MAGNETIC FIELD CLUMPING IN MASSIVE STAR–FORMING REGIONS AS DETERMINED FROM EXCITED-STATE OH ABSORPTION AND MASER EMISSION

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ABSTRACT

We have observed six high-mass-star–forming regions in the $^2\Pi_{1/2}$, $J = 7/2$ lines of OH using the Green Bank Telescope (GBT) in order to investigate whether the magnetic field, and hence the density, measured in absorption differs from that implied by maser Zeeman splitting. We detect absorption in both the 13,441 and 13,434 MHz main lines in all six sources. Zeeman splitting in the $F = 3^+ \rightarrow 3^-$ absorption line in W3(OH) implies a line-of-sight magnetic field strength of $3.0 \pm 0.3$ mG. This is significantly less than full magnetic field strengths detected from OH maser Zeeman splitting, suggesting that OH maser regions may be denser than the non-masing OH material by a factor of several. Zeeman splitting is not detected in other sources, but we are able to place upper limits on $B_z$ of 1.2 mG in G10.624−0.385 and 2.9 mG in K3-50. These results are consistent with a density enhancement of the masers, but other explanations for the lower magnetic field in absorption compared to maser emission are possible for these two sources. Absorption in one or both of the 13,442 and 13,433 MHz satellite lines is also seen in four sources. This is the very first detection of the $^2\Pi_{3/2}$, $J = 7/2$ satellite lines. Ratios of satellite-line to main-line absorption suggest enhancement of the satellite lines from local thermodynamic equilibrium values. Masers are seen in the $F = 4^+ \rightarrow 4^-$ and $3^+ \rightarrow 3^-$ transitions of W3(OH) and the $4^+ \rightarrow 4^-$ transition of ON 1. A previously undetected $4^+ \rightarrow 4^-$ maser is seen near $-44.85$ km s$^{-1}$ in W3(OH).

Subject headings: H ii regions — ISM: magnetic fields — ISM: molecules — masers — radio lines: ISM — stars: formation

1. INTRODUCTION

Hydroxyl (OH) masers are found in high-mass-star–forming regions. They trace the local velocity and magnetic field and therefore provide clues to understanding the physical conditions of material surrounding newly formed high-mass stars. However, an unanswered question is whether the physical conditions in masing regions are representative of the surrounding material. In order for OH masing to occur, a large column density of OH must have velocity coherence such that the velocity gradient along the amplification path of the masing clump does not exceed the masing line width. In principle, sufficient column density can be achieved in two ways. If a masing clump is much denser than the ambient gas, the total OH column density can be large, even if the physical extent of the clump is not. Alternatively, masing may occur along favored paths of velocity coherence even in a medium of homogeneous density.

While it is uncertain which of these two scenarios is prevalent, two pieces of evidence suggest that density enhancements may not be necessary for OH masing to occur. First, 13,434 MHz OH absorption in W3(OH) shows Zeeman splitting, indicating a line-of-sight magnetic field strength of $3.1$ mG (Güsten et al. 1994). VLBI measurements of 1665 and 1667 MHz OH masers in W3(OH) imply similar magnetic field strengths (e.g., Bloemhof et al. 1992). The magnetic field strength of collapsing (or collapsed) material scales as the density $n^k$, where $k \approx 0.5$, a result supported both by theoretical modeling (Mouschovias 1976; Fiedler & Mouschovias 1993) and observations of molecular clouds in various stages of collapse (e.g., Crutcher 1999). Since the OH absorption and maser magnetic fields are comparable, this suggests that the density at masing sites is similar to that of the ambient cloud of OH. Second, ammonia (NH$_3$) observations of W3(OH) indicate that the density of material in the clumps of maser emission is roughly the same (to within a factor of 2) as the density of the interclump material (Reid et al. 1987). Since the velocity and extent of NH$_3$ absorption is similar to that of the OH emission in W3(OH), it is a reasonable assumption that NH$_3$ and OH exist in the same cloud of material. Finally, Cesaroni & Walmsley (1991), when modeling multi-transition OH observations of W3(OH), find that maser emission in certain lines and absorption in others can be explained for the same range of densities, between $10^6$ and a few times $10^7$ cm$^{-3}$ (for a temperature of 150 K).

Is W3(OH) a special case, or is it representative of all interstellar OH maser sources? In particular, is any density enhancement required for the onset of OH masing? These are questions that motivated us to observe a wider range of sources than Güsten et al. (1994) with the high sensitivity that the Green Bank Telescope (GBT) can afford.

2. OBSERVATIONS

The observations were performed on 2004 April 11 and 12 using the National Radio Astronomy Observatory’s 2 Robert C. Byrd

1 Jansky Fellow.
Green Bank Telescope (GBT) in Green Bank, West Virginia. The GBT has an effective diameter of 100 m. Observations were taken in both circular polarizations with the Gregorian focus Ku-band receiver. The GBT spectrometer was configured in nine level mode to provide 8192 uniform-weighted spectral focus Ku-band receiver. The GBT spectrometer was configured for the 13,441.4173 MHz, Doppler shifted to the local standard time, with a bandwidth of 12.5 MHz each, centered on 13,441.4173 MHz, which allows for the detection of the LCP and RCP masers. The observation time was 2 minutes. The beams were separated by 330 arcminutes, and arcseconds. Double beam switching was employed such that the source appeared in each of the dual beams alternately for a period of 2 minutes. The beams were separated by 330 arcminutes, and arcseconds. Dynamic pointing and focusing were used, and the pointing and focus were checked hourly as well as each time the telescope was pointed at a source.

Variable rain, heavy at times, fell throughout the data collection period. During the brief interludes without precipitation, the (nonzenith) system temperature approached being receiver limited, at about 30 K. At times, the system temperature was over 100 K because of heavy precipitation and low elevation angles.

Our sources were chosen according to two criteria. First, they must contain a strong background H II region, so that absorption might be observed. Second, since it was our intent to compare the magnetic field strength in the OH gas seen in absorption with that seen in maser emission, we sought sources in which the masers indicated a uniform field distribution and eliminated any with a reversal of the line-of-sight direction of the magnetic field as determined from ground-state OH maser Zeeman splitting (Fish 2004). Only about 10 sources observable at the latitude of the GBT meet these criteria. We observed the six sources listed in Table 1.

### 3. RESULTS

The masers we detected are shown in Figures 1–4 and discussed in § 3.1. The absorption features we detected are shown in Figures 5–21 and discussed in § 3.2. The absorption spectra have been Hanning weighted for clarity, although the analyses are based on the uniform-weighted data. The antenna temperatures are related to the flux density by

\[ S = 2kT_A/A, \]

where \( A \) is the effective collecting area of the telescope. We have used the convention that Stokes \( I = 0.5(T_{A,\text{LCP}} + T_{A,\text{RCP}}) \) and Stokes \( V = 0.5(T_{A,\text{LCP}} - T_{A,\text{RCP}}) \) where LCP and RCP indicate left- and right-circular polarization, respectively. Thus, \( T_A = 1 \) K in both RCP and LCP would result in \( S = 0.59 \) Jy in Stokes I. Zeeman measurements in the OH absorption are discussed in § 3.3. Remarks about absorption line ratios are presented in § 3.4.

#### 3.1. Maser Emission

Masers were found in two sources: W3(OH) and ON 1. Parameters of the maser lines are listed in Table 2. Magnetic field estimates assume a Zeeman splitting coefficient of 0.178 km s\(^{-1}\) for the 3\(^+\) \( \rightarrow \) 3\(^-\) transition and 0.230 km s\(^{-1}\) mG\(^{-1}\) for the 3\(^-\) \( \rightarrow \) 3\(^-\) transition (Güsten et al. 1994). Zeeman splitting of OH masers is sensitive to the strength of the full, three-dimensional magnetic field, independent of its inclination to the line of sight, when the Zeeman splitting exceeds the line width.

In W3(OH), we find maser lines in both the 2\(^3\)I\(_{3/2}\), \( J = 7/2 \) transitions, \( F = 4^+ \rightarrow 4^+ \) (Fig. 1) and \( 3^+ \rightarrow 3^- \) (Fig. 2) transitions. We detect seven or eight maser line components in each circular polarization in the \( F = 4^+ \rightarrow 4^- \) transition, compared to the three previously detected with other single-dish antennas (Baudry et al. 1981; Güsten et al. 1994; Baudry & Desmurs 2002). Nearly all of these lines can be grouped into Zeeman pairs with implied full magnetic field strength ranging from 6.9 to 11.3 mG. This range agrees with previous observations by Baudry & Diamond (1998) with the Very Long Baseline Array (VLBA), whose angular resolution is sufficient to unambiguously pair most Zeeman components. The strongest masers we detect have counterparts in Table 1 of Baudry & Diamond. It is not possible to identify unambiguous counterparts to our weaker masers, which may be blends of features resolved at the sub-milliarcsecond resolution of the VLBA. The detection of the LCP and RCP masers centered at \(-44.85 \) km s\(^{-1}\) is new. There is some ambiguity as to whether the LCP maser at \(-43.66 \) km s\(^{-1}\) should be paired with the RCP maser at \(-43.54 \) or \(-43.51 \) km s\(^{-1}\), but the former is more likely because the line width of the latter is much greater than for the LCP maser. In the \( F = 3^+ \rightarrow 3^- \) transition, we find one Zeeman pair implying a line-of-sight magnetic field component of 10.3 mG, consistent with the detection by Güsten et al. (1994). ON 1 is the only other source in which we find 2\(^3\)I\(_{3/2}\), \( J = 7/2 \) masers. The \( F = 4^+ \rightarrow 4^- \) maser at 14 km s\(^{-1}\) (Fig. 3) was also detected by Baudry & Desmurs (2002), although their velocity

### Table 1: Observed Sources

| Source | R.A. (J2000) | Decl. (J2000) | Observation Time (minutes) | \( \sigma^* \) (K) |
|--------|-------------|--------------|----------------------------|-----------------|
| W3(OH) | 02 27 03.70 | +61 52 25.4  | 276                        | 0.006           |
| G10.624–0.385 | 18 10 28.61 | −19 55 49.7  | 270                        | 0.008           |
| G28.199–0.048 | 18 42 58.04 | −04 13 58.0  | 10                         | 0.026           |
| W49 | 19 10 11.04 | +09 05 20.2  | 58                         | 0.028           |
| K3+50 | +00 45.73   | +33 32 45.3  | 178                        | 0.010           |
| ON 1 | +00 09.05   | +31 31 35.2  | 20                         | 0.015           |

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

* Single-channel rms noise in Stokes I and V.
resolution was insufficient to find measurable Zeeman splitting. We do not see the strong (0.5 Jy) maser at $-0.13 \text{ km s}^{-1}$ that they do; however, we find evidence of a weak maser at $0.38 \text{ km s}^{-1}$ (LCP) and $0.24 \text{ km s}^{-1}$ (RCP; Fig. 4). While these lines are weak, we believe they are real. The peaks of the LCP and RCP lines are only 3.8 and 2.8 times the single-channel rms noise of 0.02 K, respectively, but the line widths are 8 times a single channel width. These masers can be interpreted either as $F=4^-\rightarrow 4^-$ lines at $14.9 \text{ km s}^{-1}$ or as $F=3^-\rightarrow 4^-$ lines at $14.9 \text{ km s}^{-1}$. The 1665 MHz ($^2\Pi_{3/2}, J=3/2$) masers in ON 1 are grouped in two velocity ranges: 1–4 and 10–16 km s$^{-1}$ (Argon et al. 2000); likewise, the 6035 MHz ($^2\Pi_{3/2}, J=5/2$) masers are seen from $-1$ to 2 and 13 to 16 km s$^{-1}$ (Baudry et al. 1997). Thus, either the $F=4^-\rightarrow 4^-$ or $3^-\rightarrow 4^-$ interpretation of these maser lines is consistent with the ground-state OH maser velocities.

Nevertheless, two arguments suggest that the weak maser feature in ON 1 is a maser in the $F=4^-\rightarrow 4^-$ transition. First, satellite-line emission in interstellar OH masers is generally weak compared to main-line masers. This is true in the $^2\Pi_{3/2}, J=3/2$ lines, where the 1665 and 1667 MHz masers are typically much stronger than 1612 and 1720 MHz masers. In the $^2\Pi_{3/2}, J=5/2$ lines, strong masers are found in the 6035 and 6030 MHz main lines, but 6049 MHz satellite-line emission is weak and rare (Baudry et al. 1997); while the 6016 MHz satellite line has not been seen in emission (Baudry et al. 1997; Gardner & Martín-Pintado 1983). Indeed, if photon trapping is important, inversion in the 6016 MHz satellite line may be impossible (Elitzur 1977). As for the $^2\Pi_{3/2}, J=7/2$ lines, while about a dozen masers have been found in the 13,441 MHz main-line transition, the 13,434 MHz maser in W3(OH) remains the single known maser in the other main-line transition, despite two searches encompassing 77 distinct interstellar masing sources (Baudry & Desmurs 2002; Caswell 2004). Empirically, this suggests that satellite-line $^2\Pi_{3/2}, J=7/2$ masers should be extremely rare, if they exist at all. Second, because of a smaller Zeeman coefficient, the magnetic field strength implied by a constant-velocity Zeeman splitting is higher for satellite lines

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**TABLE 2**

|TRANSITION| $v_{LSR}$ (km s$^{-1}$)| $T_A$ (K)| $\Delta v$ (km s$^{-1}$)| $v_{LSR}$ (km s$^{-1}$)| $T_A$ (K)| $\Delta v$ (km s$^{-1}$)| $B$ (mG)|
|---|---|---|---|---|---|---|---|
|**W3(OH)**| | | | | | | |
|$3^-\rightarrow 3^-$| $-42.53$| $0.15$| $0.32$| $-42.29$| $0.15$| $0.29$| $10.3$|
|$4^-\rightarrow 4^-$| $-44.94$| $1.93$| $0.18$| $-44.75$| $1.82$| $0.20$| $10.5$|
|$3^-\rightarrow 3^-$| $-43.97$| $4.01$| $0.38$| $-43.84$| $0.56$| $0.22$| $7.0$|
|$3^-\rightarrow 3^-$| $-43.66$| $9.77$| $0.24$| $-43.54$| $7.02$| $0.19$| $6.9$|
|...| ...| ...| ...| ...| ...| ...| ...|
|$3^-\rightarrow 3^-$| $-43.33$| $12.31$| $0.15$| $-43.19$| $12.36$| $0.17$| $8.2$|
|$3^-\rightarrow 3^-$| $-43.08$| $62.65$| $0.30$| $-42.93$| $63.27$| $0.31$| $8.5$|
|$3^-\rightarrow 3^-$| $-42.46$| $64.50$| $0.27$| $-42.26$| $63.35$| $0.28$| $11.3$|
|**ON 1**| | | | | | | |
|$4^-\rightarrow 4^-$| $14.09$| $1.11$| $0.20$| $14.02$| $1.14$| $0.21$| $-3.8$|
|$3^-\rightarrow 3^-$| $0.38$| $0.07$| $0.26$| $0.24$| $0.06$| $0.30$| $-8.3$|

* Magnetic field strength is 8.5 mG if paired with LCP maser at $-43.66 \text{ km s}^{-1}$. See § 3.1 for details.

b Table velocities and magnetic field assume that these are $F=4^-\rightarrow 4^-$ masers. See § 3.1 for details.
than for main lines. If the weak maser in ON 1 is actually in the $F = 3^+ \rightarrow 4^−$ transition, the implied magnetic field is $−14.5$ mG. This field strength would be much larger than that derived from any other Zeeman pair in ON 1 in the $^2\Pi_{3/2}$ ladder (see also Baudry et al. 1997; Fish 2004).

3.2. Absorption

Unlike maser emission, absorption is clearly seen in all sources in our sample in both the $F = 3^+ \rightarrow 3^−$ and $4^+ \rightarrow 4^−$ transitions. In some sources, absorption is seen in the $F = 3^+ \rightarrow 4^-$ and/or $4^+ \rightarrow 3^−$ transitions as well. We believe that this is the first clear detection of absorption in the $^2\Pi_{3/2}$, $J = 7/2$ satellite lines. Parameters of the absorption lines are given in Table 3. We summarize results for individual sources below.

**W3(OH).**—Absorption is seen in all four hyperfine transitions in W3(OH). The presence of multiple strong maser lines (see Figs. 1 and 5) in the $F = 4^+ \rightarrow 4^−$ transition is problematic for fitting Gaussian components to the absorption. The data in the velocity range from $−45.52$ to $−41.00$ km s$^{-1}$ have been excluded from the fitting of the two Gaussian components listed in Table 3 (see also Figs. 6, 7, and 8).

**G10.624−0.385.**—Absorption is seen in the $F = 3^+ \rightarrow 4^−$ transition as well as the main lines (see Figs. 9, 10, and 11).

**G28.199−0.048.**—Absorption is seen in the main lines only. The noise is high because of the short time spent on-source (see Figs. 12 and 13).

**W49.**—Very broad absorption is seen in the main lines. This absorption is broader than the frequency difference between adjacent main- and satellite-line transitions. It is possible that the absorption marked at $5.59$ km s$^{-1}$ in the $F = 3^+ \rightarrow 4^−$ transition is actually at $−9.01$ km s$^{-1}$ in the $F = 4^+ \rightarrow 4^−$ transition. However, the velocity, assuming that this component is due to the $F = 3^+ \rightarrow 4^−$ transition, is more consistent both with the other two transitions and with the H92α/He92α velocity of $6.2 \pm 2.3$ km s$^{-1}$ for the associated Hα region (De Pree et al. 1997; see Figs. 14 and 15).

**K3-50.**—Absorption is seen in all four hyperfine transitions (see Figs. 16, 17, 18, and 19).

**ON 1.**—Absorption is seen in the main lines only. While the observations occurred during a period devoid of precipitation,
the noise is still high because of the short time spent on-source (see Figs. 20 and 21).

### 3.3. Zeeman Measurements in Absorption

The magnetic field can be measured by Zeeman splitting in absorption as well as in maser emission. While the full three-dimensional magnetic field strength is obtained from Zeeman splitting of velocity-separated maser components, absorption lines are much broader than the velocity separation between LCP and RCP components, so only the line-of-sight component of the magnetic field can be measured (e.g., Sault et al. 1990).

The Stokes $V$ curve is related to the derivative of the Stokes $I$ curve by the following equation:

$$T_V(\nu) = -C \frac{dT_I(\nu)}{d\nu} B_1,$$

where $T_V(\nu)$ and $T_I(\nu)$ are the brightness temperatures of the Stokes $V$ and $I$ spectra, respectively, and $C = -1.06 \times 10^6 \text{ Hz G}^{-1}$.

for the $F = 3^+ - 3^-$ transition and $7.95 \times 10^5 \text{ Hz G}^{-1}$ for the $4^+ - 3^-$ transition (Güsten et al. 1994). Hence, if the Stokes $V$ spectrum of an absorption component is nonzero, the line-of-sight magnetic field can be measured.

W3(OH) is the only source in which the Stokes $V$ absorption spectrum shows clear evidence of Zeeman splitting. Figure 22 shows the Stokes $V$ spectrum of the $F = 3^+ - 3^-$ transition of W3(OH). The feature near $-42.4 \text{ km s}^{-1}$ is due to the maser. In the direction of lower velocity from this feature is an “S-curve.” Superposed over the data are two curves corresponding to the derivative of the Gaussian fits to the Stokes $I$ curve. The curve labeled “Main” indicates the scaled derivative of the Gaussian centered at $-45.03 \text{ km s}^{-1}$ (listed in Table 3), while the curve labeled “Both” indicates the scaled derivative of both this Gaussian and the one centered at $-47.22 \text{ km s}^{-1}$. A positive magnetic field shifts RCP to higher velocity than LCP; in absorption, this corresponds to the positive bump of the Stokes $V$ curve being at higher velocity than the negative bump. Note that in emission, a positive magnetic field results in the positive bump of the Stokes $V$ curve being at lower velocity than the negative bump, as is seen for the $42.4 \text{ km s}^{-1}$ maser Zeeman pair in Figure 22. Thus, the absorption and emission magnetic fields in W3(OH) are
consistent in sign, although the S-curves appear inverted with respect to each other. The magnetic field value that provides the best fit to the data is $2.9 \pm 0.3$ mG for the main feature and $3.0 \pm 0.3$ mG for both features combined. This is consistent with the values of $3.1 \pm 0.4$ and $3.2 \pm 0.6$ mG obtained by Güsten et al. 1994.

For the other sources, no S-curve is observed in the Stokes V spectra, but we can place upper limits on the possible magnetic field strength. From equation (1), the measurement error of the line-of-sight magnetic field component in a single channel is

$$\sigma_{B_l} = \frac{-\sigma_{T_r}}{C dT_l/d\nu}.$$  \hfill (2)

In principle, each spectral channel constitutes an independent measurement of $\sigma_{B_l}$. The overall error of the parallel magnetic field strength can be estimated as

$$\sigma_{B_{l\text{,overall}}} = \left( \sum \sigma_{B_l}^2 \right)^{-1/2},$$  \hfill (3)

where the summation is taken over all spectral channels.

Table 4 gives the 3 $\sigma$ upper limits on magnetic field strengths from absorption measurements. For comparison, the average three-dimensional magnetic field strengths obtained from OH maser Zeeman splitting are also provided. Masers from each of the $J = 3/2, 5/2,$ and $7/2$ sets of transitions are considered separately. When Zeeman splitting is detected in more than one set of transitions, the minimum and maximum average magnetic strengths obtained from OH maser Zeeman splitting in sets of transitions corresponding to different values of $J$ are quoted. The actual range of magnetic field strengths seen in maser Zeeman splitting may be greater than that listed in Table 4, but averages seem appropriate for comparison with our absorption data, since the GBT beamwidth is much greater than the angular extent of any of our sources. With the exception of the Zeeman pair centered at $-44.85$ km s$^{-1}$, Zeeman pairs in the $F = 4^+ \rightarrow 4^-$ transition detected in this work are excluded from the calculation of the average magnetic field strength in W3(OH) obtained from $J = 7/2$ masers, in deference to the much higher angular resolution obtained by Baudry & Diamond (1998). Note that the magnetic fields derived from the Zeeman pairs that we detect agree with those obtained by Baudry & Diamond in sign and magnitude to better than 1 mG.
In addition to obtaining a positive field measurement for W3(OH), we are able to place upper limits of several milligauss on $B_k$ for two other sources: K3-50 and G10.624/0.385. In K3-50 the magnitude of the line-of-sight component deduced from the Zeeman splitting of the main absorption feature is less than 2.9 mG. Measurements of OH masers give three-dimensional magnetic field strengths of $\approx 2.6$ to $\approx 7.5$ mG in the $2^3P_{3/2}, J = 3/2$ lines (Fish 2004) and $\approx 5.3$ to $\approx 9.1$ mG in the 6035 MHz $J = 5/2$ line (Baudry et al. 1997).

Our 3 $\sigma$ limit of 1.2 mG for G10.624−0.385 improves by a factor of 2 on previous observations in the OH $2^3P_{3/2}, J = 7/2$, $F = 3^+ \rightarrow 3^−$ line and is comparable to results obtained from observations in SO absorption (Uchida et al. 2001). In G10.624−0.385, VLBA observations of the 1667 MHz $J = 3/2$ line show one Zeeman pair with a magnetic field of $\approx 6.0$ mG (Fish 2004).

Four possibilities, alone or in combination, can explain the nondetection of a Zeeman pattern in the absorption in K3-50 and G10.624−0.385: (1) A reversal of the line-of-sight direction of the magnetic field exists across each source. (2) The magnetic field in K3-50 and G10.624−0.385 is inclined at a large angle relative to the line of sight. (3) The average magnetic field strength of the material sampled by $2^3P_{3/2}, J = 7/2$ OH is smaller than that sampled by $J = 5/2$ or $3/2$ OH. (4) Masers are on average denser than the surrounding OH material, and thus the magnetic field strength is greater at masing sites than for the OH as a whole.

The first explanation is possible for both these sources. While five $2^3P_{3/2}, J = 3/2$ maser Zeeman pairs were found in VLBA imaging of K3-50, they are all located on the periphery of the H II region to the north and east. It is possible that the line-of-sight direction of the magnetic field reverses on the south or west side of the source. Even if there is no reversal in K3-50, four of the five Zeeman pairs found in the VLBA images of the 1665 and 1667 MHz maser emission imply full (unprojected) magnetic field strengths less than the detectability limits in Table 4 (Fish 2004).

Only one ground-state OH maser has been found in VLBA imaging of G10.624−0.385. It would be a 12 and 15 $\sigma$ detection for the $F = 3^+ \rightarrow 3^−$ and $4^+ \rightarrow 4^−$ transitions, respectively, if the average line-of-sight magnetic field component in the region of the $J = 7/2$ absorption were the same as the full three-dimensional magnetic field strength implied by Zeeman splitting of the 1667 MHz maser. However, with only one Zeeman pair detected through synthesis imaging, it is impossible

Fig. 13.—Stokes I spectrum for the $F = 4^+ \rightarrow 3^−$ transition of G28.199−0.048. See Fig. 5 caption for more details.

Fig. 14.—Stokes I spectrum for the $F = 3^+ \rightarrow 3^−$ transition of G28.199−0.048. See Fig. 5 caption for more details.

Fig. 15.—Stokes I spectrum for the $F = 3^+ \rightarrow 3^−$ transition of W49. See Fig. 5 caption for more details. The arrow indicates where $F = 4^+ \rightarrow 3^−$ absorption would appear if at the velocity of the main absorption component.

Fig. 16.—Stokes I spectrum for the $F = 4^+ \rightarrow 4^−$ and $3^+ \rightarrow 4^−$ transitions of K3-50. See Fig. 5 caption for more details. The $F = 3^+ \rightarrow 4^−$ line is shown in greater detail in Fig. 17.
to conclude whether or not there exists a line-of-sight field reversal across the source.

The second explanation simply states that if the magnetic field is inclined at a large angle to the line of sight, its projection along the line of sight may be insufficient to produce a detectable Zeeman splitting in Stokes $V$ for the case in which the splitting is less than the line width. Assuming that the magnetic field strength of 6.0 mG for the single Zeeman pair detected with VLBI resolution in G10.624–0.385 is a typical value for the source as a whole, the required inclination angle of the magnetic field to produce a line-of-sight component less than 1.2 mG is $>78^\circ$. If the magnetic field actually is inclined $78^\circ$ to the line of sight, the expected linear polarization fraction of the two $\sigma$-components of the Zeeman pair is $\sin(78^\circ)/[1 + \cos^2(78^\circ)]=0.92$ (Goldreich et al. 1973). However, no linear polarization is detected in the maser (Fish 2004), ruling out a high inclination at the maser site, on the east side of the H$\alpha$ region. Linear polarization fractions consistent with inclination angles as large as $78^\circ$ are seen on the west side of the H$\alpha$ region, although most masers imply inclination angles much smaller than this value. Incomplete spatial coverage of OH masers across the source renders it difficult to estimate with certainty the inclination angle averaged across the source, but it is almost certainly less than $78^\circ$. Thus, while $B_l < B = 6.0$ mG in G10.624–0.385, the inclination angle is likely not large enough such that $B_l < 3 \sigma = 1.2$ mG. Still, an inclination angle smaller than $78^\circ$ in combination with another factor (such as a field reversal across the source) may suffice to reduce the average line-of-sight magnetic field strength below our detection threshold.

The third explanation is unlikely because a higher temperature is required to populate the $^2\Pi_{3/2}, J = 7/2$ states than for either the $J = 3/2$ or the 5/2 states. These higher temperatures likely require that the distribution of OH in the $J = 7/2$ states be peaked closer to the central heat source than for the $J = 3/2$ and 5/2 states, as is noted for masers in W3(OH) (Baudry & Diamond 1998). Since the density probably increases with decreasing radius, the density (and therefore average field strength) of the material sampled by OH in the $J = 7/2$ states should be higher than that of the lower states. There is no evidence that the magnetic field strengths derived from Zeeman splitting in $J = 7/2$ masers (Caswell 2004) are weaker than those derived from masers in the $J = 5/2$ (Baudry et al. 1997; Caswell & Vaile 1995) or $J = 3/2$ transitions (e.g., Fish et al. 2003). Indeed, if W3(OH) is not atypical, there is reason to believe that field
strengths deduced from OH Zeeman splitting actually increase, as measured by higher excitation states in the $^2\Pi_{3/2}$ ladder (Güsten et al. 1994; Baudry & Diamond 1998).

The fourth explanation differs from the third in that it suggests that masers may inherently occur at density enhancements in the surrounding medium. This is plausible, given the conditions of formation of interstellar OH masers. Observed maser strengths require some combination of OH enrichment and density enhancement (Elitzur 1992). OH masers are believed to form in the zone between the ionization and shock fronts (Elitzur & de Jong 1978), where instabilities lead to inhomogeneous density enhancement (e.g., simulations of García-Segura & Franco 1996). The density conditions under which OH masers form have implications that affect the physical interpretation of their phenomenology. If masers are formed preferentially at density enhancements, magnetic field measurements obtained at OH maser sites should be higher than the average magnetic field strength in the surrounding region. It would also be strong evidence that observed proper motions of OH masers (as in Bloemhof et al. 1992) are due to discrete material motions, not shifting coherence paths that could be unrepresentative of the motion of the material.

It is difficult to tell conclusively whether or not the material sampled by $J = 7/2$ absorption is at a lower density than the $^2\Pi_{3/2}$ masers in most of our sources. In K3-50, the upper limit on the magnetic field strength in the absorption falls within the range obtained from masers. In G10.624–0.385, the inclination of the magnetic field to the line of sight alone is unlikely to explain the discrepancy between our upper limit and maser field strength values. However, it is quite possible that a field direction reversal occurs across the source, which would reduce the effective average line-of-sight strength detectable through absorption. It is also not possible to rule out that there exists a field direction reversal along the line of sight. However, magnetic field directions deduced from OH maser Zeeman splitting in massive star–forming regions show an overwhelming tendency to fall into one of two categories: (1) a constant line-of-sight direction throughout the source and (2) a single reversal across the source with the property that a line can be drawn dividing the source into a region of positive magnetic field and a region of negative magnetic field (Fish 2004). A reversal of the field direction along the line of sight would produce projected regions of mixed magnetic field direction, suggesting that they are not common in massive star–forming regions.

As for W3(OH), the magnetic field measurement obtained from absorption $B_{\|} = 3.0 \pm 0.3$ mG is less than those obtained from masers projected atop the H ii region in the $^2\Pi_{3/2}, J = 3/2$ transitions (average ± standard error of the mean: $B = 5.6 \pm 0.7$ mG, from Bloemhof et al. 1992), $J = 5/2$ transitions (6.6 ± 0.5 mG, from Desmurs et al. 1998), as well as the $J = 7/2$ transitions (9.7 ± 0.4 mG, from this work and Baudry & Diamond 1998). The average magnetic field measurements from the masers projected atop the H ii region exceed the absorption magnetic field measurement by 3.3, 5.8, and 13.0 σ for the $J = 3/2$, 5/2, and 7/2 transitions, respectively. Most masers in W3(OH) have no detectable linear polarization (García-Barreto et al. 1998).
suggested that the magnetic field in W3(OH) is oriented close to the line of sight (i.e., $B_\parallel \approx B$) and therefore that the average magnetic field sampled by $J = 7/2$ absorption is less than that sampled by maser emission. The average magnetic field strength obtained from the $J = 7/2$ masers is greater than those obtained from $J = 3/2$ and 5/2 masers. As previously noted, the $J = 7/2$ masers in W3(OH) are much more tightly distributed near the center of the source than in either of the other masing $^2\Pi_{3/2}$ transitions. Yet the magnetic field strength measured from $J = 7/2$ absorption is significantly less than the value obtained from $J = 7/2$ masers. Taken together, these results suggest that $J = 7/2$ masers occur only in the highest density portions of the OH cloud, although OH likely exists in the $J = 7/2$ excited state throughout the source.

Two possible scenarios could explain the prevalence of high-density material necessary for excited-state OH maser activity. There may be a large region of higher density coincident with the distribution of $J = 7/2$ and methanol masers (Moscadelli et al. 1999) but with little small-scale clumping. Alternatively, small-scale ($\approx 10^{15}\text{ cm}$) clumping may occur throughout W3(OH) but with increased prevalence in the region where $J = 7/2$ OH masers are observed. Our data do not directly distinguish between these two scenarios. Our observations of Zeeman splitting in excited-state OH absorption allow us to measure the magnetic field (and therefore density) averaged over the entire source but not the length scale on which density fluctuations occur. Nevertheless, other evidence suggests that small-scale density variations are responsible for excited-state OH maser activity. The distribution of ground-state OH masers in W3(OH) (Reid et al. 1980) and other massive star–forming regions (Fish 2004) show clustering on a scale of $10^{15}\text{ cm}$. This is unlikely to be caused by Kolmogorov turbulence, which is a scale-free process. In addition, ammonia observations by Reid et al. (1987) show that while the optical depth of NH$_3$ is fairly constant across W3(OH), the beam-filling factor decreases from west to east. This suggests that the number of clumps is decreasing, not the density of any one clump.

### 3.4. Line Ratios

In local thermodynamic equilibrium, the relative strengths of the $F = 4^+ \rightarrow 3^-$, $3^+ \rightarrow 3^-$, $4^+ \rightarrow 4^-$, and $3^+ \rightarrow 4^-$ absorption lines are $1:27:35:1$. The ratio of the $F = 4^+ \rightarrow 4^-$ to $3^+ \rightarrow 3^-$ main lines ranges from 0.41 ($G10.624-0.385, 1\text{ km s}^{-1}$) or 0.97 to 1.62 in our sources, with 1.30 being the LTE value for optically thin lines. The satellite lines, when detected in absorption, are always enhanced relative to the expected LTE value for the $F = 4^+ \rightarrow 4^-$ line and almost always enhanced relative to the $F = 3^+ \rightarrow 3^-$ transition, the single exception being the $F = 4^+ \rightarrow 3^-$ line in W3(OH).

Matthews et al. (1986) surmise that the excitation temperatures in the hyperfine lines are not equal because of line overlaps in the $84\text{ \mu m}$ lines connecting the $^2\Pi_{3/2}, J = 5/2$ and $^2\Pi_{3/2}, J = 7/2$ states of OH. Viscuso et al. (1985) note that collisions will preferentially excite the $^2\Pi_{3/2}, J = 7/2$ negative-parity state, but that the $84.42\text{ \mu m}$ line that excites the positive-parity state may be in resonance with CO emission at 84.41 mm. Matthews et al. point out that far infrared line overlaps will equalize populations between the $F = 4^+$ and $3^+$ states, but the $F = 3^-$ state will depopulate relative to the $F = 4^-$ state. Hence, the $F = 4^+ \rightarrow 4^-$ and $3^+ \rightarrow 4^-$ absorption lines will have a lower excitation temperature than the $F = 3^+ \rightarrow 3^-$ and $4^+ \rightarrow 3^-$ lines.

For the two cases in which both satellite lines are detected, the $F = 3^+ \rightarrow 4^-$ line is stronger than the $F = 4^+ \rightarrow 3^-$ line. In addition, the $3^+ \rightarrow 4^-$ line is detected in two sources in which the $4^+ \rightarrow 3^-$ line is not detected. This is consistent with a lower excitation temperature for the $3^+ \rightarrow 4^-$ state than for the $4^+ \rightarrow 3^-$ state. However, we do not find evidence that the $F = 4^+ \rightarrow 4^-$ lines are enhanced relative to the $3^+ \rightarrow 3^-$ lines, as predicted by the Matthews et al. model.

### 4. CONCLUSIONS

We have detected $^2\Pi_{3/2}, J = 7/2$ OH absorption toward six massive star–forming regions. Main-line absorption was detected in both the $F = 3^+ \rightarrow 3^-$ and $4^+ \rightarrow 4^-$ lines toward all sources. In addition, we detected at least one satellite line in absorption toward four of the six sources. We believe that this is the first detection of the $^2\Pi_{3/2}, J = 7/2$ satellite lines in interstellar sources.

Stokes V spectra of the main lines were produced for these six sources. In the case of W3(OH), Zeeman splitting of the $F = 3^+ \rightarrow 3^-$ absorption results in a magnetic field measurement of $B_\parallel = 3.0 \pm 0.3\text{ mG}$, consistent in magnitude and sign with the $3.1 \pm 0.4\text{ mG}$ obtained by Güsten et al. (1994). W3(OH) is the only source in which a positive detection of Zeeman splitting in the $J = 7/2$ absorption has been obtained. The component of the magnetic field along the line of sight is comparable to the full magnetic field strength measured in $J = 3/2$ and 5/2 masers, suggesting that these masers do not preferentially form in high-density, low filling factor regions where the density significantly exceeds that of the surrounding, nonmasing OH. However, the line-of-sight component of the magnetic field determined from $J = 7/2$ absorption is much smaller than that determined from $J = 7/2$ masers.

The grand question is whether the small line-of-sight magnetic field strength measured in $^2\Pi_{3/2}, J = 7/2$ absorption necessarily implies density enhancement at maser sites. If $J = 7/2$ absorption occurs only where the $J = 7/2$ masers occur, then the full magnetic field strength (as deduced from the $J = 7/2$ masers) in this region ranges from 5.6 to 11.3 mG (Baudry & Diamond 1998), consistent with the range of field strengths determined from $J = 3/2$ masers at this site at the northern limb of the H II region (Bloemhof et al. 1992). Restricting consideration to the $F = 3^+ \rightarrow 3^-$ transition, the transition in which a positive result for Zeeman splitting is obtained in absorption, favors the upper end of this range of field strengths, since the only detected maser Zeeman pair implies a full magnetic field strength of 10.3 mG (Table 2). The magnetic field in this region does not appear to be significantly inclined to the line of sight (Garcia-Barreto et al. 1988), suggesting that the line-of-sight magnetic field strength is comparable to the full magnetic field strength. Since the average magnetic field strength derived from masers in this region is 9.1 mG, 3 times the field strength measured in absorption, it might be concluded that masers are denser than the surrounding, nonmasing region by a factor of 9, under the reasonable assumption that $B \propto n^{1/2}$.

However, it is likely that $J = 7/2$ absorption comes from other areas in front of the H II region as well. Bloemhof et al. (1992) identify three other regions of $^2\Pi_{3/2}, J = 3/2$ masers projected atop the H II region in W3(OH): a central clump with magnetic fields of 6.2 and 7.1 mG, a southern clump with fields of 2.3–6.0 mG, and a western clump with a magnetic field of 1.8 mG. Observations of the $^2\Pi_{3/2}, J = 9/2$ transitions, with an excitation temperature of 511 K above ground, show strong absorption at the northern clump as well as weaker absorption at the central and southern clumps (Baudry & Menten 1995).
the $^{2}\Pi_{1/2}$, $J = 3/2$ (270 K above ground) transitions, significant absorption is seen at and between all four $^{2}\Pi_{1/2}$, $J = 3/2$ maser clumps, while in the $^{2}\Pi_{1/2}$, $J = 5/2$ (415 K above ground) transitions, absorption is seen mainly along a line running through the northern, central, and southern clumps, with weaker absorption from the western clump (Baudry et al. 1993). There is no published map of $^{2}\Pi_{1/2}$, $J = 7/2$ (290 K above ground) absorption in W3(OH), but the distribution of OH in other comparable excited states suggests that strong $^{2}\Pi_{1/2}$, $J = 7/2$ absorption would be seen over the western half of the H ii region, including the sites of all four $^{2}\Pi_{1/2}$, $J = 3/2$ maser clumps. This would imply that the density at $^{2}\Pi_{1/2}$, $J = 3/2$ maser sites is about 2–4 times that of the nonmasing OH. On the other hand, 7820 MHz ($^{2}\Pi_{1/2}$, $J = 3/2$, and $F = 2^{-} \rightarrow 2^{-}$) and 8190 MHz ($^{2}\Pi_{1/2}$, $J = 5/2$, and $F = 3^{-} \rightarrow 3^{+}$) emission is seen exclusively near the northern maser clump (Baudry et al. 1993), and 6031 MHz ($^{2}\Pi_{1/2}$, $J = 5/2$, and $F = 2^{-} \rightarrow 2^{+}$) and 6035 MHz ($F = 3^{-} \rightarrow 3^{+}$) maser emission is strongest near the northern maser clump (Moran et al. 1978; Desmurs et al. 1998). In total, this suggests that while $^{2}\Pi_{1/2}$, $J = 7/2$ absorption occurs over most of the western half of W3(OH), the strongest contribution to the absorption most likely comes from the northern clump, which has the highest average magnetic field strength. The unweighted average magnetic field determined from OH masers in all transitions atop the H ii region is 6.9 mG. Because of the distribution of maser spots, this effectively gives highest weight to the northern clump and lowest weight to the eastern clump, consistent with our arguments based on the distribution of excited-state $^{2}\Pi_{1/2}$ and $^{2}\Pi_{3/2}$ OH absorption and emission. Thus, the density at maser sites is likely several ($\approx$5) times that of the nonmasing regions in W3(OH).

More precise quantitative results would require an interferometric map of $^{2}\Pi_{1/2}$, $J = 7/2$ absorption.

We are able to place upper limits of several milligauss on the line-of-sight component of the magnetic field in two other sources. The 2.9 mG limit on K3-50 is about 50% of the full three-dimensional magnetic field strengths obtained from Zeeman splitting of the $J = 3/2$ (Fish 2004) and $J = 5/2$ masers (Baudry et al. 1997). The 1.2 mG limit on G10.624–0.385 is a factor of 5 smaller than the 6.0 mG obtained from a $J = 3/2$ maser Zeeman pair (Fish 2004). It is not clear if this occurs because the masers are in higher density (and hence higher magnetic field) clumps or if other effects, such as field reversals or large angles of the magnetic field to the line of sight, are present in portions of the source.

We have detected $F = 3^{-} \rightarrow 4^{-}$ and/or $4^{+} \rightarrow 3^{-}$ satellite-line absorption in four sources. Of these two, absorption in the $3^{-} \rightarrow 4^{-}$ line is always stronger, as predicted by Matthews et al. (1986). Satellite-line absorption appears enhanced relative to the main lines, from that which would be expected in local thermodynamic equilibrium.

Maser emission was also observed toward two sources. In W3(OH) we find seven pairs of LCP and RCP masers implying magnetic field strengths from 6.9 to 11.3 mG. We detect lines components at all velocities at which strong maser features were previously observed, although we do not have the spatial resolution to separate the multiple lines detected by Baudry & Diamond (1998) using the VLBA. In addition, we find a pair of previously undetected masers centered at $-44.85$ km s$^{-1}$. In ON 1, we find the maser at 14 km s$^{-1}$ previously detected by Baudry & Desmurs (2002). We do not see the strong maser at $-0.13$ km s$^{-1}$ that they did, but we find a new weak maser centered at 0.31 km s$^{-1}$. Maser strength variability, previously noted in the $^{2}\Pi_{1/2}$, $J = 7/2$ masers of W3(OH) (e.g., Baudry & Diamond 1998), appears to be operating in ON 1 as well.

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