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OH MASERS AND THE GALACTIC MAGNETIC FIELD

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ABSTRACT

Zeeman splitting of OH maser lines yields the line-of-sight direction and the full magnitude of the magnetic field in the molecular gas in which the maser action occurs. The line-of-sight direction of the magnetic field from 17 maser sources indicates a systematic magnetic field over large regions of the Galaxy. This result suggests that the magnetic field direction is largely preserved during contraction from interstellar densities (~ 1 cm^{-3}), through those of giant molecular clouds ($\sim 10^3$ cm^{-3}), to those of OH masers ($\sim 10^7$ cm^{-3}) near newly formed massive stars, and that the Galactic magnetic field is a dominant force in the process of collapse toward stellar densities. Also, this result confirms conclusions based on rotation measures of pulsars and extragalactic radio sources that there is a large-scale Galactic field, and it offers a new and powerful method to determine the magnetic field structure in the entire disk of the Galaxy.

Subject headings: galaxies: the Galaxy — interstellar: magnetic fields — masers — stars: formation — Zeeman effect

I. INTRODUCTION

OH maser emission occurs in the molecular material associated with ultracompact H II regions, which are excited by the recent formation of massive (OB-type) stars. In the presence of a magnetic field, the Zeeman effect splits the OH spectral lines, producing pairs of right (RCP) and left (LCP) circularly polarized lines. The magnetic field strengths determined from the frequency splitting of Zeeman pairs for OH masers are typically a few milligauss (mG). For OH masers the Zeeman splitting usually *exceeds* the intrinsic maser line width, so the splitting is proportional to the *full magnitude* of the B field and not proportional to the line-of-sight component, as in the case of small splitting (compared to the line width) usually encountered in Zeeman measurements from nonmasing OH lines or the 21 cm line of atomic hydrogen.

In addition to the full magnitude of the B field, OH Zeeman measurements yield the *line-of-sight direction* of the field (i.e., whether it points toward or away from the observer). In fact, simply noting whether the RCP line(s) are shifted to higher or lower frequency compared to the LCP line(s) indicates the line-of-sight direction of the B field.

Early attempts to identify Zeeman pairs in OH maser spectra generally were not successful. Once interferometric maps were available, one usually found that proposed Zeeman components came from widely separated regions in a given maser source. It was not until very long baseline interferometric (VLBI) studies found some RCP and LCP components that came from the same position to within a maser spot size (Reid *et al.* 1980) that the Zeeman interpretation of OH maser polarization was truly verified. (For more details see Reid and Moran 1981.) However, even though Zeeman pairs identified from spectra alone (without interferometry) were not reliable, the line-of-sight direction and the approximate magnitude of the field usually turned out to be correct. This occurred because the Zeeman splitting often was comparable to the Doppler shifts of different maser spots in one source; thus most pairings of RCP and LCP maser spots would give approximately correct magnetic field information.

Davies (1974) noted that, for a sample of eight OH maser sources (and a few H I clouds), the line-of-sight direction of the magnetic field was parallel to the direction of Galactic rotation. However, this suggestion attracted little attention and, to our knowledge, no published follow-up investigations. Perhaps this occurred because (1) Davies had a small sample of sources, (2) masers were then considered exotic phenomena, and (3) Zeeman measurements for OH masers and 21 cm wavelength H I were questionable.

II. ZEEMAN EFFECT IDENTIFICATION

We decided to pursue the idea that the magnetic field detected in OH masers traces a Galactic field. We searched the available literature of the past few decades looking for candidate Zeeman pairs in OH spectra and for interferometric results that would identify them as originating from the same masing cloudlet and hence confirm them as Zeeman pairs. In Table 1 we present the data from which the Zeeman identifications were made.

As discussed above, even with VLBI observations one rarely finds Zeeman pairs where the RCP and LCP spots coincide to a small fraction of the spot sizes. For the best studied source, W3OH, only five pairs of oppositely circularly polarized spots have been detected that satisfy this strict definition of a Zeeman pair (Garcia-Barreto *et al.* 1988). The difficulty is that maser amplification is nonlinear and the amplification for one component of a Zeeman pair can be greatly different than for the other. This probably occurs because gradients in velocity and magnetic field strength over the amplification length can shift the line frequency by an amount comparable to the (often narrow) maser line width (see Cook 1966; Moran *et al.* 1978). However, Reid *et al.* (1980) found that the OH masers in W3OH have a characteristic clustering scale and that different spots within a region of size $\approx 3 \times 10^{15}$ cm probably indicate the locations of high-amplification paths through a single physical condensation or cloudlet. Thus, all maser spots tightly clustered together are likely to sample the same physical conditions, and when searching for Zeeman pairs we allowed for a separation of up to 3×10^{15} cm between the RCP and LCP spots.

We examined published spectra for clear signs of oppositely

TABLE 1

ZEEMAN PAIR DATA

Source	OH Line (MHz)	V_{LCP} (km s^{-1})	V_{RCP} (km s^{-1})	$\Delta\theta$[a] (arcsec)	References
SgrB2(N)	1665	54.3	55.4	0.02	1
G20.1−0.1	1665	46.3	49.7	0.04	2
		44.2	48.6	0.05	2
		43.1	47.5	0.03	2
G30.70−0.06	1665	90.9	91.2		3
	1667	90.9	91.2		3
		86.3	86.6		3
W49N	1612	20.9	19.8	0.03	1
	1665	20.4	17.1	0.02	1
		11.6	7.2	0.04	1
		0.6	−1.6	0.06	1
	1667	19.3	18.2	0.06	1
		14.9	13.8	0.05	1
W51M	1665	46.8	50.1	0.10	1
		56.7	61.1	0.05	1
	1667	46.8	49.0	0.06	1
	1720	57.9	58.9	0.06	1
		54.7	55.7	0.01	1
		53.1	54.1	0.02	1
		58.7	59.4	<0.01	4
		56.9	58.1	<0.01	4
W75N	1665	4.2	6.0	0.014	5
		3.8	6.5	0.02	6
		4.8	9.6	0.03	6
	6035	6.3	6.7		7
		7.3	7.6		7
		9.0	9.3		7
W3OH	1665	−47.3	−43.8	0.010	8
		−45.4	−42.2	0.001	8
		−45.5	−41.5	0.001	8
		−46.4	−43.4	0.002	8
		−44.8	−41.3	0.000	8
	1720	−45.6	−44.9	0.003	9
	6035[b]	−48.3	−47.8	0.05	10
		−46.7	−46.2	0.04	10
		−45.3	−45.0	0.02	10
		−45.0	−44.6	0.08	10
		−43.6	−43.4	0.02	10
		−43.3	−43.0	0.03	10
		−43.0	−42.6	0.01	10
		−42.6	−42.3	0.07	10
Orion	1665	8.6	7.1	0.05	11
G300.97+1.15	1665	−38.0	−39.5		12
		−35.0	−35.9		12
	1667	−38.4	−38.9		12
		−35.3	−35.6		12
G305.81−0.24	1665	−34.8	−36.4		12
	1667	−35.0	−36.0		12
G330.96−0.18	1665	−83.2	−85.9		13
	1667	−83.9	−85.6		13
G331.34−0.34	1665	−66.9	−66.2		13
	1667	−67.1	−66.4		13
G337.71−0.06	1665	−49.8	−50.8		13
	1667	−49.5	−50.0		13
G345.0−0.2	1665	−28.0	−25.8	0.01	1
	1720	−28.7	−28.0	0.10	1
G348.5−1.0	1665	−19.3	−20.4	0.20	1
	1667	−11.6	−12.7	0.40	1
	1720	−12.1	−12.8	0.40	1
NGC 6334(N)	1665	−8.1	−12.5		14
		−9.0	−12.3		15
	1667	−10.0	−12.0		15
	1720	−10.4	−11.2	<0.10	9, 15
G351.78−0.54	1665	−25.7	−28.0		16
	1667	−26.3	−27.7		16

[a] Angular separation of RCP and LCP maser spots.

[b] Using only Zeeman pairs with angular separation <0ʺ.1 after adding (0ʺ.08, −0ʺ.01) to (θ_x, θ_y) of the LCP features.

REFERENCES.—(1) Gaume and Mutel 1987; (2) Garay, Reid, and Moran 1985; (3) Caswell and Haynes 1983*b*; (4) Benson, Mutel, and Gaume 1984; (5) Haschick *et al.* 1981; (6) Baart *et al.* 1986; (7) Zuckerman *et al.* 1972; (8) Garcia-Barreto *et al.* 1988; (9) Lo *et al.* 1975; (10) Moran *et al.* 1978; (11) Hansen *et al.* 1977; (12) Caswell and Haynes 1987; (13) Caswell *et al.* 1980; (14) Gardner, McGee, and Robinson 1967; (15) Robinson, Goss, and Manchester 1970; (16) Caswell and Haynes 1983*a*.

circularly polarized features from all masing OH transitions. Where possible, we used interferometric observations that could locate the maser spots accurately enough to ensure that candidate Zeeman pairs were from the same physical condensation or cloudlet. We tried to minimize the subjectivity involved in assigning features as Zeeman pairs by "grading" the likelihood of correct pairing via a quality code. Sources with candidate Zeeman pairs in two or more OH transitions (with different frequency splittings for a given magnetic field strength) and with VLBI maps (with an angular resolution less than 0ʺ.1) confirming at least one pair were graded "A." If, instead of VLBI, connected element interferometry with an angular resolution of $\approx 1''$ (e.g., the VLA) was used to map the source, the source received a grade of "B." Sources with a grade of "C" had candidate Zeeman pairs either from two transitions or from a single transition with confirming interferometric mapping. Finally, when compiling the data, we assigned a grade of "D" to sources with candidate Zeeman pairs in only one transition with no confirming interferometry.

We do not list the grade D sources in the tables since they are numerous and the possibility of misidentification of Zeeman pairs is significant. These sources will be the subject of future interferometric observations.

We found 17 OH maser sources for which the Zeeman effect can be demonstrated convincingly (grades A, B, or C). Table 2 gives information pertaining to the location, distance, and average magnetic field for each source. The source distances, obtained from the literature, were determined with several techniques. Most of the distance estimates are from a kinematic model of circular rotation of the Galaxy. A few are from associated O star luminosity distances. Four of the sources, Orion, W51M, Sgr B2(N), and W49N, have direct measurements of distance via H_2O maser proper motions (Genzel *et al.* 1981*a*, *b*; Reid *et al.* 1988; Gwinn *et al.* 1989). Where appropriate we have rescaled distances to be consistent with a distance to the Galactic center (R_0) of 8.5 kpc and a circular rotation speed (Θ_0) of 220 km s^{-1} as recommended by the IAU (Kerr and Lynden-Bell 1986).

TABLE 2

OH MASER *B* FIELD DATA

Source	l^{II}	b^{II}	Distance[a] (kpc)	*B* Field[b] (mG)	Quality[c] Code
Sgr B2(N)	0°7	−0°0	8.5	2	C
G20.1−0.1	20.1	−0.1	3.6	7	C
G30.70−0.06	30.7	−0.1	5.5, 9.1	1	C
W49N	43.2	0.0	11.7	−4	B
W51M	49.5	−0.4	7.0	6	A
W75N	81.9	0.8	2.0	5	A
W3OH	133.9	1.1	2.2	5	A
Orion	209.0	−19.4	0.5	−3	A
G300.97+1.15	301.0	1.2	4.4	−2	C
G305.81−0.24	305.8	−0.2	3.2, 6.7	−3	C
G330.96−0.18	331.0	−0.1	5.1, 9.8	−5	C
G331.34−0.34	331.3	−0.3	4.7	2	C
G337.71−0.06	337.7	−0.0	12.1[d]	−2	C
G345.0−0.2	345.0	−0.2	3.0, 13.4	3	B
G348.5−1.0	348.5	−1.0	2.2	−3	C
NGC 6334(N)	351.4	0.7	1.7	−5	B
G351.78−0.54	351.7	−0.5	2.2	−4	C

[a] Assuming $R_0 = 8.5$ kpc and $\Theta_0 = 220$ km s^{-1}. Two values are given for some kinematic distances.

[b] Full magnitude of *B* field with sign indicating the direction of the line-of-sight component (positive pointing away from Sun). The conversion from the velocity separation of the RCP and LCP components to *B* field assumed 0.590, 0.354, 0.236, and 0.060 km s^{-1} mG^{-1} for the 1665, 1667, 1720, and 6035 MHz transitions, respectively. An average value for the *B* field was determined for each transition, and then an unweighted average over all transitions is reported in the table.

[c] See text for description.

[d] Far kinematic distance adopted by association with G337.8+0.0 (Bronfman, Nyman, and Thaddeus 1989).

III. RESULTS

Figure 1 is a plot of the Galactic plane with the locations of the OH maser sources indicated by the circles and the *B*-field *magnitude* and *line-of-sight direction* indicated by the length and direction of the arrows, respectively. Those sources with dashed arrows have kinematic distance ambiguities and are plotted at both possible locations in the Galaxy. Note that the plotted arrows are *not* true *B*-field vectors; the true vectors may be misaligned by up to about 60° with the line of sight and still produce strongly circularly polarized lines (Goldreich, Keeley, and Kwan 1973).

Compared to Davies' (1974) sample, we do not include the sources G285.2−0.0, G291.6−0.4, and NGC 6334B as these sources have a quality code of D (i.e., only one transition and no interferometric mapping). In addition, Davies finds that the *B* field of "W49" points away from the Sun, whereas we indicate that the field in W49N points toward the Sun. (This discrepancy arises because there are two sites of OH masers in the W49 complex [W49N and W49S]. The interferometric mapping of Gaume and Mutel [1987] indicates that W49N has convincing Zeeman pairs. The source W49S [presumably Davies' W49], also mapped by Gaume and Mutel, may have a field reversal within the source and in any event does not have convincing Zeeman pair identifications by the criteria adopted in this paper.) We have found 12 new sources with convincing Zeeman identifications. Ten of those 12 sources have line-of-sight *B*-field directions that point in the direction of Galactic rotation. Thus, with improved statistics and more reliable Zeeman data, we confirm Davies' hypothesis.

For the sample of 17 OH sources in Table 2, 14 have line-of-sight *B*-field directions that point in the direction of Galactic rotation. Were the distribution of *B*-field directions entirely random, the probability of obtaining this result would be only about 6%. Because this is a small probability, and because rotation measure data also suggests an ordered Galactic *B* field, we will assume throughout the rest of this paper that the OH result is significant. There are two effects that would lead one to expect some variation in the line-of-sight *B*-field direction as determined from OH maser Zeeman measurements: (1) a Galactic field that is not uniformly in the direction of Galactic rotation, and (2) local deviations of the magnetic field in regions of star formation where OH masers are found. Thus, the statistics of *B*-field directions presented in this paper seem to suggest that neither effect is a dominant one, although the limited distribution of OH masers in the Galaxy (predominantly less than 8.5 kpc from the Sun in the first and fourth quadrants) does not permit a strong statement regarding the Galactic field structure.

The magnetic field of the Galaxy, as inferred from OH maser Zeeman observations, has large-scale features with the same line-of-sight direction that span arcs (or annuli) over many kiloparsecs. Note that outside of 6 kpc from the Galactic center 9 of 10 line-of-sight *B* fields point in the direction of Galactic rotation (clockwise in Fig. 1). This result is in general agreement with the Galactic (line-of-sight) *B*-field direction deduced for the solar neighborhood within 3 kpc using rotation measures of pulsars (see Rand and Kulkarni 1989, and references therein) and extragalactic sources (Simard-Normandin and Kronberg 1980).

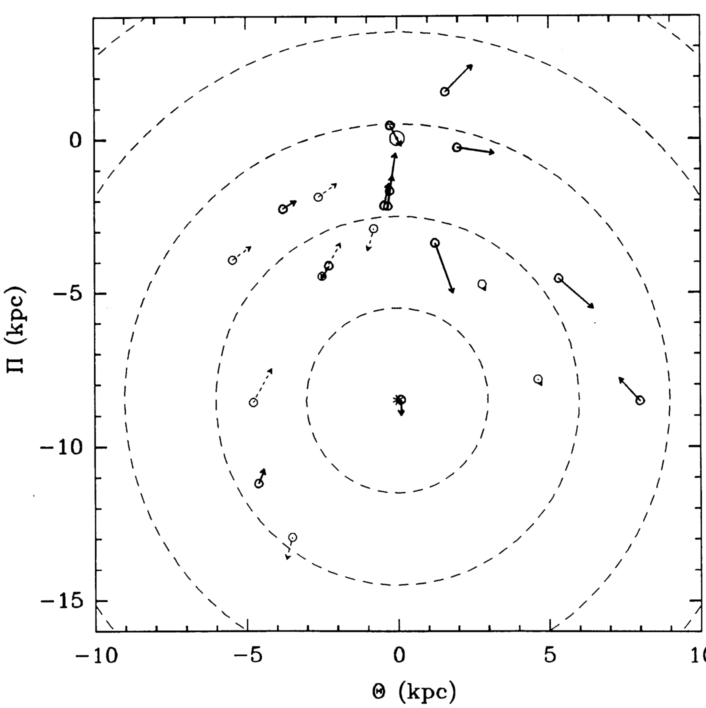

FIG. 1.—Plot of OH maser sources on the Galactic plane. Locations of the maser sources are given by circles, and the *full B*-field magnitude and *line-of-sight directions* are indicated by arrows. Sources with kinematic distance ambiguities have dashed arrows and are shown at *both* possible distances. The Sun, indicated by a ⊙, is at the origin of the plot and 8.5 kpc from the Galactic center, indicated by an asterisk (∗). Galactocentric distances of multiples of 3 kpc are indicated by dashed circles. Note that the plotted arrows are *not* true *B*-field vectors, because the true vectors may be misaligned by up to about 60° with the line of sight. Only three of the 17 sources on this plot have line-of-sight *B*-field directions pointing in the opposite sense (counterclockwise) from Galactic rotation.

There are some significant differences in the magnetic field information obtained from OH masers and from rotation measures. The rotation measure of pulsars and extragalactic sources gives the *integral* of the line-of-sight B field to the source weighted by the electron density. On the other hand, the OH Zeeman measurements give an *in situ* B field for dense ($n_{H_2} \approx 10^7$ cm^{-3}) molecular material at one position in the Galaxy. Thus, the two types of measurements sample very different regions of the Galaxy and give complementary information. However, since the rotation measure yields the *integrated* line-of-sight B field, rotation measures will not be as useful for determining the Galactic magnetic field structure on large scales, as multiple field reversals will be difficult to deal with. The rotation measure results suggest that there is a field reversal within about 1 kpc of the Sun in the approximate direction of the Galactic center. While there is no indication of this reversal in the OH maser data, the OH data are too sparse to rule out such a reversal. However, more distant field reversals are directly observed in the OH data. (Three of the 17 sources in Fig. 1 have line-of-sight field directions opposite to the direction of Galactic rotation.)

IV. CONCLUSIONS AND FUTURE WORK

The observation that OH masers spanning large regions of the Galaxy have similar line-of-sight magnetic field directions has major implications for star formation and for our understanding of the Galactic magnetic field.

a) Star Formation

We conclude that the magnetic field direction is largely preserved during contraction from interstellar densities (1 cm^{-3}), through those of giant molecular clouds (10^3 cm^{-3}), to those of OH masers (10^7 cm^{-3}) near newly formed O stars. This suggests that the magnetic field may control to a significant extent the process of collapse toward stellar densities. Recent observational findings have shown that magnetic energy densities are comparable to gravitational, thermal, and turbulent energy densities in the molecular material of star-forming regions (e.g., Reid, Myers, and Bieging 1986; Myers and Goodman 1988). In light of our increased understanding of the central role that magnetic fields play in the formation of stars, perhaps the most important conclusion presented in this paper is that the magnetic field in star-forming regions is of Galactic origin and is not generated locally.

b) Galactic Magnetic Field

We confirm the conclusions based on pulsar and extragalactic rotation measures that the Galaxy has a systematic magnetic field structure for scales of a few kiloparsecs. Indeed, the OH maser data show that the Galactic field can have the same general direction for scales of ≈ 10 kpc. However, unlike rotation measure data in which a random component of the magnetic field appears comparable to the large-scale Galactic component, the OH maser data may have little "noise" in the line-of-sight field direction. Also, in contrast to the rotation measure studies, OH maser results are free of "contamination" from local magnetic anomalies such as found in the North Polar Spur and the Gum Nebula. Furthermore, the Zeeman effect in OH masers offers the opportunity to determine the magnetic field structure across the entire Galaxy from *in situ* measurements in many regions of star formation. Unfortunately, because OH masers (in star-forming regions) are found almost entirely in the Galactic plane, it will not be possible to map the magnetic field out of the Galactic plane in this manner.

We clearly need more OH Zeeman identifications for sources at distances greater than R_0 in the first and fourth quadrants of the Galaxy and more sources in the second and third quadrants. Also, distances need to be determined for some sources. Kinematic distances may be sufficiently accurate for studies of the global properties of the Galactic magnetic field. Therefore, in most cases resolving kinematic distance ambiguities, for example with 21 cm hydrogen emission/absorption line studies, would be adequate. We plan to conduct the necessary observations in the near future.

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