linear polarization properties (Tables 6 and 7) at the position where observations using the VLA indicate only one image feature for which the emission properties could not be determined (C97).

Observations at the position of a given MERLIN maser image using the VLBA (approximately 10 mas angular resolution) reveal multiple image peaks, just as MERLIN observations of a VLA source reveal several image peaks. However, these image peaks observed using the VLBA do not have different velocities (on the scale of a line width) or different polarization properties (see also C99; H03). Indeed, the multiple peaks in the VLBA images are more likely due to inhomogeneities within a single region of maser emission than to several physically distinct maser regions coincident along the line of sight. For example, MERLIN observations at the position of F39 contain the F39A and F39C masers (Fig. 2). The velocities of the F39A and F39C masers are $v_{\text{LSR}} \approx 11.2$ and $9.7$ km s$^{-1}$, respectively (Table 4). These velocities are separated by a few line widths and indicate a difference in systemic kinematics between the F39A and F39C regions. In contrast, the peaks observed in the VLBA images (Figs. 5 and 6), F39AI–III and F39Cl–II (Table 5), are separated by much less than one line width in velocity (a separation of approximately 0.04 km s$^{-1}$ compared with a line width of approximately 0.60 km s$^{-1}$). Therefore, we conclude that the different peaks in the VLBA images of OH (1720 MHz) SNR masers are not dynamically distinct regions of maser gas but are instead emission inhomogeneities within a single volume of maser gas.

4.2. Saturation of the Maser Amplification

A critical element in the analysis of maser radiation is the degree to which the maser is saturated (e.g., Vlemmings et al. 2002; WW01; Elitzur 1998). For the case of OH (1720 MHz) SNR masers we discuss two tests: degree of linear polarization and line profile shape.

In order for maser emission to possess linear polarization, it is expected on theoretical grounds (e.g., Nedoluha & Watson 1990) that the maser needs to be at least partially saturated. This expectation has been used as evidence for partial saturation in the case of the OH (1720 MHz) SNR masers in W28, W44, IC 443, and W51, which all show linear polarization as observed using the VLA (C97; B00). In this paper the MERLIN observations contain 22 detections of linear polarization. Furthermore, there are no nondetections of linear polarization with confidence higher than 3 $\sigma$. Thus, it seems likely that the OH (1720 MHz) SNR masers are at least partially saturated.

Another test results from the fact that unsaturated maser emission is expected to deviate substantially from a pure Gaussian profile (see, e.g., Elitzur 1998). Watson et al. (2002) have examined the deviation of maser line shapes from Gaussian. Figure 12 shows the fitted Gaussians and residuals to the E24 and F39A maser lines from the MERLIN data. In the Watson et al. (2002) model, the Gaussian deviation of the line profile is quantified using the two parameters $\delta$ (defined in Watson et al.
2002) and kurtosis (the normalized fourth central moment of a distribution; e.g., Abramowitz & Stegun 1972). The fit residuals of the line profiles observed using MERLIN have deviation parameters similar to the H₂O masers considered by Watson et al. (2002; /C14/C0 
4 and a negative kurtosis), indicating that the OH (1720 MHz) SNR masers are partially saturated (have a normalized model intensity near unity).

Both of these tests indicate at least partial saturation of the OH (1720 MHz) SNR masers. Therefore, the saturated regime of the maser polarization theories proposed by both Watson et al. (2002) and Elitzur (1998) will be applied in the following discussion.

4.3. Zeeman Detections

The magnetic fields of the W28 masers have been estimated using two techniques: resolved Zeeman splitting and fitting to Stokes V. Magnetic fields calculated directly from resolved Zeeman splitting (B_{RL}) are generally thought not to depend on \( \theta \); thus, this technique measures the full magnetic field strength (e.g., Townes & Schawlow 1955). The fitting of the Stokes V profiles to obtain \( b \) using equation (1) (§3.3.2) is typically used for measuring the Zeeman effect in thermal gas. In the thermal case, \( b \) is proportional to \( B \cos \theta \), but as mentioned in §3.3.2, the dependence of \( b \) on \( \theta \) for the maser case is uncertain. For the first time we are able to directly compare these two techniques.

For the maser case in which \( x_B \ll 1 \), a number of studies have examined the dependence of \( b \) on \( \theta \) for maser emission. Nedoluha & Watson (1992) and Watson et al. (2002) suggest that for unsaturated masers the thermal interpretation (i.e., \( b \propto B \cos \theta \)) is appropriate. However, as described in §4.2, the SNR OH (1720 MHz) masers are likely at least partially saturated. In the case of a saturated maser, the \( \theta \) dependence is both more controversial and complex, possibly depending on a geometrical term in addition to \( \theta \). Here we only concentrate on the \( \theta \) dependence. Elitzur (1998) suggests that \( b \propto \cos \theta^{-1} \), while WW01 present numerical simulations that yield different results (although without a mathematical expression it is difficult to express exactly how different). Alternatively, \( b \) may be independent of \( \theta \) in the \( x_B \approx 0.1 \) case observed for the OH (1720 MHz) masers (M. Elitzur 2003, private communication), in analogy with the \( x_B > 1 \) maser case.

Figure 13 shows a plot of the derived \( B_{RL} \) versus \( B_\theta \) values for each maser. It is clear from this plot and Table 6 that \( B_{RL} \approx B_\theta \) to a high degree of coincidence. This strong correlation leads to only two viable alternatives for the dependence of \( b \) on \( \theta \) for...
the SNR OH (1720 MHz) masers: (1) there is an as yet undiscovered \( \theta \) dependence on \( b \) measured from the resolved Zeeman fitting case \((B_{\text{fit}})\), such that this dependence is the same as that of the Stokes \( I \) fitting case (whatever it may be); or (2) for the \( x_b \approx 0.1 \) case applicable to SNR OH (1720 MHz) masers there is no appreciable \( \theta \) dependence on \( b \). Although we cannot distinguish between the two, we suspect that option 2 is more likely.

In addition, it has been observed (Brogan et al. 2002) that the magnetic fields in OH (1720 MHz) SNR masers measured using Stokes fitting depend on the angular resolution of the observations: smaller beam areas yield larger magnetic field measurements. This trend is also observed in other maser species (e.g., \( \text{H}_2\text{O}; \) Sarma et al. 2001). The OH (1720 MHz) SNR masers in W28 show an increase in fitted magnetic field between VLA (C97) and MERLIN observations due to blending at VLBA scales. However, the magnetic field strengths fitted to the current MERLIN and VLBA observations are in good agreement. That is, it appears that the MERLIN beam is sufficiently small to alleviate all suppression due to blending. Indeed, since the image features in the VLBA observations have comparable emission characteristics (§ 4.1), it is not expected that an angular convolution of a VLBA image using the MERLIN beam would result in a suppression of the fitted spectral parameters (see Sarma et al. 2001).

4.4. Linear Polarization

The linear polarization state of the masers is suggested to be a diagnostic of the orientation of the magnetic field in the maser gas. In this section, both (1) the linear polarization fraction \( q \) of the masers and (2) the orientation of the linear polarization angle \( \chi \) of the masers with respect to the surrounding magnetic field are discussed. Unlike Zeeman splitting, in which the observed circular polarizations are affected by only the line-of-sight component of the magnetic field, the polarization angle \( \chi \) of the maser radiation depends on the plane-of-the-sky component of the magnetic field. Indeed, Elitzur (1996) and WW01 suggest that \( q \) and \( \chi \) depend on \( \theta \), the angle between the line of sight and the magnetic field (see also a comparison of these models by Gray 2003). In the case of W28, the orientation of the magnetic field in the maser region may be independently constrained using existing observations of the synchrotron continuum radiation from the SNR. Furthermore, since the magnetic field is likely to be aligned parallel to the shocked SNR/molecular cloud interface that creates the maser conditions (e.g., Balsara et al. 2001), a comparison between the polarization state of the masers and observations of the shocked environment in W28 is also possible.

4.4.1. Correction for Faraday Effects

The linear polarization properties of the synchrotron emission from W28 on large angular scales (2°–6') have been studied by a number of groups (Milne & Wilson 1971; Kundu & Velusamy 1972; Milne & Dickel 1975; Dickel & Milne 1976; Milne 1987, 1990). These studies find that the position angle of the synchrotron linear polarization \( \chi^{\text{synch}} \) is quite constant at approximately 80° along the eastern side of the remnant where the region E and F masers are located. Since \( \chi^{\text{synch}} \) is perpendicular to the plane of sky orientation of the magnetic field (e.g., Rybicki & Lightman 1979), \( \chi^{\text{synch}} = -10° \). The assumption that \( \chi^{\text{synch}} \) remains constant down to the size scales relevant to the maser emission of a few hundred milliarcseconds is essential to compare the two since no higher resolution synchrotron polarization studies exist. Certainly on a few arcminute size scales the \( \chi^{\text{synch}} \) is quite uniform (see, e.g., Dickel & Milne 1976) and also the \( \chi^{\text{maser}} \) is fairly uniform from maser to maser (i.e., Figs. 14 and 15). However, that this is an assumption should be borne in mind during the following discussion.

For all measurements of linear polarization percentage and position angle, Faraday depolarization and rotation are of concern. Because of the continuous nature of synchrotron emission, the above studies have been able to use the observed wavelength dependence of the polarization properties to correct for Faraday rotation and estimate the depolarization. In particular, Dickel & Milne (1976) have made a careful study of Faraday effects toward W28 (albeit at 2° size scales). These authors do not find evidence for Faraday rotation near the maser locations where the rotation measure is RM \( \approx 0 \) rad m\(^{-2}\). At nearby locations, not coincident with the masers (approximately 2° to the east and west), the RM rises to 33 rad m\(^{-2}\). Thus, we view 33 rad m\(^{-2}\) as a strict upper limit but assume RM \( \approx 0 \) rad m\(^{-2}\) for the remaining discussion. This assumption is limited by the fact that a value of RM in the direction of the masers in excess of approximately 15 rad m\(^{-2}\) (equivalent to a Faraday rotation of the position angle by approximately 25°) could invalidate the alignment comparisons made between the synchrotron and maser polarization that we base on RM = 0 ± 15 rad m\(^{-2}\).

As discussed in B00, stimulated maser emission can only be Faraday depolarized along the gain length of the maser. The gain lengths and ionization fractions suggested for SNR OH (1720 MHz) masers are such that this effect must be small (see B00 for details). Indeed, Dickel & Milne (1976) find that the synchrotron depolarization toward the E and F maser locations is only 3%. These two facts combined suggest that there is little Faraday depolarization of the maser radiation.

4.4.2. Interpretation of Maser Emission

The difference between the linear polarization angle of the synchrotron observations (\( \chi^{\text{synch}} \)) and the linear polarization angles measured from the masers (\( \chi^{\text{maser}} \), \( \chi \) in Table 7) is shown in Figure 14. The difference between \( \chi^{\text{maser}} \) and \( \chi^{\text{synch}} \) is distributed about 0°, with FWHM approximately 30°, indicating a good agreement between the synchrotron and maser polarization.

![Figure 14](https://example.com/image.jpg)
states. The simultaneous presence of a weaker (by about an order of magnitude), turbulent component of the magnetic field (e.g., Balsara et al. 2001) could account for the small (10%) relative differences in the masers’ polarization results (Tables 7 and 8). The good agreement between the polarization states of the synchrotron emission and the maser emission indicates that the maser polarization angle, $\chi_{\text{maser}}$, is perpendicular to the projected magnetic field orientation (P.A. $B_i$) in the maser region.

For the case in which $\chi_{\text{maser}} \perp \text{P.A.}_B$ for maser radiation, WW01 suggest $\theta \geq 55^\circ$ and $q \approx 5\%$ for partial saturation of the maser, which is consistent with suggestions made by Elitzur (1998). B00 review the observations of linear polarization in the W28, W44, W51, and IC 443 masers using the VLA, which indicate polarization fractions $q \approx 5\%$–10\%, implying $\theta \approx 60^\circ$. Observations of linear polarization in the IC 443 masers using the VLBA indicate $q < 15\%$ (I. M. Hoffman & W. M. Goss 2004, unpublished). The current MERLIN and VLBA data (Figs. 10 and 11) are in good agreement with VLA observations of W28 (C97) and also indicate $q \approx 5\%$–10\% and $\theta \approx 60^\circ$. From this comparison between observations and theoretical suggestions, it appears that the OH (1720 MHz) SNR masers. The line-of-sight component of the magnetic field detected using Zeeman splitting does not change sign throughout the maser regions, consistent with previous observations (cf. B00).

4.4.3. Comparison with Observations of Shocked Gas

Figure 16 shows the plane-of-the-sky component of the SNR magnetic field indicated by the masers superimposed on an image of the postshock gas (CO $J = 3 \rightarrow 2$; Arikawa et al. 1999). The magnetic field in the shocked gas is suggested to have been swept and compressed into a plane parallel with the shock (Frail & Mitchell 1998; Arikawa et al. 1999; Dubner et al. 2000; Balsara et al. 2001). Figure 16 indicates that the orientation of the magnetic field in the masers is consistent with the suggested orientation of the magnetic field in the shock.

Considering the good agreement between the orientation of the shocked gas and the orientation of the linear polarization angle of the maser emission, we feel that our assumption of $\text{RM} = 0 \pm 15\text{rad m}^{-2}$ (§4.4.1) in the direction of the masers is the most physically plausible scenario.
4.5. Linear Polarization Profiles

Both the linear polarization fraction of the maser radiation ($q$) and the position angle of the linearly polarization emission ($\chi$) are observed to vary smoothly as a function of velocity across the maser line profiles; $q$ varies by approximately 1% and $\chi$ varies by approximately 5% (Figs. 10 and 11; Tables 7 and 8). No variation of $q$ or $\chi$ within an OH (1720 MHz) SNR maser has been observed previously, although variations of such small magnitude are not inconsistent with previous analyses. However, this linear polarization structure is not expected from the Zeeman splitting or the linear polarization theory discussed in the previous sections.

A variation in the observed $q$- and $\chi$-values is not necessarily an intrinsic property of the maser emission. There are two possible explanations for the observed variations: (1) small changes, as a function of frequency, in the rotation measure and depolarization due to the interstellar medium between the observer and the maser; and (2) Faraday rotation and depolarization within the gain length of the maser. In order to quantify the processes in explanation 1, measurements similar to the observations of the synchrotron emission described in §4.4 would be required. However, continuum observations would need to have at least 100 mas angular resolution in order to sample adequately the change in sign of $\partial I / \partial \phi$ between the F39A and F39C masers. Since applying explanation 1 requires additional observations, we do not discuss it further here. The possible contribution of explanation 2 in OH (1720 MHz) SNR masers has been examined previously. B00 find that the gain length of the masers is comparable to the Faraday depolarization length scale, indicating that Faraday rotation cannot contribute significantly to the observed polarization angle. Similarly, H03 discuss that the observed electron column density (in IC 443) is not sufficient for Faraday rotation to affect significantly the polarization state of the masers. However, although the maser gain lengths do not appear to be significantly affected by Faraday processes, we examine the possibility that explanation 2 may contribute at the few percent level.

The polarization angle ($\chi$) is determined by the orientation of the plane-of-the-sky component of the magnetic field in the gas (§4.4). In order for the polarization angle to change across the line profile, either of two processes may occur: (1) a change in the magnetic field orientation in the maser gas as a function of velocity depth into the maser, or (2) a change in the relationship between the magnetic field in the maser gas and the emergent polarization state. Since theoretical investigations suggest only a parallel or perpendicular relationship (without a smoothly varying transition through intermediate angles) between the maser magnetic field and the polarization state (e.g., WW01), explanation 2 is less likely. In explanation 1, the change in the magnetic field orientation may be in the plane of the sky ($\chi$) or along the line of sight ($\theta$).

However, a large variation of $\theta$ by many tens of degrees would be apparent in our previous Zeeman fitting to $\partial I / \partial \phi$ (§3.3.2). Using existing models, we can only conclude that (1) there is a smooth change in $\theta$ or $\chi$ (or both) by about 10°, but that (2) $\theta$ does not change so much that the relationship between the maser magnetic field and the polarization state transitions from the parallel regime to the perpendicular regime (cf. Deguchi & Watson 1986).

5. CONCLUSIONS

Using MERLIN, we have imaged all but two of the OH (1720 MHz) SNR masers in W28 with intensity greater than 1 Jy beam$^{-1}$ as observed using the VLA by C97. Of the 28 MERLIN detections, we have detected 4 masers (approximately 15%) using the VLBA+Y1, consistent with other VLBI detection rates of OH (1720 MHz) SNR masers. Based on MERLIN data with a resolution of 200 mas and VLBA data with a resolution of 15 mas, the masers have deconvolved sizes of 90–350 mas (225–875 AU) with compact cores 20 mas (50 AU), consistent with theoretical expectation and previous observations.

Based on a number of constraints, the masers appear to be partially saturated, allowing quantitative theoretical examination of the polarization state of the emission. These data contain the first direct detection of resolved Zeeman splitting in OH (1720 MHz) SNR masers. Analysis of the circular polarization profiles indicates magnetic fields in the maser gas $|B| \approx 0.75$ mG. The linear polarization state of the masers is in good agreement with (1) theoretical expectations of the shock geometry, (2) theoretical suggestions concerning the radiative transfer in the masers, and (3) the magnetic field determined using observations of the synchrotron emission from W28, indicating a projected position angle of $-10^\circ$ for the magnetic field in the limb of the SNR near the masers. In addition, the position angle of the magnetic field measured using the linear polarization of the masers is in good agreement with both the orientation of the shock observed using thermal molecular emission (e.g., Frail & Mitchell 1998) and the magnetic field orientation expected from the SNR expansion (e.g., Balsara et al. 2001).

The polarization properties of the masers are observed to change as a function of velocity within the profile, indicating small (approximately 10°) changes in the magnetic field orientation within the maser gas. Using theoretical models, the angle between the line of sight and the magnetic field vector is inferred to be $\theta \approx 60^\circ$.

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