DISCOVERY OF THE ZEEMAN EFFECT IN THE 44 GHz CLASS I METHANOL (CH$_3$OH) MASER LINE

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ABSTRACT

We report the discovery of the Zeeman effect in the 44 GHz Class I methanol (CH$_3$OH) maser line. The observations were carried out with 22 antennas of the Expanded Very Large Array toward a star-forming region in OMC-2. Based on our adopted Zeeman splitting factor of $\zeta = 1.0$ Hz mG$^{-1}$, we detect a line-of-sight magnetic field of $18.4 \pm 1.1$ mG toward this source. Since such 44 GHz CH$_3$OH masers arise from shocks in the outflows of star-forming regions, we can relate our measurement of the post-shock magnetic field to field strengths indicated by species tracing pre-shock regions, and thus characterize the large-scale magnetic field. Moreover, since Class I masers trace regions more remote from the star-forming core than Class II masers, and possibly earlier phases, magnetic fields detected in 6.7 GHz Class II and 36 and 44 GHz Class I methanol maser lines together offer the potential of providing a more complete picture of the magnetic field. This motivates further observations at high angular resolution to find the positional relationships between Class I and Class II masers, and masers at various frequencies within each category. In particular, CH$_3$OH masers are widespread in high- as well as intermediate-mass star-forming regions, and our discovery provides a new method of studying the magnetic field in such regions, by observing small physical scales that are not accessible by any other lines.

Key words: ISM: clouds – ISM: magnetic fields – masers – polarization – radio lines: ISM – stars: formation

1. INTRODUCTION

The presence of magnetic fields in star-forming regions presents theoretical and observational challenges because of the computational complexity involved in incorporating magnetic fields in simulations, and the difficult observations that are required to measure their strengths and directions (Troland et al. 2008). While the role of magnetic fields in regulating the onset of star formation is still a matter of debate (e.g., Crutcher et al. 2009), it has become increasingly clear that magnetic fields play a critical role in carrying angular momentum away from the protostar during collapse (McKee & Ostriker 2007, and references therein). Moreover, the outflows along which this takes place may be driven by dynamically enhanced magnetic fields in the protostellar disk (Banerjee & Pudritz 2006). In particular, the driving of outflows along magnetic field lines may be critical in allowing accretion to continue onto high-mass protostars (Banerjee & Pudritz 2007). Observational studies of such protostellar disks and outflows are difficult, due to the need for high angular resolution. Interstellar masers, being compact and intense, offer a means of probing regions at high angular resolution. For years, their effectiveness as probes of star-forming regions was overshadowed by a perception that the specialized conditions in which such masers form necessarily prevented them from being linked to conditions on larger scales. However, recent discoveries indicate that rather than being a measure in isolated atypical fragments, the magnetic fields measured in masers are indeed linked to the larger scale magnetic field. Fish & Reid (2006) found a relative consistency in the magnetic fields measured in clusters of mainline (1665 and 1667 MHz) OH masers across a massive star-forming region and concluded that magnetic fields are ordered in massive star-forming regions. More recently, Vlemmings et al. (2010) have determined from polarization observations of 6.7 GHz CH$_3$OH masers toward Cepheus HW2 that the masers probe the large-scale magnetic field.

The 6.7 GHz CH$_3$OH masers mentioned above are examples of Class II methanol masers, which are known to be probes of the early phases of high-mass star-forming regions (Vlemmings 2008, and references therein). Yet another class of masers, namely Class I methanol masers, may probe even earlier phases of star-forming regions (Pratap et al. 2008). Such Class I CH$_3$OH masers are believed to be formed in collisional shocked regions in protostellar outflows (Cragg et al. 1992; Sandell et al. 2005). Together, Class I and Class II CH$_3$OH masers offer a unique window into star-forming regions by allowing us to observe the smallest physical scales that are not accessible via any other lines. Given the value of measuring the magnetic field in disks and outflows, we have embarked on a long-term plan to measure magnetic fields in CH$_3$OH masers. In 2009, we discovered the Zeeman effect in the 36 GHz Class I CH$_3$OH maser line toward the high-mass star-forming region M8E (Sarma & Momjian 2009). The Zeeman effect remains the most direct method for measuring magnetic field strengths (e.g., Crutcher 1999).

In this Letter, we report the discovery of the Zeeman effect in the 44 GHz Class I CH$_3$OH maser line. The observations were carried out with 22 antennas of the Expanded Very Large Array (EVLA) toward OMC-2. OMC-2 is a filamentary structure containing several sites of active star formation (e.g., Takahashi et al. 2008), and located about 12° northeast of the Trapezium OB cluster in Orion (Castets & Langer 1995), at a distance of 450 pc (Genzel & Stutzki 1989). In Section 2, we present details of the observations and reduction of the data. The analysis involved in extracting magnetic field information from the Zeeman effect is given in Section 3. The results are presented and discussed in Section 4.

2. OBSERVATIONS AND DATA REDUCTION

Observations of the $7_0 - 6_1$ A$^+$ methanol maser emission line at 44 GHz were carried out using 22 antennas in the D-configuration of the EVLA of the NRAO$^3$ in two 2 hr sessions on 2009 October 25 and November 25. Table 1 lists

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$^3$ The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
Table 1
Parameters for EVLA Observations

| Parameter                      | Value                  |
|-------------------------------|------------------------|
| Observation dates             | 2009 Oct 25 and Nov 25 |
| Configuration                 | D                      |
| R.A. of field center (J2000)  | 05°35′30″−27′66″       |
| Decl. of field center (J2000) | −05°09′39″.6          |
| Total bandwidth               | 1.56 MHz               |
| No. of channels               | 256                    |
| Channel spacing               | 0.04 km s\(^{-1}\)     |
| Total observing time          | 4 hr                   |
| Rest frequency                | 44.069488 GHz          |
| Velocity at band center\(^a\) | 13.2 km s\(^{-1}\)     |
| Target source velocity        | 11.6 km s\(^{-1}\)     |
| FWHM of synthesized beam      | 1′.93 × 1′.58          |
| P.A.                          | −10°.40                |
| Line rms noise\(^b\)          | 8 mJy beam\(^{-1}\)    |

Notes.
\(^a\) The line was centered in the second half of the 1.56 MHz band in order to avoid aliasing (see Section 2).
\(^b\) The line rms noise was measured from the Stokes \(I\) image cube using maser line free channels.

the observing parameters and other relevant data for these observations. The data were correlated using the old VLA correlator, and in order to avoid the aliasing known to affect the lower 0.5 MHz of the bandwidth for EVLA data correlated with the old VLA correlator, the spectral line was centered in the second half of the 1.56 MHz wide band. The source 3C147 (J0542+4951) was used to set the absolute flux density scale, while the compact source J0607−0834 was used as an amplitude calibration.

The editing, calibration, Fourier transformation, deconvolution, and processing of the data were carried out using the Astronomical Image Processing System (AIPS) of the NRAO. After applying the amplitude gain corrections of J0607−0834 on the target source OMC-2, the spectral channel with the strongest maser emission signal was split, then self-calibrated in both phase and amplitude in a succession of iterative cycles (e.g., Sarma et al. 2002). The final phase and amplitude solutions were then applied to the full spectral-line \(uv\) data set, and Stokes \(I\) and \(V\) image cubes were made with a synthesized beamwidth of 1′.93 × 1′.58; the maser emission was unresolved in these observations. Further processing of the data, including magnetic field estimates, was done using the MIRIAD software package.

3. ANALYSIS

For cases in which the Zeeman splitting \(\Delta v_z\) is much less than the line width \(\Delta v\), the magnetic field can be obtained from the Stokes \(V\) spectrum, which exhibits a scaled derivative of the Stokes \(I\) spectrum (Heiles et al. 1993). Here, consistent with AIPS conventions, \(I = (RCP+LCP)/2\) and \(V = (RCP−LCP)/2\); RCP is the right-circular polarization and LCP is the left-circular polarization incident on the antennas, where RCP has the standard radio definition of clockwise rotation of the electric vector when viewed along the direction of wave propagation. Since the observed \(V\) spectrum may also contain a scaled replica of the \(I\) spectrum itself, the Zeeman effect can be measured by fitting the Stokes \(V\) spectra in the least-squares sense to the equation

\[
V = aI + b \frac{dl}{d\nu}
\]

(Troland & Heiles 1982; Sault et al. 1990). The fit parameter \(a\) is usually the result of small calibration errors in RCP versus LCP and is expected to be small. In these observations, \(a\) was of the order of \(10^{-4}\) or less. While Equation (1) is strictly true only for thermal lines, numerical solutions of the equations of radiative transfer (e.g., Nedoluha & Watson 1992) have shown that it gives reasonable values for the magnetic fields in masers also. In Equation (1), the fit parameter \(b = zB \cos \theta\), where \(z\) is the Zeeman splitting factor (Hz mG\(^{-1}\)), \(B\) is the magnetic field, and \(\theta\) is the angle of the magnetic field to the line of sight (Crutcher et al. 1993). The value of the Zeeman splitting factor \(z\) for CH\(_3\)OH masers is very small, because CH\(_3\)OH is a non-paramagnetic molecule. Following the treatment of Vlemmings (2008) for the Zeeman splitting of 6.7 GHz methanol masers, we derive the Zeeman splitting factor using the Landé \(g\)-factor based on laboratory measurements of 25 GHz methanol masers (Jen 1951) and find \(z = 1.0\) Hz mG\(^{-1}\). Since the actual Landé \(g\)-factor for the 44 GHz line is not known, it is not possible to estimate the uncertainty in \(z\). It is unlikely, however, that the measured Landé \(g\)-factor will be vastly different from the value used here, since the \(B_\text{los}\) values derived below seem to agree well with projections about the field and densities (see Section 4). In fact, if the measured value of the Landé \(g\)-factor turns out to be vastly different, the Zeeman interpretation of these observations may have to be revised. Needless to say, these observations and the above considerations motivate immediate measurement of the Landé \(g\)-factor in the 44 GHz CH\(_3\)OH maser line.

4. RESULTS AND DISCUSSION

Figure 1 shows our Zeeman effect detection in the 44 GHz CH\(_3\)OH maser toward OMC-2. As described in Section 3, we determined magnetic fields by fitting the Stokes \(V\) spectra in the least-squares sense using Equation (1). The fit parameter \(b\) (see Equation (1)) obtained by this procedure, together with the Zeeman splitting factor \(\Delta v = 1.0\) Hz mG\(^{-1}\) discussed in Section 3, then gives \(B_\text{los} = 18.4 ± 1.1\) mG for the 44 GHz Class I CH\(_3\)OH maser toward OMC-2. By convention, a positive value for \(B_\text{los}\) indicates a field pointing away from the observer.

In order to investigate the connection of our detected field to quantities in the larger region, we looked at the 850 \(\mu\)m polarization map of Poidevin et al. (2010) observed with the James Clerk Maxwell Telescope. Their map is reproduced in Figure 2. For reference, the position of our CH\(_3\)OH maser is marked in this figure. We have used the position of the strongest 44 GHz CH\(_3\)OH maser from the high angular resolution phase referenced VLA A-configuration observations (HPBW = (0′.15)\(^4\)) of Slysh & Kalenskii (2009). Associated with this position is a CO outflow (Takahashi et al. 2008; Williams et al. 2003) marked in red in Figure 2; the position angle of this CO outflow is 30°. Also shown in green in Figure 2 is the outflow detected in the 2.12 \(\mu\)m shocked H\(_2\) emission line from Stanke et al. (2002); the position angle of this outflow is ~31°, identical to that of the CO outflow. In their high angular resolution VLA observations referred to above, Slysh & Kalenskii (2009) observed six 44 GHz methanol masers spread out along a line aligned at an angle approximately 30° east of north. Upon comparing all of the above information to the 850 \(\mu\)m polarization map of Poidevin et al. (2010), it appears likely that the outflow is aligned along the local magnetic field, and the methanol masers are excited in collisional shocks along the outflow. Maser amplification is particularly efficient in directions approximately perpendicular.

\(^4\) HPBW = half-power beamwidth
toward the 44 GHz Class I CH$_3$OH maser in OMC-2. The curve superposed on Figure 1. Stokes $I$ (top histogram) and $V$ (bottom histogram) profiles of the maser toward the 44 GHz Class I CH$_3$OH maser in OMC-2. The curve superposed on $V$ in the lower frame is the derivative of $I$ scaled by a value of $B_{\text{los}} = 18.4 \pm 1.1$ mG. to the shock propagation, and the compression of an ordered magnetic field from this orientation would give the following relationship:

$$\frac{B_0}{\rho_0} = \frac{B_1}{\rho_1},$$

where $0$ and $1$ refer to the pre-shock and post-shock (maser) regions, respectively, and $\rho$ is the gas density (e.g., Sarma et al. 2008). In the discussion below, we will use the molecular hydrogen number density $n$ instead of $\rho$. If $B_0$ and $n_0$ are known, then we can use our detected value of $B_{\text{los}}$ to find $n_1$, and compare it to the density at which the 44 GHz CH$_3$OH maser is excited. Poidevin et al. (2010) used the Chandrasekhar–Fermi method to estimate the value of the magnetic field in this region from their 850 $\mu$m observations and found it to be 0.13 mG; we adopt this as our value of $B_0$. We will use $n_0 = 10^4$ cm$^{-3}$, which was obtained by Castets & Langer (1995) based on $^{13}$CO observations toward OMC-2 (also see Poidevin et al. 2010). Finally, we adopt $B_1 = 2B_{\text{los}}$, based on statistical grounds (Crutcher 1999). Using these values in Equation (2), we get $n_1 \sim 10^6$ cm$^{-3}$ for the post-shock number density. This is in excellent agreement with theoretical models that show the 44 GHz CH$_3$OH maser action is maximized in regions with density $10^3$–$10^6$ cm$^{-3}$ (Pratap et al. 2008, and references therein). Another way of looking at this is that, knowing $n_0$ from observations and $n_1$ from theoretical models for CH$_3$OH masers, our observed values of $B_{\text{los}}$, and hence $B_1$, allow us to get a measure of the large-scale magnetic field $B_0$.

Our detected value of $B_{\text{los}}$ in the 44 GHz Class I CH$_3$OH maser line toward OMC-2 is similar to the fields ($\sim 25$ mG) detected in our recent discovery of the Zeeman effect in the 36 GHz Class I CH$_3$OH line toward the high-mass star-forming region M8E (Sarma & Momjian 2009). It is also similar to the fields obtained from the 6.7 GHz Class II CH$_3$OH maser line observed by Vlemmings (2008), who detected significant magnetic fields with the 100 m Effelsberg telescope in this line toward 17 sources, with an average value of 23 mG. The possibility of a fake Zeeman pattern due to beam squint is brought up every time there is a new Zeeman detection, but it is unlikely in our maser observations; this is discussed in more detail in Sarma & Momjian (2009). Since Class I and Class II CH$_3$OH masers likely trace different spatial regions (Ellingsen 2005, and references therein), the similarities in the fields measured in these masers suggest that CH$_3$OH masers may trace the larger scale magnetic fields in star-forming regions. Another possibility might be that Class I masers occur in the very early stages of star formation (before the formation of an ultracompact H II region), and Class II masers occur later on. In that case, the similarity in $B_{\text{los}}$ for these two classes may indicate that the magnetic field strength remains the same during the early stages of the star formation process. It is possible, however, that the similarities may result simply from selection effects due to orientation and/or the shock process. Therefore, a larger statistical sample as well as measurements of the Landé $g$-factor are needed in order to test possible correlations or anti-correlations between fields measured in Class I and Class II masers and at different frequencies within each of these types.

Finally, we use our observed value for the magnetic field to compare the magnetic and dynamical energies in these masering regions. The magnetic energy density is given by $3B_{\text{los}}^2/8\pi$. Here, we have used the relation $B^2 = 3B_{\text{los}}^2/8\pi$. Figure 2. Distribution of H$_2$ jets (green) and CO outflows (red) in OMC-2 and OMC-3, superimposed on 850 $\mu$m polarization data (thin vectors), taken from Figure 7 of Poidevin et al. (2010). The gray scale is the 850 $\mu$m intensity and is displayed to show the location of the filament. The reference position is $\alpha_{2000} = 05^h 35^m 48^s, \delta_{2000} = -05^\circ 00^\prime 0^\prime\prime$. The thick black cross shows the location of our 44 GHz CH$_3$OH maser.
by Crutcher (1999) on statistical grounds. For $B_{\text{los}} \approx 18$ mG from these observations, the magnetic energy density will be $4 \times 10^{-5}$ erg cm$^{-3}$. The kinetic energy density (thermal and turbulent) is given by $(3/2)n_k\sigma^2$, where $\sigma = \Delta v/(8\pi n_2)^{1/2}$ is the velocity dispersion and the mass $m = 2.8 \, n_p$ (assuming $10^4$ He; $n_p$ is the proton mass). Since masers occur only in special directions along which they have developed the required velocity coherence, the velocity dispersions in the masing region may be greater than that traced by masers. If we use $\Delta v = 5 \, km\, s^{-1}$—a reasonable value (see, e.g., McKee 1999), and $n = 10^6$ cm$^{-3}$, the density quoted in Pratap et al. (2008) at which maser action is maximized, we get a kinetic energy density equal to $3 \times 10^{-7}$ erg cm$^{-3}$. Even if $\Delta v$ is as high as $20 \, km\, s^{-1}$, as quoted by Takahashi et al. (2008) for the CO (3–2) outflow marked at our CH$_3$OH maser position in Figure 2, we will get kinetic energy density equal to $5 \times 10^{-6}$ erg cm$^{-3}$. Therefore, the magnetic energy is dominant by at least an order of magnitude, indicating that the magnetic fields are dynamically significant in these regions. Also of interest is that the magnetic energy appears to be dominant in different regions supporting Class I and Class II masers (e.g., this work; Sarma & Momjian 2009; Vlemmings 2008).

5. CONCLUSIONS

We have reported the discovery of the Zeeman effect in the 44 GHz Class I methanol (CH$_3$OH) maser line. We detected a magnetic field $B_{\text{los}} = 18.4 \pm 1.1$ mG toward a star-forming region in OMC-2. There may be systematic bias in this value due to the assumed Zeeman splitting factor of $\zeta = 1.0 \, Hz \, mG^{-1}$, which is based on laboratory measurements in the 25 GHz CH$_3$OH maser line. Still, such values for $B_{\text{los}}$ imply that the magnetic energy may be dominant by at least an order of magnitude over the kinetic energy density, meaning that the magnetic field is dynamically significant in these regions. By assuming a feasible configuration for the shocks that give rise to 44 GHz CH$_3$OH masers, we find that our detected value of $B_{\text{los}}$ leads to a value for the density in the post-shock region ($n_1 = 10^6 \, cm^{-3}$) that agrees with the value predicted by theoretical models for maximizing maser action in the methanol line at 44 GHz. Alternatively, if we know the pre-shock density $n_0$ (e.g., from molecular line observations) and $n_1$ (from theoretical models of masers), we can use our detected $B_{\text{los}}$ to find the large-scale magnetic field. Together with the magnetic fields detected in the 36 GHz Class I CH$_3$OH maser line (Sarma & Momjian 2009), and 6.7 GHz Class II CH$_3$OH masers (Vlemmings 2008), our observations reveal the potential for obtaining a more complete picture of the magnetic field in star-forming regions, since Class I and Class II masers are found at different distances from the protostar, likely trace different physical conditions, and may be excited at different stages of the star formation process.

Given that Class I and Class II methanol masers allow observation of star-forming regions on small physical scales that are inaccessible to other lines, and the possibility that these masers may trace the large-scale magnetic field, we believe that our discovery motivates several observational approaches. A high angular resolution study of the association between 36 GHz and 44 GHz Class I methanol masers is now possible due to the new 36 GHz receivers on the EVLA. Likewise, a high angular resolution study of the association between Class I and Class II methanol masers is warranted. Identification of other maser sites where the Zeeman effect could be measured would allow for the conclusions above to be placed on a statistical footing. Moreover, the OMC-2 region that we have studied is forming intermediate stars (Takahashi et al. 2008). Observations of magnetic fields in 44 GHz CH$_3$OH masers in high-mass star-forming regions, and the other studies described above, may yield important clues in the unsolved areas of high-mass star formation. Finally, there is also a pressing need for laboratory measurements of the Zeeman splitting coefficients for various types of Class I and Class II CH$_3$OH masers.

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REFERENCES

Banerjee, R., & Pudritz, R. E. 2006, ApJ, 641, 949
Banerjee, R., & Pudritz, R. E. 2007, ApJ, 660, 479
Castets, A., & Langer, W. D. 1995, A&A, 294, 835
Cragg, D. M., Johns, K. P., Godfrey, P. D., & Brown, R. D. 1992, MNRAS, 259, 203
Crutcher, R. M. 1999, ApJ, 520, 706
Crutcher, R. M., Hakobian, N., & Troland, T. H. 2009, ApJ, 692, 844
Crutcher, R. M., Troland, T. H., Goodman, A. A., Heiles, C., Kazes, I., & Myers, P. C. 1993, ApJ, 407, 175
Ellingsen, S. P. 2005, MNRAS, 359, 1498
Fish, V. L., & Reid, M. J. 2006, ApJ, 643, 99
Genzel, R., & Stutzki, J. 1989, ARA&A, 27, 41
Heiles, C., Goodman, A. A., McKee, C. F., & Zweibel, E. G. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson, AZ: Univ. Arizona Press), 279
Jen, C. K. 1951, Phys. Rev., 81, 197
McKee, C. F. 1999, in The Origin of Stars and Planetary Systems, ed. C. J. Lada & N. D. Kylafis (Dordrecht: Kluwer), 29
McKee, C. F., & Ostriker, E. C. 2007, ARA&A, 45, 565
Nedoluha, G. E., & Watson, W. D. 1992, ApJ, 384, 185
Poidevin, F., Bastien, P., & Matthews, B. C. 2010, ApJ, 716, 893
Pratap, P., Shute, P. A., Keane, T. C., Batterby, C., & Sterling, S. 2008, AJ, 135, 1718
Sandell, G., Goss, W. M., & Wright, M. 2005, ApJ, 621, 839
Sarma, A. P., & Momjian, E. 2009, ApJ, 705, L176
Sarma, A. P., Troland, T. H., Crutcher, R. M., & Roberts, D. A. 2002, ApJ, 580, 928
Sarma, A. P., Troland, T. H., Romney, J. D., & Huynh, T. H. 2008, ApJ, 674, 295
Sault, R. J., Killeen, N. E. B., Zhuendizinas, J., & Loushin, R. 1990, ApJS, 74, 437
Slysh, V. I., & Kalenski, S. V. 2009, Astron. Rep., 53, 519
Stanke, T., McCaughrean, M. J., & Zinnecker, H. 2002, A&A, 392, 239
Takahashi, S., Saito, M., Ohashi, N., Kusakabe, N., Takakuwa, S., Shimajiri, Y., Tamura, M., & Kawabe, R. 2008, ApJ, 688, 344
Troland, T. H., & Heiles, C. 1982, ApJ, 252, 179
Troland, T. H., Heiles, C., Sarma, A. P., Ferland, G. J., Crutcher, R. M., & Brogan, C. L. 2008, arXiv:0804.3396
Vlemmings, W. H. T. 2008, A&A, 484, 773
Vlemmings, W. H. T., Surcis, G., Torstensson, K. J. E., & van Langevelde, H. J. 2010, MNRAS, 404, 134
Williams, J. P., Plambeck, R. L., & Heyer, M. H. 2003, ApJ, 591, 1025