NH₃(3,3) AND CH₃OH NEAR SUPERNOVA REMNANTS: GBT AND VLA OBSERVATIONS

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ABSTRACT

We report on Green Bank Telescope 23.87 GHz NH₃(3,3) emission observations in five supernova remnants (SNRs) interacting with molecular clouds (G1.4–0.1, IC 443, W44, W51C, and G5.7–0.0). The observations show a clumpy gas density distribution, and in most cases the narrow line widths of ~3–4 km s⁻¹ are suggestive of maser emission. Very Large Array observations reveal 36 and/or 44 GHz CH₃OH maser emission in a majority (72%) of the NH₃ peak positions toward three of these SNRs. This good positional correlation is in agreement with the high densities required for the excitation of each line. Through these observations we have shown that CH₃OH and NH₃ maser emission can be used as indicators of high-density clumps of gas shocked by SNRs, and provide density estimates thereof. Modeling of the optical depth of the NH₃(3,3) emission is compared to that of CH₃OH, constraining the densities of the clumps to a typical density of the order of 10⁵ cm⁻³ for cospatial masers. Regions of gas with this density are found to exist in the post-shocked gas quite close to the SNR shock front, and may be associated with sites where cosmic rays produce gamma-ray emission via neutral pion decay.

Key words: ISM: individual objects (G1.4-0.1, – W44, – G5.7-0.0, – IC 443, – W51C) – masers

1. INTRODUCTION

Interactions between supernova remnants (SNRs) and molecular clouds (MCs) can cause perturbations in the gas that may affect the evolution of the surrounding interstellar medium. For example, it has long been suggested that star formation might be triggered in the parent cloud. Details of such a proposed triggering process have not been clearly outlined and confirmed, partly due to the complexity of the regions in the inner Galaxy where the SNR/MC interactions are more probable. Another plausible effect of SNR/MC collisions is the acceleration of Galactic cosmic rays, since shock-induced particle acceleration can generate relativistic energies. Models of cosmic-ray acceleration usually relate the brightness of resulting γ-ray emission due to neutral pion decay using the gas number density (e.g., Drury et al. 1994; Abdo et al. 2010; Cristofari et al. 2013). The density estimates deduced from γ-ray emission measurements are often larger (10–20 times) than those inferred from X-ray observations, indicating that a strongly clumped medium is required to produce the γ-ray emission (e.g., Slane et al. 2015). Detailed density estimates, and density gradients, in regions associated with γ-ray emission are thus of interest to constrain the inputs of cosmic-ray acceleration models. Observations of transitions of various molecules excited by the passing shock provide a tool to derive densities and can also provide kinematic information of the gas. An overall understanding of the conditions in the interacting cloud, both pre- and post-shock, may provide basic facts to guide models of both SNR-induced star formation and cosmic-ray acceleration.

SNR/MC interactions are identified in different ways, for example, via shock excited OH 1720 MHz emission (Claussen et al. 1997; Wardle & Yusef-Zadeh 2002), near-infrared H₂ emission, and broad molecular line widths exceeding those of cold molecular gas (Reach et al. 2005). In addition to the 1720 MHz OH, other shock-excited masers detected in SNR/MC regions include the Class I 36 and 44 GHz methanol (CH₃OH) masers, which can be used to estimate densities in the maser-emitting region (Sjouwerman et al. 2010; Pihlström et al. 2011, 2014; McEwen et al. 2014). In characterizing physical parameters of gas clouds in general, the ammonia (NH₃) molecule is commonly used as a probe of dense (n ≥ 10³ cm⁻³) environments. Ratios of the line intensities allow estimates of rotational excitation temperatures, heating, and column densities (e.g., Ho & Townes 1983; Morris et al. 1983; Okumura et al. 1989; Coil & Ho 1999). Illustrating examples of where NH₃ information can be combined with that of maser species include the high-resolution observations of NH₃ in the inner 15 pc of the Galactic center (GC) region (Coil & Ho 1999, 2000; McGary et al. 2001) and the recent detections of Class I 36 and 44 GHz CH₃OH maser emission toward Sgr A East (Sjouwerman et al. 2010; Pihlström et al. 2011; McEwen et al. 2016). These observations reveal a close positional agreement between the NH₃ emission peaks and the location of CH₃OH masers. A similar spatial coincidence between NH₃ and 44 GHz CH₃OH masers has also been found toward W28 (Sjouwerman et al. 2010; Nicholas et al. 2011; Pihlström et al. 2014).

A relatively general picture of the distribution of OH and CH₃OH masers in SNRs comes from observations of Sgr A East, W28, and G1.4–0.1 (e.g., Sjouwerman et al. 2010; Pihlström et al. 2011, 2014; McEwen et al. 2014). Based on these observations, it has been shown that CH₃OH masers are typically found offset from 1720 MHz OH masers (e.g., Claussen et al. 1997; Frail & Mitchell 1998; Yusef-Zadeh et al. 2003; Sjouwerman et al. 2010; Pihlström et al. 2014). This indicates that particular maser species and transitions are tracing different shocked regions, or alternatively, different regions in one shock. Consistently, bright 36 GHz CH₃OH masers have been found to trace regions closer to the alleged shock front, and OH masers are more likely to trace the post-shocked gas. The location of the 44 GHz masers relative to the shock front has been less clear.

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To further develop the general picture of the pre- and post-shock gas structures in SNRs/MCs, including the presence and spatial positions of different molecular transitions through the interaction region, the NRAO Green Bank Telescope (GBT) was used to survey five SNRs (W51C, W44, IC 443, G1.4 −0.1, and G5.7−0.0) for NH₃ emission (Section 2.1). Here we report on the spatial distribution of the NH₃(3,3) emission compared to that of the 36 and 44 GHz CH₃OH maser emission previously observed by Pilström et al. (2014) in G1.4−0.1 and the emission detected in new observations in W51C, W44, and G5.7−0.1 using the Very Large Array (VLA; Section 2.2). Section 3 discusses the results from the observations. Estimates of the temperature and density ranges most suitable for the formation of NH₃(3,3) masers in an SNR environment are provided using model calculations (Section 4) and compared to those of the CH₃OH masers (Section 5).

### 2. OBSERVATIONS AND DATA REDUCTION

#### 2.1. GBT Observations and Data Reduction

Observations were carried out using the GBT in 2013 January through May under the project code GSLT051174. An original list of 17 possible targets was considered based on previously known SNR/MC interaction sites (detected via 1720 MHz OH masers). The allocated time allowed four targets to be fully mapped (G5.7−0.0, IC 443, W44, and G1.4−0.1) and one target to be partially mapped (W51C). Characteristics of each SNR observed, such as size and systemic velocity, can be found in Table 1. It should be noted that the source G5.7−0.0 has not yet been confidently classified as an SNR because it is very faint in the radio and does not have a typical shell-like morphology (Brogan et al. 2006). It is considered an SNR candidate since it displays nonthermal emission and is associated with a 1720 MHz OH maser, indicative of an MC/SNR shocked interaction (Hewitt & Yusef-Zadeh 2009).

The sources were surveyed for NH₃ emission using the seven-beam K-band focal plane array (KFPA) and spectrometer. The observations were made with dual polarization, 50 MHz of bandwidth, having a total velocity coverage of about 600 km s⁻¹ and a velocity resolution of about 0.5 km s⁻¹. Venus, Jupiter, Saturn, and the Moon were used as calibrators depending on which source was visible at the time of each observation. The DECLAT and RALONG standard spectral line survey mapping modes were used, with a slew rate of around 3°6 s⁻¹. In-band and out-of-band frequency switching were utilized depending on the proximity of the SNR to the GC, assuming possible velocities ±200 km s⁻¹, or more for |ℓ| < 25°.

The data reduction and calibration were carried out using the GBT pipeline following standard procedures outlined in the GBTPipeline User’s Guide. The GBT pipeline procedure was used to automate the calibration and combine the data from multiple observing sessions. The pipeline estimates the atmospheric opacity by using real-time weather monitored data. Astronomical calibrator sources were used to correct the system temperatures of the beams by applying gain factors (one for each beam and polarization) that were acquired using venuscal, jupitercal, saturncal, and mooncal procedures in GBTPipeline. In a few instances the reported system temperatures were corrupted, in which case average gain factors were calculated from all observing sessions combined. This caused a slightly larger error of the absolute flux density value measured, but this does not affect the results reported on in this paper. Finally, the beginning and ending channels were clipped during the pipeline procedure, which varied for each data set.

Channel averaging, continuum subtraction, and imaging were carried out in AIPS using standard data reduction and imaging tasks applied to single-dish data. Every two channels were averaged, and all the data were Hanning-smoothed. A third-order polynomial fit was subtracted from the line free channels over the entire bandwidth. An additional third-order polynomial fit was subtracted (outside AIPS) from the NH₃ emission in W44 and IC 443 to make the baselines more linear, which we suspect were affected by severe weather conditions at the time of the observations. Some of the SNRs are very large, and the full mapping could not be completed during one observing session; therefore, the mapped regions were produced by combining different data sets from different observing sessions. As a result, the rms noise level varies across these maps, which can primarily be attributed to the varying weather conditions on the different days of observation. The average rms noise values in a line-free channel for each target using the GBT are listed in column (8) of Table 1.

#### 2.2. VLA Observations and Calibration

The VLA was used to search for CH₃OH emission toward the NH₃ peak positions found with the GBT (excluding positions previously searched). Note that one of the primary reasons for the GBT observations was to obtain positions of NH₃ peaks. Even though some of the detected NH₃ emission was very weak, e.g., in W44, it was still included in the VLA search. The data were acquired on 2014 September 4 (project code 14A-191) using the Kα- and Q-band receivers. To cover the spatial extent of the NH₃ emission, 1 (11), 11 (17), and 12 (14) pointings at 36 (44) GHz were used in G5.7−0.0, W44, and W51C, respectively. The array was in D configuration, resulting in typical synthesized beam sizes of 2°65 × 1°90 at...

### Table 1

| Source        | Other Name | R.A. (J2000) | Decl. (J2000) | SNR Size (R.A' × Decl') | Vₐₕₗₜ (km s⁻¹) | Distance (kpc) | GBT Channel Noise (mJy bm⁻¹) |
|---------------|------------|--------------|---------------|-------------------------|----------------|----------------|-------------------------------|
| G049.2−0.7    | W51C       | 19 23 50     | +14 06 00     | 30 × 20                 | 70.0           | 6.0            | 17                            |
| G005.7−0.0    | ...        | 17 59 02     | −24 04 00     | 8 × 8                   | 13.0           | 3.2            | 16                            |
| G034.7−0.4    | W44        | 18 56 00     | +01 22 00     | 25 × 30                 | 45.0           | 2.5            | 16                            |
| G189.1+3.0    | IC 443     | 06 17 00     | +22 34 00     | 45 × 45                 | 5.0            | 1.5            | 12                            |
| G001.4−0.1    | ...        | 17 49 39     | −27 46 00     | 10 × 10                 | −2.0           | 8.5            | 18                            |

Note:
* SNR candidate (Brogan et al. 2006).
36 GHz and 2"11 × 1"84 at 44 GHz. The VLA primary beam is 1"25 at 36 GHz and 1"02 at 44 GHz.

A total of 512 frequency channels were used across a 128 MHz bandwidth (channel separation close to 1.9 km s^{-1}), centered on the sky frequency of the given target estimated using the previously known OH maser emission. The data were calibrated and imaged using standard procedures in AIPS pertaining to spectral line data. For each pointing position, the on-source integration time was approximately 1 (2) minutes at 36 (44) GHz. The precise integration time varied somewhat between the positions depending on how the observations fit within the scheduling block. The typical final rms noise values were between about 12 and 40 mJy beam^{-1} per channel, depending on the observed frequency and observing conditions. Under ideal weather conditions, the theoretical rms noise would be close to 10 mJy beam^{-1}. Degraded weather and a varying number of antennas in the array are consistent with the slightly higher measured rms noise. No 36 or 44 GHz continuum emission was found in any of the observed fields.

2.3. Radio Continuum and CO Line Images

To visualize the spatial distribution emission across each SNR, low-frequency radio continuum maps were assembled from archival data. The 21 cm IC 443 map was taken from the NRAO VLA Sky Survey (Condon et al. 1998). The 21 cm images of W44 and G1.4−0.1 were made from VLA archive data taken in 1984 and 1995, respectively, using standard AIPS calibration and imaging procedures. The 90 cm W51C and G5.7−0.0 images were obtained and adapted from Brogan et al. (2006) and Brogan et al. (2013), respectively. A comparison of the NH$_3$ and CH$_3$OH distribution with CO(1−0) is also presented, using images from the Dame et al. (2001) Milky Way CO survey.

3. RESULTS

3.1. NH$_3$ Emission

NH$_3$(3,3) emission was detected toward all the SNRs observed. Four of the targets (G5.7−0.0, W44, W51C, and IC 443) display compact clumps of emission, with the majority having relatively narrow line widths of ∼3–4 km s^{-1} (see Figures 1–4). G1.4−0.1 has a much more extended distribution of the emission and has peaks combined into broader lines with widths closer to 8−16 km s^{-1} (Figure 5). The peak position, velocity centroid, velocity width, and peak flux density of each emission region are listed in Table 2. For each SNR, the brightest spectral profiles are plotted in Figures 1–5. Included in Figures 1–5 are the spatial positions of the NH$_3$ emission regions overlaid on radio continuum maps outlining details and boundaries of each SNR (in grayscale and contours). In addition, the radio continuum is overlaid on CO(1−0) maps averaged over the velocities corresponding to those of the NH$_3$ emission. This shows the interacting MCs with respect to each SNR.

The narrow line widths may indicate maser emission from the metastable NH$_3$(3,3) transition. In the case of G1.4−0.1, the extended emission, combined with broader line widths, may be the result of maser emission mixed with thermal emission. The angular resolution of theGBT is not sufficient to set strong limits of the brightness temperature, which could have provided further information on the possibility of maser emission. With no data from the lower metastable states (the (1,1) and (2,2) transitions) and with limited resolution, further studies to investigate the candidate maser will have to be performed.

3.2. CH$_3$OH Maser Candidates

CH$_3$OH maser emission was detected in two SNRs (W44 and W51C) and in the one candidate SNR (G5.7−0.0) observed. Typical FWHMs range from about 0.7 to 10 km s^{-1}. Features labeled as detections all had a signal-to-noise ratio greater than 5 in the centroid channel, and emission was detected in three or more channels. The positions, centroid velocities, FWHMs, and peak flux densities of the candidate maser features found in our new VLA observations are listed in Table 3. The FWHMs are narrow, and example spectral profiles of the brightest maser associated with each SNR can be found in Figures 1–3. Note that due to the combination of a small VLA field of view and the limited observing time, the CH$_3$OH emission search did not cover the entire SNR/MC interaction regions.

The emission regions were unresolved with the VLA, except for the 36 GHz emission in G5.7−0.0. The emission in this source was marginally resolved and had three peak flux density positions. CH$_3$OH maser candidates were detected in the majority of the pointings. Although 44 GHz maser candidates were visible toward W51C, we chose not to include those in Table 3, due to a significantly increased noise in this data set caused by a standing wave feature of unknown origin.

3.3. CH$_3$OH and NH$_3$ Association

Table 2 lists the NH$_3$ regions that have positional association with 36 and/or 44 GHz CH$_3$OH candidate masers. The brightest NH$_3$ regions associated with W44, W51C, and G5.7−0.0 have both 36 and 44 GHz CH$_3$OH candidate maser association. Overall, 14 out of 20 (72%) positions observed in both the NH$_3$(3,3) and CH$_3$OH display emission from both molecular species.

4. OPTICAL DEPTH MODELING

The relative intensity of co-located molecular emission transitions can be used to estimate the physical condition of the gas. In McEwen et al. (2014), the MOLPOP-CEP code for coupled radiative transfer and level population calculations was used to estimate the conditions conducive for 36 and 44 GHz CH$_3$OH masers in SNRs. To compare the range of temperature and densities producing NH$_3$(3,3) maser emission with that of the CH$_3$OH maser, the same code was used to determine the optical depth of the NH$_3$(3,3) transition. Following the same assumptions of the SNR conditions as in McEwen et al. (2014), an external radiation field of 2.725 K from the CMB and a 30 K dust radiation field were used in the models. Energy levels for the NH$_3$(3,3) molecule were incorporated using the Leiden Atomic and Molecular Database (LAMDA), which includes 22 and 24 energy levels for the ortho- and para-species, up to 554 and 294 cm^{-1}, respectively (Schöier et al. 2005). The collision rate coefficients were also adopted from LAMDA, including temperatures ranging from 15 to 300 K. The optical
depth was calculated for the NH$_3$(3,3) line for a density range of $10^2$–$10^3$ cm$^{-3}$, a temperature range of 20–300 K, and a fractional abundance of NH$_3$ of $10^{-7}$. The results are plotted in Figure 6, showing a well-defined peak of the optical depth around a density of $10^5$ cm$^{-3}$ with an increasing peak value for warmer temperatures.

5. DISCUSSION

The fact that CH$_3$OH and NH$_3$(3,3) trace the same clumps of gas allows estimates of the density and temperature in localized regions. If the regions are within the positional error bars of $\gamma$-ray emission, these estimates may provide interesting information of the conditions of gas that may be linked to cosmic-ray
Figure 2. Top left: NH$_3$ emission distribution (grayscale) overlaid on 90 cm radio continuum (contours at 25, 37.5, 50, 75, 100, and 125 mJy beam$^{-1}$) of G5.7−0.0. Top right: 36 GHz (white plus signs) and 44 GHz (white triangles) CH$_3$OH masers detected with the VLA with respect to NH$_3$ emission peaks (white diamonds), 1720 MHz OH masers (white crosses), and continuum emission (grayscale). Middle left: 3–23 km s$^{-1}$ CO($1$−$0$) emission (Dame et al. 2001), which indicates the location of an interacting MC around the velocity of the OH maser (∼13 km s$^{-1}$), with respect to the radio continuum (contours). Middle right: −16 to −36 km s$^{-1}$ CO emission, which indicates the locations of another interacting MC around the velocities of the NH$_3$ and CH$_3$OH (∼−26 km s$^{-1}$), with respect to the radio continuum (contours). Bottom left: example spectral profiles of the NH$_3$ emission region (a). Bottom right: example spectral profiles of the brightest 44 GHz CH$_3$OH maser detected (A44-1).
acceleration. Here we discuss the density and positions of the shocked regions with respect to the SNRs.

5.1. Density and Temperature

McEwen et al. (2014) estimated the conditions conducive for CH$_3$OH 36 and 44 GHz masers in SNRs. Their results show a comparably brighter 36 GHz maser in higher-density regimes ($n > 10^5$ cm$^{-3}$) and a more dominant 44 GHz maser at lower densities ($n < 10^5$ cm$^{-3}$) for an optimal temperature $T < 150$ K. The (3,3) inversion transition of NH$_3$ has a temperature of about 100 K above ground, and therefore the emission distribution will emphasize excited gas. NH$_3$(3,3) maser emission can occur via collisions with H$_2$.
Figure 4. Top left: NH$_3$ emission peak (black diamond) overlaid on 21 cm radio continuum (contours at 20, 80, 140, and 200 mJy beam$^{-1}$) of IC 443. Bottom left: NH$_3$ emission peak (black diamond) and 1720 MHz OH masers (black plus signs) with respect to the continuum emission (grayscale). Top right: $-5$ to $15$ km s$^{-1}$ CO emission (Dame et al. 2001), which indicates the location of the interacting MC, with respect to the radio continuum (contours). Bottom right: example spectral profile of the NH$_3$ emission region (a).
Figure 5. Top left: NH$_3$ emission distribution (grayscale) outlined by 21 cm radio continuum (contours at 4.3, 8.6, 17.2, and 34.4 mJy beam$^{-1}$) of G1.4$-$0.1. The bright NH$_3$ regions (labeled a through d) have spectral features listed in Table 2. Top right: average positions of the 36 GHz CH$_3$OH masers (white plus signs) in each pointing (white circles labeled with the letters A through E and the average velocity in km s$^{-1}$) detected by Pihlström et al. (2014) with respect to 1720 MHz OH masers (white crosses), and continuum emission (grayscale). Middle left: 20–30 km s$^{-1}$ CO emission (Dame et al. 2001) with respect to the radio continuum (contours). Middle right: −15 to −30 km s$^{-1}$ CO emission, which indicates the locations of another interacting MC, with respect to the radio continuum (contours). Bottom row: example spectral profiles of the NH$_3$ emission in region b (left) and region A (right).
molecules (Walmsley & Ungerechts 1983; Mangum & Wootten 1994; Zhang & Ho 1995). Through statistical calculations it was found that NH₃(3,3) masers occur in gas with temperatures around 200 K and densities on the order of 10⁵–10⁶ cm⁻³ (e.g., Mauersberger et al. 1986; Mangum & Wootten 1994). Consistent with previous calculations, the MOLPOP-CEP estimates performed for our SNR environment (Section 4) show optimal NH₃ maser conditions at relatively high temperatures ($T > 150$ K) and a relatively narrow density peak around $n \approx 10^5$ cm⁻³. At those densities, there is, in fact, little difference in the inverted optical depth between the 36 and 44 GHz masers (McEwen et al. 2014), perhaps explaining the range of line ratios observed in the SNRs (Table 3), where in some locations the 36 GHz maser is brighter, and the 44 GHz maser in others. That the line ratios of the 36 and 44 GHz CH₃OH are on average unity further agrees with a relatively high temperature in the clumps. It thus seems that the co-located clumps of NH₃(3,3) and CH₃OH masers trace gas regions with $T \geq 150$ K and $n \approx 10^5$ cm⁻³.

G1.4–0.1 is the exception, where both 36 GHz CH₃OH and NH₃ emission is profuse and 44 GHz is lacking. Here, the line widths of the NH₃ are greater and the emission may be at least partly thermal. In this case, the 36 GHz methanol might be tracing the densest clumps in the interaction regions. A better understanding of the NH₃ thermal versus nonthermal emission here could be attained by also obtaining observations of the NH₃(1,1) and (2,2) emission that may be thermal, providing even stronger limits on the temperature and density. Interferometric observations would also be helpful to tie down the brightness temperature of the NH₃(3,3) lines.

### 5.2. Spatial Trends

The general picture of the spatial distribution of collisionally pumped masers in SNRs was outlined in Section 1, where regions close to the shock front harbor 36 GHz CH₃OH masers, and post-shock regions harbor 1720 MHz OH masers. This depiction was based largely on observations of Sgr A East, W28, and G1.4–0.1 (e.g., Sjouwerman et al. 2010; Nicholas et al. 2011; Pihlström et al. 2011, 2014). With our new data, this picture is further strengthened.

#### Table 2

| NH₃ pos | R.A. (J2000) | Decl. (J2000) | $V_p$ (km s⁻¹) | $\Delta V$ (km s⁻¹) | $I_p$ (Jy bm⁻¹) | CH₃OH Maser Association (GHz) | VLA Data | Comment |
|---------|-------------|--------------|----------------|-------------------|----------------|-------------------------------|-----------|---------|
| W51Ca   | 19 22 42.15 | +14 09 54.0  | 60.7           | 4.1               | 0.12           | 36                            | Y         | Figure 1 |
| W51Cb   | 19 22 42.15 | +14 09 54.0  | 65.5           | 3.4               | 1.39           | 36 & 44                       | Y         |         |
| W51Cc   | 19 22 12.07 | +14 02 48.0  | 68.7           | 3.4               | 0.19           | 36 & 44                       | Y         |         |
| W51Cd   | 19 22 15.36 | +14 03 48.0  | 71.2           | 4.3               | 0.10           | 44                            | Y         |         |
| W51Ce   | 19 22 19.07 | +14 05 12.0  | 70.8           | 4.0               | 0.07           | 44                            | Y         |         |
| W51Cf   | 19 22 37.62 | +14 09 54.0  | 66.9           | 3.1               | 0.06           | b                             | Y         |         |
| W51Cg   | 19 22 46.28 | +14 08 18.0  | 66.9           | 3.1               | 0.06           | b                             | Y         |         |
| W51Ch   | 19 22 38.05 | +13 58 12.0  | 61.0           | 4.0               | 0.06           | b                             | Y         |         |
| G5.7–0.0a| 17 58 45.05 | −24 08 48.0  | −25.1          | 3.7               | 0.37           | 36 & 44                       | Y         | Figure 2 |
| W44a    | 18 56 44.21 | +01 23 34.7  | 40.9           | 4.4               | 0.06           | 36                            | Y         |         |
| W44b    | 18 56 48.21 | +01 18 52.7  | 44.6           | 5.5               | 0.07           | 36 & 44                       | Y         | Figure 3 |
| W44c    | 18 56 58.62 | +01 18 46.7  | 46.5           | 4.0               | 0.05           | 36 & 44                       | Y         |         |
| W44d    | 18 56 46.21 | +01 21 16.7  | 41.9           | 3.4               | 0.05           | b                             | Y         |         |
| W44e    | 18 56 01.80 | +01 12 40.7  | 44.0           | 3.6               | 0.06           | a                             | Y         |         |
| IC443a  | 17 16 42.97 | +22 32 23.9  | −6.1           | 6.7               | 0.06           | a                             | Y         | Figure 4 |
| G1.4–0.1a| 17 49 48.14 | −27 44 42.0  | −31.7          | 11.7              | 0.16           | 36                            | Y         |         |
| G1.4–0.1b| 17 49 41.36 | −27 48 60.0  | −20.6          | 8.3               | 0.07           | c                             | N         | Figure 5 |
| G1.4–0.1c| 17 49 20.10 | −27 48 24.0  | −37.5          | 16.0              | 0.17           | c                             | N         |         |
| G1.4–0.1d| 17 49 24.62 | −27 50 18.0  | −9.7           | 12.6              | 0.09           | c                             | N         |         |
| G1.4–0.1A| 17 49 31.09 | −27 47 36.3  | −23.4          | 11.7              | 0.10           | 36                            | Y         | Figure 5 |
| G1.4–0.1B| 17 49 37.59 | −27 44 20.4  | −31.7          | 13.2              | 0.61           | 36                            | Y         |         |
| G1.4–0.1C| 17 49 46.79 | −27 44 08.8  | −31.0          | 15.9              | 0.12           | 36                            | Y         |         |
| G1.4–0.1E| 17 49 49.97 | −27 49 14.9  | −18.5          | 14.1              | 0.12           | 36                            | Y         |         |

Notes.

a) Searched in a previous study by Pihlström et al. (2014), but no CH₃OH was detected.
b) Searched in this study, but no CH₃OH was detected.
c) This area has not been searched to date.
First, our comparison (Figures 1–5) of the NH$_3$, CH$_3$OH, and CO(1–0) shows a strong correlation in position and velocity, where both NH$_3$ and CH$_3$OH are directly associated with the nearby MCs. As evidenced by the CO maps, the extent of the MCs follows and is associated with radio continuum contours. This is consistent with the presence of SNR/MC interactions, providing the necessary excitation mechanism for both NH$_3$ and CH$_3$OH. Second, the OH maser velocities listed in Table 1 are, for most cases, offset in velocity from the CH$_3$OH and NH$_3$. Again, this may imply that the OH is occurring further in the post-shock region, resulting in a different velocity than the gas closer to the front.

An illustrating example is W44, which is interacting with a giant MC (CO G34.875−0.625) with a $V_{LSR}$ around 48 km s$^{-1}$ (e.g., Seta et al. 1998, 2004; Dame et al. 2001; Yoshikawa et al. 2013; Cardillo et al. 2014). The brightest rim of this MC is overlapping with the brightest rim of the continuum emission (Figure 3). The NH$_3$ and CH$_3$OH clumps coincide in position and velocity with the MC, but are offset from the OH detection. Noteworthy details include the SNR candidate G5.7−0.0. The centroid velocity of the NH$_3$ emission is around $-25$ km s$^{-1}$, almost 40 km s$^{-1}$ offset from the known OH maser at +13 km s$^{-1}$ (Hewitt & Yusef-Zadeh 2009), but instead matches well with the velocity of the CO emission detected at the same position SW of the radio continuum (Figure 2). To the NE, closer to the OH maser, the CO gas instead has a higher, positive velocity (3–23 km s$^{-1}$), agreeing with the OH velocity (Dame et al. 2001; Liszt 2009). This may be understood with the gas density differences required for the excitation of the transitions.

### 5.3. Association with $\gamma$-Ray Emission

W44, W51C, and G5.7−0.0 are all detected in $\gamma$-rays (e.g., Aharonian et al. 2008; Abdal et al. 2009; Feinstein et al. 2009; Giuliani et al. 2011; Uchiyama et al. 2012), which are thought to originate from the SNR/MC interaction. In W44, for example, Uchiyama et al. (2012) report on using a pre-shock density of 200 cm$^{-3}$ and a post-shock density of $7 \times 10^3$ cm$^{-3}$, almost 15 times smaller than the post-shock density close to the shock front we have derived. If the $\gamma$-rays, just as the 36 GHz masers, are produced close to the shock front, our derived densities may provide additional information for the $\gamma$-ray emission estimated from neutral pion decay models.

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**Table 3**

| Source | $\nu$ (GHz) | Name | R.A. (J2000) | Decl. (J2000) | $V_p$ (km s$^{-1}$) | $\Delta V$ (km s$^{-1}$) | $I_p$ (Jy bm$^{-1}$) |
|--------|-------------|------|--------------|--------------|-----------------|----------------|-----------------|
| W51C   | 36          | B36-1 | 19 22 42.69  | +14 09 55.5  | 57.6            | 6.0            | 0.25            |
|        | 36          | B36-2 | 19 22 42.21  | +14 09 51.5  | 59.6            | 4.7            | 0.14            |
|        | 36          | B36-3 | 19 22 42.76  | +14 10 02.0  | 57.6            | 3.0            | 0.13            |
|        | 36          | B36-4 | 19 22 41.42  | +14 09 03.5  | 74.1            | 10.0           | 0.24            |
|        | 36          | F36-1 | 19 22 25.70  | +14 06 35.0  | 65.9            | 3.1            | 0.43            |
|        | 36          | F36-2 | 19 22 26.01  | +14 06 36.0  | 65.9            | 2.5            | 0.54            |
|        | 36          | F36-3 | 19 22 26.11  | +14 06 37.0  | 63.8            | 4.0            | 0.50            |
|        | 36          | L36-1 | 19 22 12.08  | +14 02 49.5  | 67.9            | 4.0            | 0.43            |
|        | 36          | L36-2 | 19 22 07.34  | +14 02 18.5  | 76.2            | 4.0            | 0.19            |
| G5.7−0.0 | 36      | A36-1 | 17 58 44.99  | −24 08 38.0  | −26.4           | 3.5            | 0.38            |
|        | 36          | A36-2 | 17 58 45.17  | −24 08 39.5  | −26.4           | 4.0            | 0.26            |
|        | 36          | A36-3 | 17 58 44.85  | −24 08 36.5  | −26.4           | 4.0            | 0.21            |
|        | 44          | A44-1 | 17 58 44.89  | −24 08 37.0  | −24.4           | 1.8            | 1.31            |
|        | 44          | A44-2 | 17 58 44.88  | −24 08 37.0  | −24.4           | 3.0            | 0.35            |
| W44    | 36          | A36-1 | 18 56 43.96  | +01 23 54.2  | 40.9            | 3.0            | 0.25            |
|        | 36          | F36-1 | 18 56 48.39  | +01 18 45.7  | 42.9            | 2.0            | 0.09            |
|        | 36          | G36-1 | 18 56 50.82  | +01 18 17.3  | 42.9            | 4.5            | 0.14            |
|        | 36          | G36-2 | 18 56 50.86  | +01 18 21.8  | 40.9            | 4.5            | 0.11            |
|        | 36          | G36-3 | 18 56 52.49  | +01 18 12.3  | 47.1            | 7.0            | 0.12            |
|        | 36          | K36-1 | 18 56 58.46  | +01 18 41.7  | 45.0            | 2.7            | 0.30            |
|        | 44          | K44-1 | 18 56 49.86  | +01 18 43.2  | 56.9            | 0.7            | 0.21            |
|        | 44          | L44-1 | 18 56 48.36  | +01 18 46.2  | 45.0            | 1.6            | 0.31            |
|        | 44          | P44-1 | 18 56 57.86  | +01 17 27.7  | 35.6            | 1.1            | 0.26            |
|        | 44          | Q44-1 | 18 56 59.69  | +01 19 17.2  | 6.7             | 1.5            | 0.24            |

**Figure 6.** Peak inverted optical depth vs. number density of H$_2$, with a clear peak for densities around $10^5$ cm$^{-3}$. 

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6. CONCLUSIONS

The combination of the presented GBT and VLA data has shown that there is a close correlation between NH$_3$(3,3) and CH$_3$OH 36 and 44 GHz maser emission in SNRs interacting with MCs. That the NH$_3$(3,3) is truly maser emission is not confirmed, but under this assumption the data are consistent with clumps of gas of densities $n \sim 10^5$ cm$^{-3}$ and temperatures $T > 150$ K.

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