The Astrophysical Journal, 670:L117–L120, 2007 December 1
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EFFELSBERG OBSERVATIONS OF EXCITED-STATE (6.0 GHz) OH IN SUPERNOVA REMNANTS AND W3(OH)

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Received 2007 August 24; accepted 2007 October 5; published 2007 October 23

ABSTRACT

Although masers in the 1720 MHz transition of OH are detected toward many supernova remnants (SNRs), no other OH transition is seen as a maser in SNRs. We present a search for masers at 6049 MHz, which has recently been predicted to produce masers by pure collisional excitation at conditions similar to that required for 1720 MHz masing. The Effelsberg 100 m telescope was used to observe the excited-state 6016, 6030, 6035, and 6049 MHz lines of OH toward selected SNRs, most of which have previously detected bright 1720 MHz masers. No excited-state masers are found toward SNRs, consistent with previous observations of the 6049 MHz and other excited-state transitions. We do not see clear evidence of absorption toward SNR target positions, although we do see evidence of absorption in the molecular cloud at +50 km s^{-1} near Sgr A East. Weak absorption is detected at 6016 MHz toward W3(OH), whereas stronger, narrower emission is seen at 6049 MHz, suggesting that the 6049 MHz emission is a low-gain maser. We conclude that the conditions in SNRs are not conducive to excited-state maser emission, especially in excited-state satellite lines.

Subject headings: ISM: individual (Sagittarius A East, W3) — masers — radiation mechanisms: nonthermal — radio lines: ISM — supernova remnants

1. INTRODUCTION

About two dozen supernova remnants (SNRs) are known to host 1720 MHz OH masers (Green 2006 and references therein). The excitation mechanism for 1720 MHz masers in SNRs is commonly believed to be collisional excitation from a C-type shock (Lockett et al. 1999; Wardle 1999). Other ground-state OH transitions are sometimes seen in absorption (e.g., Goss 1968), which can be helpful for modeling the physical conditions in the 1720 MHz masing region (Hewitt et al. 2006). However, to date, no other OH transition (or transition of any other molecule) has been detected as a maser associated with an SNR. The detection of a second maser transition in SNRs would place strong constraints on the physical conditions (density, temperature, OH fraction, ortho-to-para H_2 ratio, etc.) in the masing region, especially if spatial coincidence with a 1720 MHz maser was observed. Excited-state transitions, which occur at higher frequencies, would be especially useful if detected toward the Galactic center, where angular scattering is large (see § 1 of Pihlström et al. 2007).

Another motivation for finding a second masing transition in SNRs is to confirm the Zeeman interpretation of splitting seen between the left- and right-circular polarization (LCP and RCP, respectively) components at 1720 MHz. Differences between LCP and RCP velocities are used to compute the magnetic field strengths in SNRs (e.g., Brogan et al. 2000); these magnetic field strengths are important for quantifying magnetic pressures. However, Elitzur (1996, 1998) shows that circular polarization can be generated by non-Zeeman mechanisms when the maser is saturated and when splitting is small compared to a line width, as is the case in SNR 1720 MHz masers. Although there are theoretical reasons for believing the Zeeman interpretation of SNR 1720 MHz maser splitting (see § 4.1 of Brogan et al. 2000), direct confirmation of the magnetic field strengths from a second OH transition would lead to a greater confidence in the derived magnetic field strengths.

Theoretical modeling predicts that collisions alone can excite several transitions of OH. In the low-density ($n \sim 10^5$ cm^{-3}) regime, only the 1720 MHz transition is inverted, but at higher number and/or column densities the 6049 MHz transition also becomes inverted, with some overlap in parameter space allowing simultaneous inversion of the 1720 and 6049 MHz lines (Pavlakis & Kylafis 2000; Wardle 2007; Pihlström et al. 2007). At still higher densities ($n \sim 5 \times 10^6$ cm^{-3}), the 4765 and 1612 MHz transitions become inverted (Pavlakis & Kylafis 1996; Pihlström et al. 2007). The 6035 MHz line may also become inverted at high temperatures ($T \sim 200$ K; Pavlakis & Kylafis 2000). Regardless of the details of the pump mechanism, weak inversion (emission) is predicted in the 6049 MHz line, and weak anti-inversion (enhanced absorption) is predicted in the 6016 MHz line, from the structure of the OH level diagram alone, when infrared trapping becomes important (Litvak et al. 1969; Elitzur 1977).

Few observations have sought excited-state OH masers in SNRs. McDonnell et al. (2007) looked for 6030, 6035, and 6049 MHz OH maser emission toward southern SNRs but did not detect any 6049 MHz emission. Although they did find three new 6030 and 6035 MHz maser sources, McDonnell et al. (2007) believe that these masers are associated with H II regions and therefore represent emission from star-forming regions (SFRs), not SNRs. In states of higher excitation, Pihlström et al. (2007) searched for emission in the 4.7 GHz Λ-doubling triplet and in the 7.8 and 8.2 GHz quadruplets, toward four SNR complexes (as well as in the 23.8 GHz quadruplet toward Sgr A East), but they did not detect any emission. Pihlström et al. (2007) also cross-correlated positions of single-peaked and irregular-spectrum 1612 MHz masers, from blind surveys in the literature, with positions of known SNRs, but they found no probable associations.

For small velocity differences along the amplification path, the 6049 MHz transition is theoretically the most promising transition in which to find new OH SNR masers, given that the collisional excitation conditions require only slightly higher densities than those that produce 1720 MHz masers. We report

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TABLE 1
OBSERVED SOURCES

Source	R.A.[a] (J2000)	Decl.[a] (J2000)	V_{LSR}[b] (km s^{-1})	σ[c] (mJy)	Notes[d]
Supernova Remnant Pointings					
3C 58	02 05 38.1	+64 49 41	0	11	X
Crab Nebula	05 34 31.9	+22 00 52	0	26	X
IC 443 G	06 16 43.6	+22 32 34	−5	4	…
Sgr A East SW[e]	17 45 38.0	−29 01 15	−130	31	…
Sgr A East NW[e]	17 45 40.2	−28 59 45	130	41	…
Sgr A East S	17 45 43.0	−29 01 25	60	34	A?
Sgr A East N	17 45 44.5	−28 58 45	50	28	X, A?
Sgr A East SE	17 45 48.0	−29 01 00	60	23	X, A?
Sgr A East NE	17 45 48.5	−28 59 45	60	23	A
Sgr D	17 48 52.7	−28 11 18	0	12	…
G1.4−0.1	17 49 28.1	−27 47 35	0	18	…
W28 A	18 00 45.2	−23 17 43	10	9	…
W28 C	18 01 34.7	−23 24 00	10	18	…
W28 F	18 01 51.6	−23 18 58	10	9	…
W28 E	18 01 51.6	−23 17 44	10	9	…
G16.7+0.8	18 20 58.3	−14 21 52	20	6	…
Kes 69	18 33 12.0	−10 00 40	70	6	…
SNR 027.3+00.1	18 40 35.1	−04 57 45	35	6	…
3C 391 E	18 49 22.6	−00 57 32	110	6	…
3C 391 W	18 49 37.1	−00 55 31	110	6	…
Kes 78	18 51 24.0	−00 08 23	85	6	…
W44 A	18 55 27.2	+01 33 46	45	8	…
W44 B	18 56 00.9	+01 12 57	45	8	…
W44 E	18 56 29.1	+01 29 39	45	11	…
W44 D	18 56 29.3	+01 20 29	45	8	…
W44 F	18 56 36.7	+01 26 35	45	6	…
W51 C	19 22 54.1	+14 15 42	70	6	…
Other Pointings					
W3(OH)	02 27 03.8	+61 52 26	0	8	A, M
AU Gem	07 45 28.6	+30 46 43	15	6	X
ON 1	20 10 09.1	+31 31 34	10	9	M
NML Cyg	20 46 25.5	+40 07 00	0	9	X
NGC 7027	21 07 01.6	+42 14 10	70	14	X

[a] Pointing center of observations; units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[b] Center LSR velocity of observations.
[c] Average rms noise in the four transitions after Hanning smoothing.
[d] A = absorption; M = maser emission; and X = pointing without 1720 MHz masers.
[e] Includes circumnuclear disk.

on targeted observations of the four 6.0 GHz lines, mostly toward SNRs with bright 1720 MHz masers.

2. OBSERVATIONS

We observed 32 target positions with the Effelsberg 100 m telescope in two runs on 2007 July 12 and 13. Pointing centers are given in Table 1. Observations were taken in position-switched mode using the 5 cm primary focus receiver. The full width at half-maximum (FWHM) beam size of the telescope is approximately 130″ at the 6.0 GHz frequencies of OH. The assumed sensitivity of the telescope is 1.55 K Jy^{-1}.

Data were collected using both the AK90 8192-channel autocorrelator as well as the fast Fourier transform spectrometer (FFTS). The AK90 was configured to produce eight spectral windows of 10 MHz bandwidth, each divided into 1024 spectral channels with an effective channel spacing of 0.5 km s^{-1}. Two spectral windows, one each for LCP and RCP, were centered at the systemic LSR (local standard of rest) velocity of the source in each of the four transitions at 6016.746, 6030.747, 6035.092, and 6049.084 MHz. On the second day, velocities were shifted by 20 km s^{-1}, to confirm that features present in the data were not artifacts of the autocorrelator. Data from the FFTS were of lesser quality but were used to confirm that suspected features were not artifacts of the AK90 system.

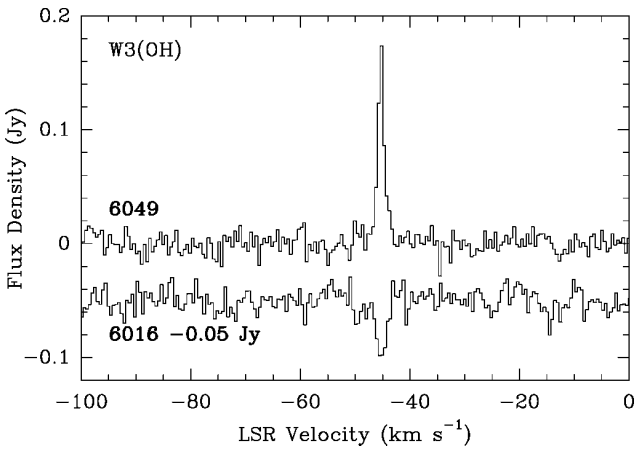

FIG. 1.—Spectra of the 6016 and 6049 MHz transitions in W3(OH). Emission in the 6049 MHz transition is stronger than absorption in the 6016 MHz transition. A single-Gaussian fit to the emission is narrower than a similar fit to the absorption.

The data were reduced using the Continuum and Line Analysis Single-dish Software (CLASS) package. Hanning smoothing was applied to the data to remove the effects of correlated noise generated by strong continuum and line sources. Polynomial baselines were removed from the scans.

3. RESULTS

Table 1 summarizes our results. We do not detect masers or thermal emission in any of the 6.0 GHz transitions toward SNRs at a typical level of 30 mJy (5 σ). This limit is approximately an order of magnitude better than that previously obtained toward southern SNRs (McDonnell et al. 2007) and is comparable to the noise limits obtained in other transitions by Pihlström et al. (2007).

The SFRs W3(OH) and ON 1 were observed to confirm the reliability of the system. In both cases, bright masers were detected at both 6030 and 6035 MHz. Since our spectral resolution was insufficient to resolve the maser line widths, the reader is referred to previously published literature for information on the 6030 and 6035 MHz masers in these two sources. We note, however, that we do not see emission in W3(OH) near −70 km s^{-1} at 6030 MHz to a 4 σ level of 30 mJy in Stokes I (after Hanning-smoothing the spectral resolution to 1 km s^{-1}, to eliminate ringing from the bright masers), as previously reported by Fish et al. (2006). It is not clear whether these masers are variable or whether the original detection was an artifact of the Effelsberg autocorrelator system.

In the satellite lines, 6016 MHz absorption and 6049 MHz emission are seen at the same velocity toward W3(OH), as shown in Figure 1. A single-Gaussian fit to the 6049 MHz emission gives 165 mJy centered at −45.30 ± 0.03 km s^{-1}, with an FWHM line width of 1.39 ± 0.08 km s^{-1}. These values are consistent with those obtained by Guilloteau et al. (1984), when they use the Meerts & Dymanus (1975) rest frequency of 6049.084 MHz for the transition. The parameters for the 6016 MHz absorption are −52 mJy at −45.22 ± 0.13 km s^{-1} and a line width of 1.96 ± 0.28 km s^{-1}. The emission and absorption span the same velocity range (full width at zero power), although the peak of the emission is narrower (FWHM) than the peak of the absorption, in qualitative agreement with the observations of Baudry et al.

(1997). The agreement in velocities suggests that the 6016 MHz absorption and the 6049 MHz emission come from the same physical region in W3(OH).

Generally, no absorption is seen toward these SNRs. Likely absorption is detected in the main lines in the Galactic center region (Fig. 2), although spectral baselines are poor due to strong continuum flux. The velocity ($\sim+50$ km s^{-1}), width (17.5 ± 1.5 km s^{-1} for 6030 MHz and 20.1 ± 1.0 km s^{-1} for 6035 MHz), and location of the strongest absorption (on the east side of Sgr A East) are all consistent with the densest ^{13}CO seen in the data of Zylka (1996), suggesting that the excited-state molecular content is strongest in that region. Similar but weaker features are seen in other scans on the eastern side of Sgr A East, but we cannot rule out that absorption-like features seen near $+50$ km s^{-1} in the other Sgr A scans are due to errors in baseline removal. As discussed in § 4.2, this absorption may be due to the unusual molecular cloud in the region rather than its interaction with the SNR. Otherwise, no absorption is seen in any of the four transitions in any of the other sources, even when scans from separate sources (excluding the Galactic center sources) are aligned in velocity and co-added.

We also observed AU Gem and NML Cyg, the only two evolved stars in which excited-state OH emission has previously been reported (Zuckerman et al. 1972; Claussen & Fix 1981). In neither case do we detect any emission. This is consistent with the Expanded Very Large Array observations of Sjouwerman et al. (2007) taken less than 2 months previously, in which no maser emission is definitively detected in either the 6030 or 6035 MHz transitions toward NML Cyg.

4. DISCUSSION

Although our original interest was in the 6.0 GHz OH transitions in SNRs, we start off the discussion with our findings on our reference source, the SFR region W3(OH).

4.1. *Satellite Lines in W3(OH)*

The 6049 MHz ($F = 3 \rightarrow 2$) emission in W3(OH) is stronger than the 6016 MHz ($F = 2 \rightarrow 3$) absorption, as noted in the calculations by Guilloteau et al. (1984), who did not detect the 6016 MHz absorption at all. This effect, in which 6016 MHz absorption is enhanced relative to the expected LTE value (from 6030 and 6035 MHz absorption) and the 6049 MHz line is seen in weak absorption or even emission, was seen in other SFRs by Whiteoak & Gardner (1976) and Gardner & Martín-Pintado (1983). This behavior was predicted by Elitzur (1977), who showed that anti-inversion at 6016 MHz and inversion at 6049 MHz should occur whenever the 120 μm radiation linking the first-excited $J = 5/2$ state with the ground $J = 3/2$ state in the $^2\Pi_{3/2}$ ladder is optically thick, regardless of the details of the pump mechanism.

Interestingly, a similar phenomenon is seen in the next highest state in the $^2\Pi_{3/2}$ ladder. Absorption in the 13442 MHz ($F = 3 \rightarrow 4$) transition is always stronger than at 13433 MHz ($F = 4 \rightarrow 3$) and is always enhanced from LTE values compared to the main lines (Fish et al. 2005). The Elitzur (1977) result is generalizable: whenever intraladder decays dominate and are optically thick, the $\Delta F = +1$ line will be seen in enhanced absorption, and the $\Delta F = -1$ line will be seen in emission or reduced absorption. For the 13.4 GHz transitions, infrared overlaps in the 84 μm transitions linking the $J = 7/2$ and 5/2 states may also be important, as proposed by Matthews et al. (1986).

We find that a Gaussian fit to the 6049 MHz emission in W3(OH) is also *narrower* than the fit to the 6016 MHz absorption, even though the full width at zero power of the two lines is the same. This is consistent with weak inversion and suggests that the 6049 MHz emission should be understood as a low-gain maser, as discussed by Baudry et al. (1997). Further sensitive observations at higher spectral resolution will be required to confirm the maser nature of the 6049 MHz emission. High angular resolution interferometric observations would be particularly useful, to determine the size and brightness temperature of the 6049 MHz emission region as well as to isolate the region of emission and determine whether the inversion exists over the entire source or merely in cluster C (in the nomenclature of Fish & Sjouwerman 2007), which must be a region of very high excitation based on the presence of highly excited OH (Baudry et al. 1993; Baudry & Diamond 1998).

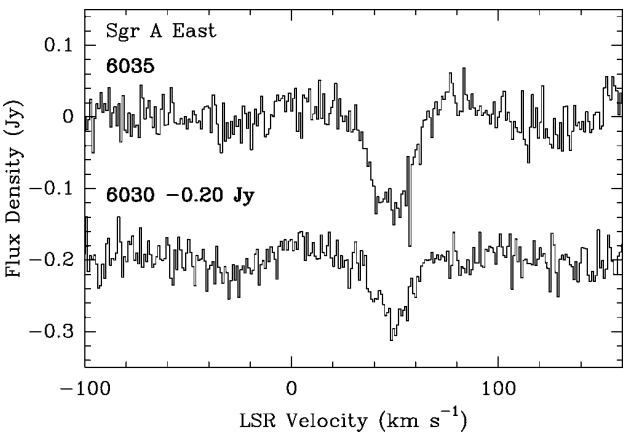

FIG. 2.—Spectra of the 6030 and 6035 MHz transitions in Sgr A East. The sharp spike near $+60$ km s^{-1} is a correlator artifact. Weak baseline ripples are still present after polynomial baseline fitting.

In general, satellite-line masers are seen almost exclusively in the lowest states of the $^2\Pi_{3/2}$ and $^2\Pi_{1/2}$ ladders. In the $^2\Pi_{3/2}$, $J = 3/2$ rotational state, masers are seen in the 1612 MHz transition in evolved stars and some SFRs, and 1720 MHz masers are seen in SNRs and some SFRs. Masers in the $^2\Pi_{1/2}$, $J = 1/2$ state are seen only in SFRs, with 4765 MHz ($F = 1 \rightarrow 0$) masers being much more common than 4660 MHz ($F = 0 \rightarrow 1$) masers (e.g., Gardner & Martín-Pintado 1983; Cohen et al. 1995), in agreement with Elitzur (1977). Even though the brightest main-line 6030 and 6035 MHz masers in SFRs can have flux densities of several hundred janskys (e.g., Fish & Sjouwerman 2007), the only other satellite-line maser found to date is the low-gain 6049 MHz maser in W3(OH). It thus appears to be a general result that it is extremely difficult to invert satellite lines, except in the lowest rotational state in each ladder.

4.2. *Sgr A East*

We see 6030 and 6035 MHz absorption near $+50$ km s^{-1} in pointings on the eastern side of Sgr A East. The absorption at 6035 MHz is deeper than at 6030 MHz, as would be expected for thermal absorption. It is unlikely that this absorption is a part of the interaction of the SNR with the molecular cloud or that it is located at the interaction region (with most 1720 MHz masers in the slightly higher velocity range $V_{\rm LSR} = 53$–68 km s^{-1}; Pihlström & Sjouwerman 2006), although interferometric confirmation, as with the Expanded Very Large Array (EVLA), will be required to establish the location of the absorption. The molecular material is denser to the east and partially obscured by the cir-

cumnuclear disk to the west (McGary et al. 2001; Herrnstein & Ho 2005), consistent with our absorption detections as well as the ground-state absorption detected by Karlsson et al. (2003).

The detection of excited-state absorption toward Sgr A East but not toward any other SNR may be the result of a chance alignment or of the special conditions in the Galactic center region, or a combination thereof. The difference between Sgr A East and the other SNRs may be due to the fact that, in the case of Sgr A East's line of sight, there is the geometry of a dense cloud with a relatively intense radio continuum background, resulting in a larger column density and absorption of OH, or the difference may be due to how the cloud is heated: the $+50$ km s^{-1} cloud toward Sgr A East may be heated not by the impact of the SNR into the cloud (Herrnstein & Ho 2005) but by a strong local radiation field absorbed by high-metallicity material, the dissipation of kinetic energy, or collisions of local clumps in a steep gravitational potential, etc., providing a larger column density of OH in excited states. As this absorption is likely not due to the SNR, further studies are required to investigate its origin.

Interferometric observations would be very helpful to our understanding of the distribution of excited-state OH in the molecular cloud near Sgr A East. Higher angular resolution than that provided by Effelsberg will be required in order to understand the origin of the 6.0 GHz absorption in Sgr A East. This absorption is an obvious target for reobservation with the EVLA, when a sufficient number of antennas are equipped with the new C-band (4–8 GHz) receivers.

4.3. *Other Sources*

No emission was seen in any 6.0 GHz transition toward SNRs. To date, a total of 23 Λ-doublet transitions have been observed toward SNRs: the quadruplets at 1.6, 6.0, 7.7, 8.1, and 23.8 GHz and the triplet at 4.7 GHz. Only the 1720 MHz transition produces a detectable maser. After 1720 MHz, the 6049 MHz transition is the next one that is predicted to go into inversion as densities are increased (Pihlström et al. 2007; Wardle 2007), yet searches for 6049 MHz masers have not uncovered any detections (see also McDonnell et al. 2007). Searches for SNR OH masers at 4765 and 1612 MHz, the next two transitions expected to produce masers via collisional excitation, have also produced only nondetections (Pihlström et al. 2007). It is probable that no OH masers, other than in the 1720 MHz transition, will be detected toward SNRs with current instrumentation.

Absorption at 6016 MHz is not seen toward any SNR, despite predictions that it should be anti-inverted. With the exception of 6030 and 6035 MHz absorption toward Sgr A East, we do not see any absorption toward SNRs. Much more sensitive observations will be required to test whether or not excited-state $\Delta F = +1$ transitions are in enhanced absorption in SNRs.

No emission was seen toward the evolved stars AU Gem and NML Cyg. Excited-state OH maser emission has previously been reported in the 4750 MHz transition toward AU Gem (Claussen & Fix 1981) and in the 6035 (and possibly 6030) MHz transition toward NML Cyg (Zuckerman et al. 1972), although subsequent observations have failed to confirm these detections (e.g., Sjouwerman et al. 2007). It is likely that excited-state OH maser emission from evolved stars is temporary and extremely rare (Sjouwerman et al. 2007). Our continued nondetection of excited-state emission toward these stars supports this hypothesis.

This work was based on observations with the 100 m telescope of Max-Planck-Institut für Radioastronomie at Effelsberg. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Facility: Effelsberg

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