

## Magnetic fields in supernova remnants from OH (1720 MHz) masers

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**Abstract.** Supernovae have a profound effect on the morphology, kinematics, and metallicity of galaxies. The impact of supernova shocks on surrounding molecular clouds is also thought to trigger new generations of star formation. A critical ingredient in such interactions and, indeed, all aspects of supernova remnant (SNR) evolution are magnetic fields. In recent years, OH (1720 MHz) masers have been used as signposts for the interaction of SNRs with molecular gas. In addition to tracing SNR/molecular cloud interactions, the OH (1720 MHz) maser line also provides a unique opportunity to measure the strength of the post-shock magnetic field via Zeeman splitting. Recent results from efforts to both detect the magnetic fields and resolve the maser spot sizes of OH (1720 MHz) masers toward W51C using the VLBA and W44 using MERLIN are presented. These observations have yielded magnetic field detections between 0.5 and 2.5 mG and large maser spot sizes of about  $10^{15}$  cm.

### 1. Introduction

OH (1720 MHz) masers have been found in  $\sim 20$  SNRs, or 10% of the known SNRs in our Galaxy (Frail et al. 1996; Green et al. 1997). Maser theory suggests that OH (1720 MHz) masers originate in the post-shock molecular gas behind C-type shocks (Lockett et al. 1999; Wardle 1999). These theories also suggest that these OH masers are collisionally pumped at densities of  $\sim 1 \times 10^5$  cm $^{-3}$  and temperatures in the range  $50 \text{ K} \lesssim T \lesssim 125 \text{ K}$ . Hence, observations of this OH maser line can serve as a powerful probe of SNR/molecular cloud interactions. Using the thermal Zeeman equation, VLA<sup>1</sup> OH (1720 MHz) Zeeman observations toward SNR-OH masers in our galaxy have resulted in magnetic field detections ( $B_\theta$ ) between 0.1 and 4 mG toward 10 different SNRs (see Brogan et al. 2000 and references therein). These observations are the first *direct* magnetic field estimates of the post-shock gas in SNRs.

An interesting question concerning SNR–OH (1720 MHz) masers is whether the observed magnetic field values vary with resolution. Some evidence of this effect may be indicated from the ten-fold increase in  $B_\theta$  measured with the VLBA<sup>1</sup> ( $\sim 2$  mG) toward the W28 maser spot F39 compared to the average

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value measured throughout W28 with the VLA ( $\sim 0.4$  mG; Claussen et al. 1999). However, this particular spot did not have a positive VLA Zeeman detection so a direct comparison is not possible. In addition, Claussen et al. (1999) find that the maser spots observed toward W28 are large compared to H II region masers, with sizes ranging from 50 to 180 mas. Based on the W28 E30 maser being completely resolved out by the VLBA, Claussen et al. (1999) estimate that W28 E30 is larger than  $\sim 400$  mas. While large for masers, these size estimates are in agreement with Lockett et al. (1999) who estimate that the maser size scale must be less than  $\sim 2 \times 10^{16}$  cm or 460 mas at the distance of W28 (3 kpc). It is currently unclear whether the large sizes observed by Claussen et al. are intrinsic to SNR–OH masers or if interstellar scattering is responsible.

Thus, additional high resolution SNR–OH (1720 MHz) maser observations toward previous VLA Zeeman detection sites are needed to determine whether the apparent increase in  $B_\theta$  with higher resolution is real, and whether the true sizes of these masers are large or if scattering plays a significant role. In order to address these issues, we are engaged in a program to observe SNR–OH masers with an intermediate angular resolution with MERLIN<sup>2</sup>. However, since many of the candidate SNRs are at declinations too low for MERLIN, we are also using the VLBA to look at SNR–OH masers that are located farther away than W28 so that their angular size will be smaller. A survey of masers at different distances may also help to resolve the issue of intrinsic size vs. scattering since masers located farther away will presumably suffer more scattering.

## 2. VLBA Observations of W51C

W51 is composed of two H II region complexes (W51A and W51B), as well as the SNR W51C, and is  $\sim 6$  kpc away (Koo, Kim, & Seward 1995). VLA  $\sim 1''$  resolution observations by Brogan et al. (2000) of the two OH (1720 MHz) masers in W51C did not resolve the spots but found peak flux densities of 2.7 and 4.8 Jy beam<sup>-1</sup>, respectively. Zeeman analysis of these data yielded  $B_\theta$  for W51C(1) of  $+1.5 \pm 0.05$  mG and  $+1.9 \pm 0.1$  mG for W51C(2).

In order to resolve these maser spots and to determine whether the observed Zeeman field strength changes with resolution, we recently made OH (1720 MHz) VLBA observations toward W51C. The resulting spectral line data have a beam size of  $17.8 \times 8.4$  mas (PA =  $-21.9^\circ$ ), and a spectral resolution of  $0.9$  km s<sup>-1</sup>. Figure 1 shows our VLBA images of the W51C(1) and W51C(2) OH (1720 MHz) maser regions. It is clear from the figure that W51C(2) is now resolved into two separate features, a and b. Fig. 1 also indicates the linear dimensions of the resolved spot sizes for W51C(1) and W51C(2a). The Stokes I and V profiles from the peaks of the maser spots along with the value of  $B_\theta$  as fitted from the thermal Zeeman equation are also shown on Figure 1.

Several interesting results have emerged from these VLBA data. First, all of the maser spots appear to be elongated, especially W51C(1) which has an aspect ratio of 1:4. Two, the estimated linear minor axes ( $\sim 1 \times 10^{15}$  cm) are in good agreement with estimates for the expected width of the post-shock gas with

<sup>2</sup>MERLIN is a UK national facility operated by University of Manchester on behalf of PPARC

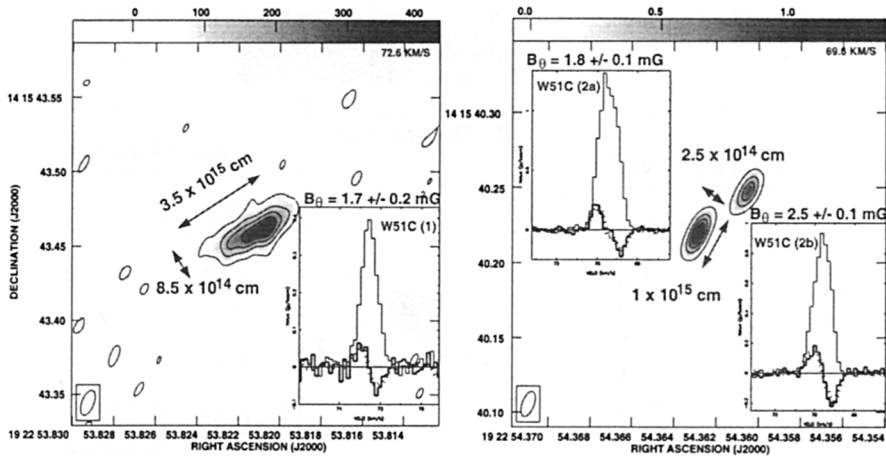


Figure 1. VLBA images and Stokes I and V profiles of W51C OH (1720 MHz) masers. The fitted magnetic field strengths are also shown.

temperatures between 50 to 125 K (Wardle 1999; Lockett et al. 1999). Three, the VLBA integrated flux densities are about a factor of two less than those obtained with the VLA, indicating that about half the maser flux is distributed on size scales  $\gtrsim 200$  mas. Four, the brightness temperatures indicated by the integrated flux densities are quite high ( $\sim 10^9$  K), suggesting that these masers are saturated since this is near the maximum  $T_B$  possible due to collisional pumping (Pavlaakis & Kylafis 1996). Five, the VLBA  $B_\theta$  are slightly higher than those found with the VLA; this is likely a combination of the improved spectral resolution and the fact that W51C(2) is composed of two separate maser spots at slightly different velocities unresolved with the VLA.

### 3. MERLIN Observations of W44

VLA polarization observations of the OH (1720 MHz) masers in W44 by Claussen et al. (1997) yielded Zeeman magnetic field measurements between  $-0.24$  to  $-0.6$  mG for region F and  $-0.46$  to  $-0.56$  mG for region E. Similar to the situation described for W51C, the VLA with  $\sim 1''$  resolution was unable to fully resolve the maser spots. Our subsequent MERLIN OH (1720 MHz) observations of the W44 regions E and F with a beam size of  $293 \times 147$  mas have resulted in significantly higher  $B_\theta$ 's for region F between  $-0.7$  and  $-1.2$  mG. Figure 2 shows images and Stokes I and V profiles of the two W44 F24 maser spots. Like the case of W51C, this increase may be a result of improved spatial and spectral resolution. The MERLIN region E maser data have field strengths only slightly higher ( $-0.5$  to  $-0.8$  mG) than those found with the VLA. These MERLIN data also show that the OH (1720 MHz) maser spots are elongated, but in several cases the cores of the features are not resolved. Indeed, Claussen et al. (1999) discovered an unresolved core for the W44 E11 maser spot in their VLBA observations with 40 mas resolution. Despite the fact that there appear to be unresolved cores for most of the features, many of the spots are also missing

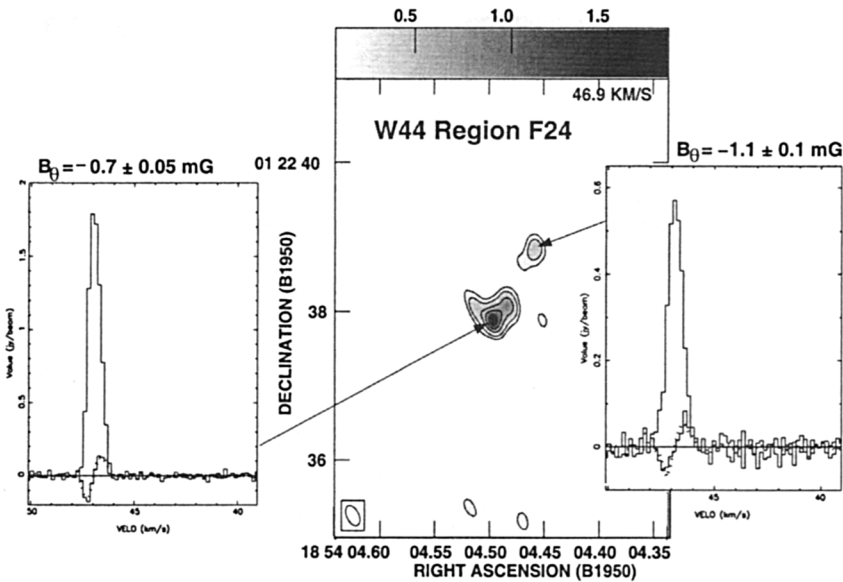


Figure 2. MERLIN images and Stokes I and V profiles of W44 region F24 OH (1720 MHz) masers. The fitted field strengths are also shown.

up to half of the total flux density observed with the VLA (see Claussen et al. 1999). Note that at the distance of W44 ( $\sim 3$  kpc), 200 mas is  $\sim 1 \times 10^{16}$  cm.

#### 4. Conclusions

From these new OH (1720 MHz) Zeeman observations it appears likely that spectral resolution is a key factor in determining the observed magnetic field strengths, along with the need to resolve the different maser spots. These masers also have core/halo structures and are elongated with minor axes of  $\sim 10^{15}$  cm in agreement with the shock calculations of Lockett et al. (1999) and Wardle (1999). Forthcoming VLBA observations of G349.7+0.2 and CTB37A will help to better quantify these findings.

#### References

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