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EXCITED-STATE OH MASERS AND SUPERNOVA REMNANTS

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ABSTRACT

The collisionally pumped, ground-state 1720 MHz maser line of OH is widely recognized as a tracer for shocked regions and observed in star-forming regions and supernova remnants. Whereas some lines of excited states of OH have been detected and studied in star-forming regions, the subject of excited-state OH in supernova remnants—where high collision rates are to be expected—is only recently being addressed. Modeling of collisional excitation of OH demonstrates that 1720, 4765, and 6049 MHz masers can occur under similar conditions in regions of shocked gas. In particular, the 6049 and 4765 MHz masers become more significant at increased OH column densities where the 1720 MHz masers begin to be quenched. In supernova remnants, the detection of excited-state OH line maser emission could therefore serve as a probe of regions of higher column densities. Using the Very Large Array, we searched for excited-state OH in the 4.7, 7.8, 8.2, and 23.8 GHz lines in four well-studied supernova remnants with strong 1720 MHz maser emission (Sgr A East, W28, W44 and IC 443). No detections were made, at typical detection limits of around 10 mJy beam^{-1}. The search for the 6 GHz lines were done using Effelsberg since the VLA receivers did not cover those frequencies, and are reported on in an accompanying letter (Fish and coworkers). We also cross-correlated the positions of known supernova remnants with the positions of 1612 MHz maser emission obtained from blind surveys. No probable associations were found, perhaps except in the Sgr A East region. The lack of detections of excited-state OH indicates that the OH column densities suffice for 1720 MHz inversion but not for inversion of excited-state transitions, consistent with the expected results for C-type shocks.

Subject headings: ISM: individual (IC 443, Sagittarius A East, W28, W44) — masers — supernova remnants

1. INTRODUCTION

Masers observed in the 1720 MHz satellite line of OH are often associated with supernova remnants (SNRs). They originate in the shocked region where the expanding SNR collides with a molecular cloud. During the collision, a nondissociative C-type shock can produce the temperature and density conditions required for 1720 MHz maser emission to occur (Wardle 1999; Lockett et al. 1999). The C-type shock model requires shock speeds of the order of 25 km s^{-1}, and shock chemistry predicts the conditions to be right for masers behind the shock wave. Such velocities and spatial positions are in good agreement with previous observations of SNRs (e.g., Claussen et al. 1997; Yusef-Zadeh et al. 2003; Frail & Mitchell 1998). A natural, next step would be to perform very long baseline interferometric (VLBI) observations to measure the physical sizes of the masing regions, and to track the SNR expansion with time. However, a major hurdle at 1720 MHz is the angular broadening due to interstellar scattering. For example, in the direction of the Galactic center, pronounced scattering ($\Theta_{\rm obs} \sim 500$ mas at 1.6 GHz) has been measured (van Langevelde et al. 1992). To overcome this problem, Hoffman et al. (2003) conducted MERLIN and VLBA observations of the 1720 MHz masers in IC 443, positioned at a Galactic longitude believed to be little affected by scattering. In another project, Claussen et al. (2002) used a nearby pulsar to estimate the interstellar scattering effect close to W28.

A more general method that could work at any position on the sky would be using higher frequency transitions tracing the same type of gas (shocked by the SNR/cloud collisions). Higher frequency masers are less susceptible to scattering effects, which scale as λ^2. Finding higher frequency lines would be particularly interesting for the Sgr A East region, since some 1720 MHz masers found here have velocities very offset from what is expected in the SNR model (Yusef-Zadeh et al. 1996; Karlsson et al. 2003). These offset velocity masers coincide on the sky with the circumnuclear disk and might therefore arise under different conditions. Proper motion studies of masers in the Sgr A complex would thus indicate whether the kinematics really differ for the offset velocity masers and the Sgr A East masers. Higher frequency excited-state OH masers thus could be used for astrometric and proper motion VLBI studies along the heavily scattered Galactic plane and in the Galactic center.

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Modeling of the three lower rotational states of OH has demonstrated that in star-forming regions (SFRs) satellite line 1720 and 4765 MHz, and mainline 6035 MHz masers can occur under similar conditions in regions of shocked gas (Gray et al. 1991, 1992). The 4765 and 6035 MHz masers become more significant at increased column densities where the 1720 MHz masers begin to switch off. Detection of excited-state OH maser emission could therefore serve as a probe of regions of higher OH column densities in SNRs ($N_{\rm OH} \sim 3 \times 10^{17}$ cm^{-2} instead of $N_{\rm OH} \sim 3 \times 10^{16}$ cm^{-2} for the 1720 MHz masers). However, calculations of the $N_{\rm OH}$ resulting from C-type shocks are only able to produce relatively low values, $N_{\rm OH} \simeq 10^{16}$ cm^{-2} (Lockett et al. 1999; Wardle 1999), which may be a limiting factor in the formation of excited-state OH masers in SNRs. It should be noted that detailed observations of OH and H_2O in IC 443 require an OH production scenario involving both J- and C-type shocks (Snell et al. 2005; Hewitt et al. 2006), indicating that estimating the OH column density could be more complicated than previously thought.

In this work we present the details and results of our search for higher frequency OH transitions in SNRs with the Very Large Array (VLA). We also report on the results of a literature search for collisionally excited 1612 MHz masers associated with SNRs.

2. DATA COLLECTION

2.1. *Observations of Excited-State* OH *Lines*

Four well-studied SNRs with strong 1720 MHz masers (ranging from at least 2.5–70 Jy) were selected (W44, W28, IC 443, and Sgr A East). Under project ID AP490, we have observed all excited-state OH lines with excitation levels less than 500 K above ground in the receiver bands[3] of the VLA: the Λ-doubling triplet at 4.7 GHz and the quadruplets at 7.8 and 8.2 GHz (see Fig. 1). For Sgr A East we have also observed the quadruplet around 23.8 GHz (510 K above ground). The 23.8 GHz lines were only observed in Sgr A East as this SNR lies in the region with the highest known interstellar scattering, so observations in this region would best benefit from a smaller λ. In addition, this region is complex and dense, and might therefore provide the best location to search for emission at 23.8 GHz. The limited bandwidth available at 23.8 GHz ($\sim$36 km s^{-1}) may possibly exclude the detections of masers with velocities much offset from the systemic local standard of rest (LSR) velocity.

W28, W44, and Sgr A East were observed in CnB configuration 2005 July 5, and IC 443 was observed in the C-configuration 2005 September 5. Based on the positions of the strongest 1720 MHz masers (>2.5 Jy; Claussen et al. 1997), three regions were selected in W28, two regions in W44 and Sgr A East, respectively, and one region in IC 443. Given that the line widths of most detected 1720 MHz masers are relatively narrow, we observed with a channel separation of 12.207 kHz ($\lesssim$1 km s^{-1} at 4.7 GHz) and a bandwidth of 1.56 MHz (which was changed to 48.828 kHz separation at 3.1 MHz bandwidth for the 23.8 GHz observations only). Using 4 IF (intermediate-frequency) mode at the VLA, we could observe two transitions within each band simultaneously in dual circular polarization centered on the systemic LSR velocity of the source. For the 4.7 GHz triplet, we used the redundant IF for the 4750 MHz line, centered at another velocity (see Table 1).

[3] The currently ongoing upgrade to the Expanded VLA (EVLA) will also allow observations of the 6.0 GHz lines, as well as the 13.4 GHz lines later during the final stages of the upgrade. However, these transitions were not observable during this project. See Fish et al. (2007) for the 6.0 GHz lines in these four SNRs.

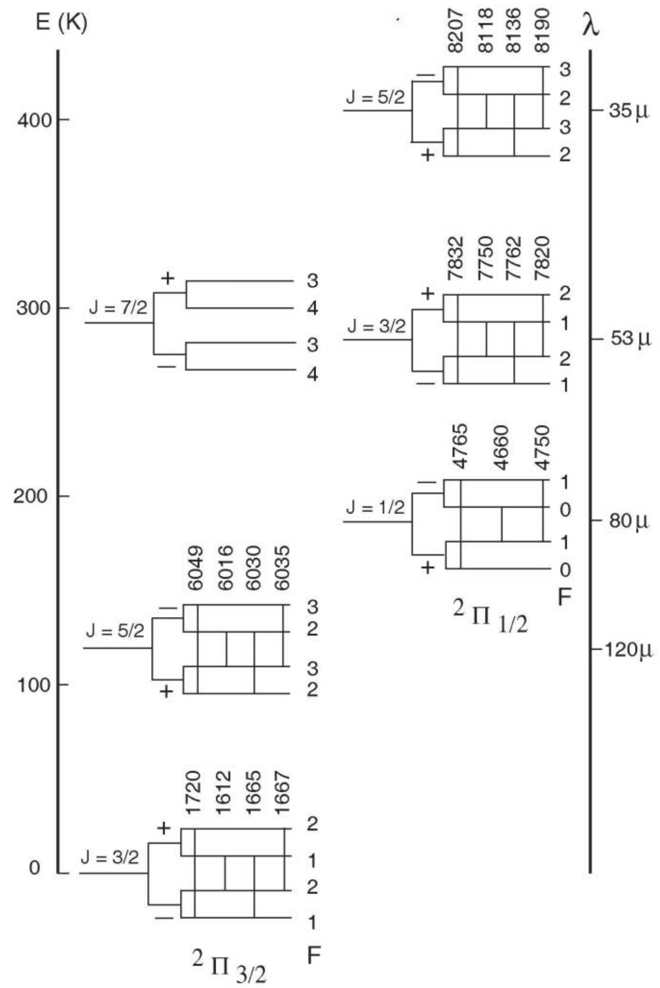

FIG. 1.—Energy level diagram for the OH molecule, showing transitions presently observable with the (E)VLA with excitation levels less than 500 K. Transition frequencies are in units of MHz.

The data were calibrated using NRAO's Astronomical Image Processing System (AIPS), and imaged with natural weighting using standard AIPS procedures. If continuum emission existed in the field, this continuum was subtracted in the u-v plane before imaging. In Table 1 we summarize the results of the observations, including the pointing positions. For each pointing position and frequency, we integrated on source for 5 minutes. The typical final rms noise was $\leq$10 mJy per channel, except for Sgr A East where it was $\leq$15 mJy due to image fidelity issues in this complex region. The field of view at 4.7, 7.8, 8.2, and 23.8 GHz was 9.6′, 5.8′, 5.5′, and 1.9′, respectively.

2.2. *Collisionally Excited* 1612 MHz OH *Masers*

Models of collisional excitation that predict 1720 MHz maser emission also predict 1612 MHz masers in regions of higher density ($n \sim 10^7$ cm^{-3}) or higher column density (Pavlakis & Kylafis 1996). Since 1612 MHz emission traces much denser material than 1720 MHz, 1612 MHz masers are not primarily expected in the immediate vicinity of 1720 MHz masers. We therefore cross-correlated the positions of known SNRs with the locations of known 1612 MHz maser emission in the literature. The positions of the SNRs were taken from the SNR catalog of Green (2006), and the 1612 MHz masers were selected from blind surveys (te Lintel Hekkert et al. 1991; Sevenster et al. 1997a, 1997b,

TABLE 1
Observational Parameters

Pointing	R.A. (J2000.0)	Decl. (J2000.0)	Transition (MHz)	V_{sys}[a] (km s^{-1})	ΔV_{ch}[b] (km s^{-1})	Beam Size[c] (arcsec)	Mean rms[c] (mJy beam^{-1})
IC 443	06 16 43.61	+22 32 39.78	4750.7, 4660.2, 4765.6	−4.6	0.9	5.1 × 4.3	13.2
			7761.7, 7820.1, 7832.0, 7749.9	−4.6	0.6	3.0 × 2.8	8.4
			8135.9, 8189,6, 8207.4, 8118.1	−4.6	0.5	3.0 × 2.7	6.5
Sgr A East	17 45 44.31	−29 01 18.34	4750.7	64.0	0.8	7.7 × 3.4	13.8
			4750.7	132.0	0.8	7.7 × 3.4	14.5
			4660.2, 4765.6	64.0	0.8	7.7 × 3.4	14.1
			7761.7, 7820.1, 7832.0, 7749.9	64.0	0.5	7.0 × 2.5	11.4
			8135.9, 8189,6, 8207.4, 8118.1	64.0	0.5	5.7 × 2.6	9.5
			23817.9, 23826.6, 23838.9, 23805.3	64.0	0.7	1.4 × 0.8	9.4
Sgr A East	17 45 40.62	−28 59 43.98	4750.7	64.0	0.8	5.8 × 3.9	15.1
			4750.7	132.0	0.8	5.8 × 3.9	14.1
			4660.2, 4765.6	132.0	0.8	5.8 × 3.9	14.6
			7761.7, 7820.1, 7832.0, 7749.9	132.0	0.5	5.4 × 2.6	11.9
			8135.9, 8189,6, 8207.4, 8118.1	132.0	0.5	5.3 × 2.5	9.5
			23817.9, 23826.6, 23838.9, 23805.3	132.0	0.7	1.2 × 0.9	9.5
W28A	18 00 45.55	−23 17 43.33	4750.7	6.3	0.9	5.9 × 4.0	8.6
			4750.7	76.3	0.9	5.9 × 4.0	8.8
			4660.2, 4765.6	6.3	0.9	6.2 × 4.2	8.7
			7761.7, 7820.1, 7832.0, 7749.9	6.3	0.6	4.2 × 2.6	9.1
			8135.9, 8189,6, 8207.4, 8118.1	6.3	0.6	4.5 × 2.6	7.4
W28CD	18 01 39.35	−23 25 01.97	4750.7	14.1	0.9	5.7 × 4.0	9.2
			4750.7	84.1	0.9	5.9 × 4.1	8.0
			4660.2, 4765.6	14.1	0.9	6.2 × 3.9	8.6
			7761.7, 7820.1, 7832.0, 7749.9	14.1	0.6	4.8 × 2.6	9.1
			8135.9, 8189,6, 8207.4, 8118.1	14.1	0.5	4.1 × 2.8	7.2
W28EF	18 01 51.64	−23 18 21.02	4750.7	11.7	0.9	6.7 × 3.6	8.3
			4750.7	81.7	0.9	6.9 × 3.5	9.2
			4660.2, 4765.6	11.7	0.9	7.2 × 4.3	8.9
			7761.7, 7820.1, 7832.0, 7749.9	11.7	0.6	4.6 × 2.8	9.1
			8135.9, 8189,6, 8207.4, 8118.1	11.7	0.5	5.0 × 2.6	7.1
W44EF[d]	18 56 33.02	+01 27 54.40	4750.7	6.3	0.9	5.3 × 3.9	8.9
			4750.7	76.3	0.9	5.3 × 3.9	10.3
			4660.2, 4765.6	6.3	0.9	6.2 × 3.7	8.9
W44E[d]	18 56 29.14	+01 29 14.15	7761.7, 7820.1, 7832.0, 7749.9	6.3	0.6	3.9 × 2.5	8.1
			8135.9, 8189,6, 8207.4, 8118.1	6.3	0.6	3.9 × 2.4	6.3
W44F[d]	18 56 36.90	+01 26 34.65	7761.7, 7820.1, 7832.0, 7749.9	6.3	0.6	4.4 × 2.4	8.0
			8135.9, 8189,6, 8207.4, 8118.1	6.3	0.6	4.1 × 2.4	6.5

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] The observed bandwidth was centered on the systemic LSR velocity, and covered ~96, 58, 55, and 36 km s^{-1} for the 4.7, 7.8, 8.2, and 23.8 GHz lines, respectively.
[b] Velocity resolution, with no online Hanning smoothing applied during the observations.
[c] The transitions were imaged separately, but lines close in frequency have similar beam sizes and channel rms. The listed value is the mean of the transitions.
[d] At lower frequencies W44E and W44F were observed in one beam centered at their mean position, W44EF. At higher frequencies, they were observed separately as W44E and W44F.

2001). Since most 1612 MHz masers with a double-peaked spectrum are associated with evolved stars (e.g., Habing 1996), we constrained our cross-correlation to sources with single-peaked or irregular spectra, which resulted in a final sample of 184 sources. No probable associations were found within a minimum search radius of 10′, suggesting that the higher column densities suitable to produce collisionally excited 1612 MHz SNR maser emission do not occur frequently in SNRs. A special case may be Sgr A East in the Galactic center region where a much more sensitive 1612 MHz OH survey is available (Sjouwerman et al. 1998), and which we will further discuss separately in § 3.6.

3. DISCUSSION

3.1. *Other Detections of Excited-State* OH *Lines*

No detection of either absorption or emission was made in any of the lines searched for excited-state OH (but see Fish et al. (2007) for possible 6030/6035 MHz main-line absorption in Sgr A East). This may seem somewhat surprising, since modeling of the three lower rotational states of OH in SFRs has demonstrated that 1720, 4765, and 6035 MHz masers can occur under similar conditions in regions of shocked gas (Gray et al. 1991, 1992). Observations of SFRs support the coexistence of these lines. Indeed, a search for excited-state OH masers at 4765 and 6035 MHz in a sample of SFRs with 1720 MHz masers resulted in high detection rates (MacLeod 1997). About one-third of the 1720 MHz masers have associated 4765 MHz masers, and as many as about two-thirds display 6035 MHz masers, indicating that the excited-state OH masers may form under similar conditions to the 1720 MHz masers. This is further supported by detailed mapping of the SFR W 3 (OH), showing that a third of the 4765 MHz spots are spatially coincident with 1720 MHz masers (Palmer et al. 2003). In several SFRs, rotational lines as high as ~500 K above ground (in the seventh-lowest rotational level, $^2\Pi_{3/2}, J = 9/2$) have been detected in absorption and emission, including weak maser emission (e.g., in W 3 (OH) and Sgr B2

Baudry et al. 1981; Gardner et al. 1987; Wilson et al. 1990; Baudry & Desmurs 2002; Fish et al. 2007).

Most SFRs show main-line 1665/1667 MHz masers, although there are exceptions: Niezurawska et al. (2004) report on 4765 MHz masers associated with SFRs that display 1720 MHz emission without main line emission, suggesting that these regions could contain shocks with similar properties to SNR shocks. Despite observations of coexisting 1720, 4765, and 6035 MHz masers in SFRs, we have not been able to find higher excitation lines in SNRs. In contrast to SNRs, however, where 1720 MHz masers are thought to be collisionally pumped, the main-line 1665/1667 and 6035 MHz masers are probably radiatively excited. It should be pointed out that the models by Gray et al. (1991, 1992) predicting copropagating 1720, 4765, and 6035 MHz masers include a strong far-infrared radiation field associated with the parent star, suitable for SFRs. Hence, radiative pumping routes are likely to be critical for producing simultaneous 1720, 4765 MHz satellite line emission and 6035 MHz main-line emission.

3.2. *Predicted* OH *Maser Transitions in SNRs*

Existing models predict a sequence of inversions as the number density (n_{H_2}) or the column density of OH (N_{OH}) is increased (Pavlakis & Kylafis 1996, 2000; Lockett et al. 1999; Wardle 2007). To predict the maser optical depths in all 1.6, 4.7, 6.0, 7.8, 8.2, and 13.4 GHz transitions, we have used MOLPOP.[4] The MOLPOP program solves the molecular level population equations using the escape probability method for a homogeneous slab. We use the Offer et al. (1994) collision rate coefficients for the lowest 24 energy levels, with an ortho-para ratio of 3:1. Thus, the 23.8 GHz transitions are not included in this model. Following the results by Lockett et al. (1999), we start with postshock gas properties typically producing 1720 MHz masers in SNRs: molecular density $n_{H_2} \sim 10^5$ cm^{-3}, temperature $T \sim 75$ K, OH fraction $f_{OH} \sim 10^{-5}$, and thermal line widths. Using these values, in Figure 2 we plot the maser optical depth as a function of OH column density, N_{OH}. These results are consistent with those of Wardle (2007). With the given parameters, the model does not predict any significant maser optical depths in any of the 7.8, 8.2, and 13.4 GHz lines, nor in the individual 1665, 1667, 4660, 4750, 6016, 6030, or 6035 MHz lines. Note that the 6035 MHz masers modeled by Gray et al. (1991, 1992) thus must be due to IR pumping and therefore will not be discussed further below. At low column densities, 1720 MHz maser emission is produced. At progressively higher column densities, first 6049 MHz masers turn on, then 1720 MHz masers turn off, so that there is an overlap range in which the OH column density is simultaneously low enough to produce a detectable 1720 MHz maser and high enough to produce 6049 MHz maser emission as well. At still higher column densities, the 4765 and 1612 MHz masers turn on and the 6049 MHz masers turn off. The transition between 1720 MHz masing and 1612/4765 MHz masing occurs when the 79 μm transitions between the $^2\Pi_{3/2}, J = 3/2$ states and the $^2\Pi_{1/2}, J = 1/2$ states (Fig. 1) become optically thick (Elitzur 1976). It is worth noting that in the low-temperature ($T < 120$ K) regime, the collisionally excited masers occur only in satellite-line transitions ($\Delta F = \pm 1$, see Fig. 1). At higher temperatures, main lines ($\Delta F = 0$) can become inverted as well via collisions and local line overlap (e.g., Pavlakis & Kylafis 1996, 2000).

Inversion of the 1720 MHz maser using the Offer collision rates depends on the hydrogen ortho-para ratio (Pavlakis & Kylafis 1996). To test the reliability of our results, we also calculated the level populations using hard sphere cross sections and obtained results similar to those found using the Offer rates with an ortho-para ratio of 3.

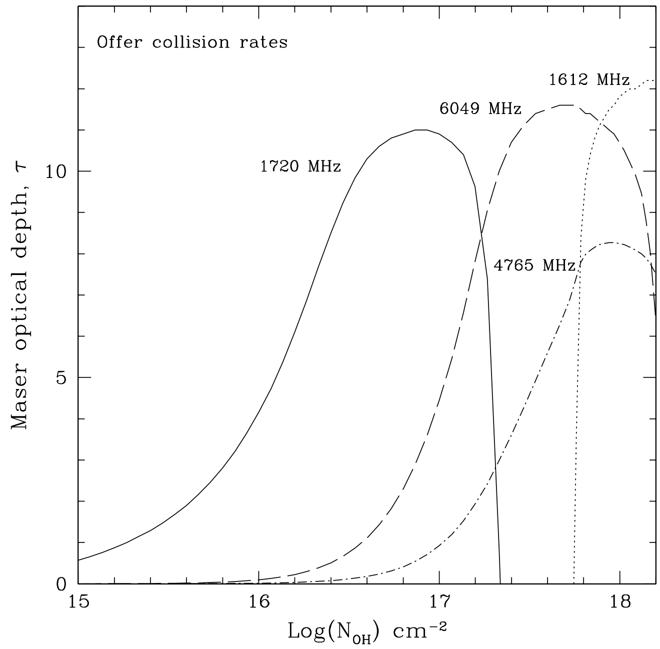

FIG. 2.—Expected maser optical depths in inverted transitions in a gas component typically producing 1720 MHz masers ($n = 10^5$ cm^{-3}, $T = 75$ K, $f_{OH} = 10^{-5}$), using the Offer et al. (1994) collision rates.

The only OH transition observed to produce a detectable maser in SNRs is the 1720 MHz transition. A targeted search for 6049 MHz masers toward 36 SNRs failed to detect a single maser (McDonnell et al. 2007). Recently, we also used the Effelsberg telescope to search for the four 6 GHz lines in W28, W44, IC 443, and Sgr A East, with no detections (Fish et al. 2007). As noted in § 2.1, the 1612 MHz masers detected in the te Lintel Hekkert et al. (1991) and Sevenster et al. (1997a, 1997b, 2001) blind surveys do not produce any detections associated with SNRs (but see § 3.6). Finally, in this work, we fail to obtain positive detections at 4765 MHz or any other excited-state transition.

3.3. *Detectability of Predicted Masers*

One reason why no excited-state OH lines have been detected may be due to sensitivity. The maser emission will be amplified according to $T_m \simeq T_{bg} e^{\tau}$, where T_m is the brightness temperature of the maser, T_{bg} is the brightness temperature of the background continuum radiation, and positive τ is the maser optical depth. By comparing the brightness temperature of a known 1720 MHz maser and its background continuum, we can calculate the maser optical depth and compare it to the values predicted in Figure 2. If consistent, the results can be scaled to estimate the predicted maser brightness temperatures in the excited states.

As an example, we consider Sgr A East. We select the region where a 0.18 Jy maser occurs at +55 km s^{-1} (Yusef-Zadeh et al. 1996). At that position, the background continuum at 1720 MHz corresponds to a brightness temperature of $T_{bg} \sim 100$ K, and the maser brightness temperature is $T_m \sim 2.3 \times 10^5$ K. Assuming all continuum is in the background, this implies a lower limit to optical depth of $\tau \sim 8$, well in agreement with Figure 2 and other existing models (Lockett et al. 1999; Wardle 2007). To estimate the T_m for the transition at 4765 MHz, the 1720 MHz brightness temperature is scaled using the spectral index $\alpha = -1$ measured

[4] Available at http://www.pa.uky.edu/~moshe/molpop.zip.

in Sgr A East by Pedlar et al. (1989). The brightness temperature of a synchrotron emitter changes as $T_b \propto \lambda^{2-\alpha}$ (Rybicki & Lightman 1979), yielding a 4765 $T_{\rm bg} \sim 5$ K. An optimistic reading of Figure 2 in the region where 1720 MHz emission still occurs will give a $\tau \sim 2$, resulting in $T_m \sim 40$ K. Indeed, this is below the 5 σ detection limit in our VLA observations, which is 50 mJy or 115 K. Thus, it might be difficult to detect 4765 MHz masers copropagating with 1720 MHz masers without deeper integrations than those presented in § 2.

A similar estimate for the 6049 MHz line, assuming a $\tau \sim 6$ and $T_{\rm bg} \sim 2.5$ K yields $T_m \sim 1 \times 10^3$ K, which should be easier to detect. With the upgrade of the VLA to EVLA, the 6.0 GHz lines will be observable and are thus warranted a deeper search. However, we note that to date, searches for 6049 MHz have proved negative. This indicates that the 1720 MHz masers occur only in regions of low column densities, insufficient for the formation of 4765 and 6049 MHz masers.

3.4. *Column Density Effects*

The most straightforward explanation of the absence of detectable excited-state OH maser emission in SNRs is that highest column density peaks produce the 1720 MHz masers but are not high enough to generate maser emission in any other transition. We note that the search presented here is biased toward regions with existing 1720 MHz masers, and could thus be biased against regions with the higher column densities needed for the excited-state OH (Fig. 2). Estimates of the OH column densities are available via thermal absorption in the ground state transitions of OH, when sufficient background continuum emission is present. Absorption of 1667 MHz OH in W28 implies $N_{\rm OH} \simeq 2 \times 10^{16}$ cm^{-2}, for an adopted excitation temperature $T_{\rm ex}$ of 10 K (Yusef-Zadeh et al. 2003), indicating low column densities with little possible inversion of the excited-state OH (Fig. 2). Similar observations of IC 443 show OH absorption in molecular clumps with $N_{\rm OH}$ ranging between 0.7×10^{16} and 1.4×10^{17} cm^{-2} (Hewitt et al. 2006). Slightly higher column densities of the order of (2–3) $\times$ 10^{17} cm^{-2}, assuming $T_{\rm ex} \simeq 10$ K, are derived for Sgr A East (L. O. Sjouwerman 2007, private communication). With measured OH column densities of the order of 10^{16}–10^{17} cm^{-2}, models based on the Offer et al. (1994) collision rates allow the possibility that there might exist a few regions in SNRs with sufficient column densities for the 6049 MHz line to be inverted (Fig. 2). Our nondetections are, however, consistent with regions of lower column densities, where 1720 MHz masers are strong, and little or no inversion has occurred in the higher transitions.

3.5. *Temperature and Density*

An alternative explanation to the absence of excited-state OH masers could be that the density or temperature is too high. Models of 1720 MHz emission imply that the optimal postshock density in which 1720 MHz masers occur is of the order $n_{\rm H_2} \sim 10^5$ cm^{-3}, with temperatures $T \sim 50$–125 K (Lockett et al. 1999; Wardle 1999). Millimeter observations of multiple molecular lines in IC 443 suggest that there may be regions of much higher temperature and density in SNRs. In particular, in IC 443, the 1720 MHz masers occur within the IC 443 cloud complex G (DeNoyer 1979). From the millimeter data, the medium in this clump appears to fit a two-component model with both a cool, low-density ($T \sim 80$ K, $n \sim 10^5$ cm^{-3}) component, and a warmer, higher density ($T \sim 200$ K, $n \sim 3 \times 10^6$ cm^{-3}) component (van Dishoeck et al. 1993). Similar numbers were derived by Turner et al. (1992). At densities of the order of 10^6 cm^{-3}, but with lower temperature ($T = 75$ K), previous modeling has already shown that the 1720 MHz transition may still be weakly inverted (Lockett et al. 1999).

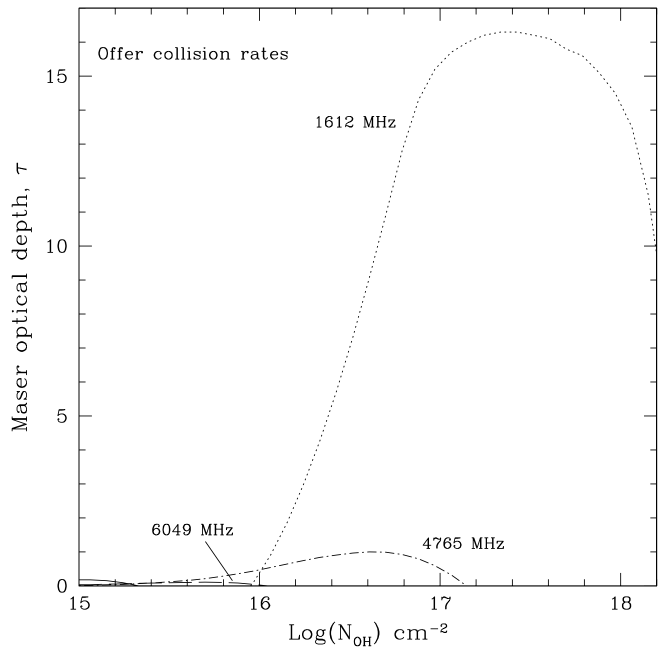

Fig. 3.—Expected maser optical depths in the inverted transitions in a high-density ($n = 5 \times 10^6$ cm^{-3}, $T = 200$ K) gas component. At these high temperatures and densities, the 1720 MHz maser is quenched and the 1612 MHz line dominates.

Here we calculate the expected maser optical depths in a warmer, higher density region, again using MOLPOP assuming thermal line-widths, $T \simeq 200$ K, and $n \sim 5 \times 10^6$cm^{-3}, we achieve the results shown in Figure 3. As expected, the 1720 MHz line is quenched at this higher density. The 4765 MHz transition is only modestly inverted with maser optical depths of the order of 0.5–1 at column densities $N_{\rm OH} \sim 10^{16}$–10^{17} cm^{-3}. Even weaker inversion is seen in the 6049 MHz line. We therefore conclude that if the molecular medium is commonly composed of two components like those in IC 443, the 1720 MHz masers must be associated with the cooler, lower-density component. A warmer component will not be able to produce excited-state OH masers, and as a consequence, we conclude that it is not the density that primarily constrains the formation of excited-state OH.

We note that at higher densities, the model predicts a strong maser line in the 1612 MHz transition (Fig. 3). However, 1612 MHz masers in general are not correlated with SNRs (§ 2.2), which could indicate that warm, dense regions like the one in IC 443 G modeled by van Dishoeck et al. (1993) are rare in SNRs.

3.6. *A Possible Exception: Sgr A East*

Sgr A East is a very complicated region and has been studied in detail in the past. In particular, it has been surveyed for 1612 MHz masers to find OH/IR stars (Sjouwerman et al. 1998 and references therein). However, 1612 MHz emission can also originate from the interaction of a SNR and its surrounding ISM (§ 2.2; Fig. 3). We therefore turned to the list of double peaked 1612 MHz masers found by Sjouwerman et al. (1998) where some maser sources are attributed to the +50 km s^{-1} molecular cloud (MC). The individual MC spectra shown may not represent the true emission (and absorption) in the cloud, or be complete for emission of the cloud (e.g., see the "maxmap" in their Fig. 8), as the data reduction and search were focused on finding double-peaked OH/IR stars. However, their MC list does partly represent compact 1612 MHz emission, either thermal or low-gain masing not attributed to stars, and therefore is relevant in this respect.

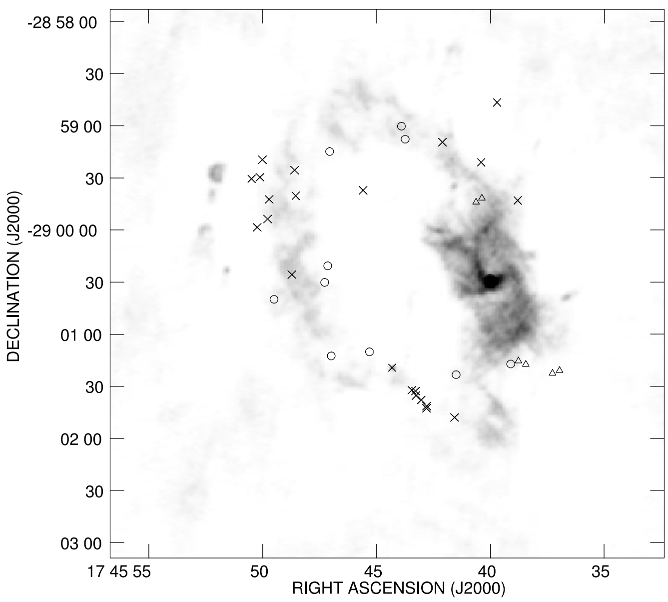

Fig. 4.—Sgr A East 1720 MHz masers (*crosses*) superimposed on 1.7 GHz continuum image (*gray scale*) taken from Pihlström & Sjouwerman (2006). The triangles are high-velocity 1720 MHz masers related to the circumnuclear disk and not to the SNR/MC interaction. The circle denotes positions of 1612 MHz emission in this region.

In Figure 4 we plot the locations of the pure MC 1612 MHz emission (*circles*) from Sjouwerman et al. (1998) on top of the 1720 MHz SNR masers (*crosses*) and 1.7 GHz radio continuum (*gray scale*) taken from Pihlström & Sjouwerman (2006). The following observations can be made:

1. All regions of 1612 MHz emission have one or more peaks in the $V_{\rm LSR}$ range of 30–70 km s^{-1}, i.e., closely following the $V_{\rm LSR}$ gradient over, and range of the +50 km s^{-1} molecular cloud.
2. The 1612 MHz emission avoids regions of 1720 MHz emission (the closest possible association is about 0.5 pc in projection), which is to be expected as a reflection of column density differences (Figs. 2 and 3).
3. The 1612 MHz emission is colocated with the radio continuum outlining the SNR, but not on top of the regions of the strongest radio continuum emission.
4. No 1612 MHz emission is seen near the compact H ii regions in the east and south: i.e., the 1612 MHz emission is probably not related to SFRs.

We note that no 4765 MHz emission (this work) nor 6049 MHz emission (Fish et al. 2007) is detected toward Sgr A East, so there does not exist a continuous density gradient where the 1720, 6049, 4765, and then 1612 MHz transitions, respectively, are purely collisionally pumped. Based on these data, we are not able to determine whether the 1612 MHz emission is purely thermal emission from the cloud. It could also be pumped by the interstellar radiation field and perhaps amplifying the background radio continuum, or indeed collisionally pumped stimulated emission resulting from the reverse shock in the SNR. To address these questions in the Galactic center (GC), a more specific observational setup will be required to properly account for details like, for example, missing zero-spacing flux. As the GC is a special case, it is beyond the scope of this paper. Pending a more detailed analysis of the GC region we therefore assume that there generally is no collisionally excited 1612 MHz emission due to SNR/MC interactions, with a possible exception in the GC.

4. CONCLUDING REMARKS

For OH column densities $N_{\rm OH} \sim 10^{16}$–10^{18} cm^{-2}, models of collisionally pumped excited-state OH in SNRs predict inversions in the 1720, 4765, and 6049 MHz lines, while no significant maser optical depths will be produced in other transitions of the 4.7, 7.8, 8.2, and 23.8 GHz lines. We have presented the results from a search of all these excited-state OH transitions in four, well-known SNRs, with no detections. These VLA observations could not tune to the 6049 MHz line, which is also predicted to have large optical depths under conditions similar to those of 1720 MHz masers. However, a few recent searches for the 6049 MHz line in SNRs have yielded no detections (Fish et al. 2007; McDonnell et al. 2007). In the future, the EVLA upgrade will allow for a targeted, deeper search for 6049 MHz in these SNRs.

Our nondetections are consistent with regions of lower column densities ($N_{\rm OH} \leq 5 \times 10^{16}$ cm^{-2}), where 1720 MHz masers are strong, and little inversion occurs in the higher transitions. Based on VLA and single-dish observations by Yusef-Zadeh et al. (1995) & Hewitt et al. (2007), such a postshock medium may have a large filling factor. Hewitt et al. (2007) found that a large part of the 1720 MHz maser flux is undetected using VLA baselines, indicating a widespread distribution of weaker 1720 MHz emission. This likely reflects large postshock regions of low column density, or alternatively, regions of different temperature and density from what is normally expected for 1720 MHz maser production. In turn, such a gas component will provide little chance of excited-state OH maser emission. If this is the case, excited-state OH will not be detected either coincident with or offset from detected 1720 MHz masers in SNRs. The nondetections imply a low OH column density in SNRs, in agreement with the rather low estimates of the $N_{\rm OH} \simeq 10^{16}$ cm^{-2} expected to be produced in C-type shocks (Wardle 1999; Lockett et al. 1999).

From these results we draw the conclusion that in the regions where 1720 MHz masers are found, the OH column densities are insufficient for excited-state OH masers to exist. This is supported by the absence of 1612 MHz masers in SNRs, which require 1–2 orders of magnitude higher column densities than the 1720 MHz masers. However, the upper limit to the column density must be even stricter to avoid producing 6049 and 4765 MHz masers.

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Facilities: VLA

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