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Zeeman splitting of OH masers and the galactic magnetic field

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Abstract. Zeeman measurements of OH masers are used to probe the magnetic field around regions of massive star formation. Previous observations suggested that OH maser field directions were aligned in a clockwise sense in the Milky Way, but recent data from a large-scale VLA survey do not support this hypothesis. However, these observations suggest that the magnetic field of the Milky Way is correlated on kiloparsec scales.

1. Introduction

Davies (1974) first noted a potential correlation between magnetic fields deduced from OH maser Zeeman splitting and a large-scale Galactic field. He noted that the line-of-sight magnetic field directions deduced from 8 OH maser sources and 7 H I clouds were consistent with an overall clockwise Galactic field. Reid & Silverstein (1990) performed a literature search to identify Zeeman pairs in additional OH maser sources. Of the 17 sources they found, 14 had line-of-sight field directions consistent with a clockwise Galactic field. Baudry et al. (1997) conducted a 5 cm survey to detect 6031 and 6035 MHz excited-state OH maser emission in northern-hemisphere H II regions. They identified Zeeman-pattern emission in 14 sources. To this sample they added the non-overlapping sources from Reid & Silverstein and Caswell & Vaile (1995). While they found that the majority of the sources did, indeed, indicate a clockwise Galactic field, this fraction was not statistically significant. In this paper we report analysis of a large sample of OH maser sources observed recently with the VLA.

2. Galactic Field Structure

Ninety-one OH maser sources were observed by Argon, Reid, & Menten (2000) using the VLA in the A-configuration. Each source was observed in dual circular polarization in at least one of the ground-state, main-line $^2\Pi_{3/2} J = 3/2$ OH transitions (1665 and 1667 MHz), and some sources were also observed in one or both satellite-line transitions (1612 and 1720 MHz). The survey represents

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a nearly-complete (greater than 80%) sample of interstellar OH maser regions above $-45°$ declination with peak flux density greater than 1 Jy in each circular polarization in at least one main-line transition.

For each of the 91 sources in the survey, maser lines were identified in each polarization in the observed spectra. Those maser spots that coincided within a projected distance on the sky of 3×10^{15} cm were identified as Zeeman pairs. This length is the characteristic clustering scale obtained from VLBI maps of W3 OH (Reid et al. 1980). In some cases, several maser lines in one or both polarizations prevented unambiguous pairing of maser spots within the clustering scale; when all such pairings implied a magnetic field in the same sense (e.g., all RCP lines at higher velocity than all LCP lines), the line-of-sight direction was determined, even though the full magnitude of the field was unknown. Kinematic distances to the sources were assumed, using $R_0 = 8.5$ kpc and $\Theta_0 = 220$ km s^{-1}. A distance ambiguity exists for sources inside the solar circle in the first and fourth Galactic quadrants. When this ambiguity could not be satisfactorily resolved, such as by H I absorption, O-star luminosity, or high Galactic latitude, the near kinematic distance was assumed.

A plot of the line-of-sight field directions on the plane of the Milky Way appears in Figure 1. Those arrows pointing away from the Sun for $0° < l < 180°$ and toward the Sun for $180° < l < 360°$ are consistent with a clockwise Galactic field. Twenty-one of the 40 sources have magnetic fields that point in the direction of Galactic rotation. This suggests that there is not a uniform, tangential Galactic field. However, this does not preclude a more complex organized Galactic magnetic field, such as a bisymmetric spiral, in which field lines reverse directions at different Galactocentric radii or in different spiral arms.

While we do not have enough data to make strong statistical statements about correlations of field directions in each spiral arm, we are able to detect structure on smaller scales. A two-point spatial correlation function was calculated on the data in order to assess the degree to which the magnetic field is correlated on various scales. We define two sources to be correlated if both their line-of-sight field directions are consistent with either a clockwise or counterclockwise Galactic field and anti-correlated if their line-of-sight field directions imply opposite senses of the Galactic field. Maser sources with separations less than a specified distance contributed $+1$ if the fields are correlated and -1 if the fields are anti-correlated. The correlation function was evaluated at several maser source separations selected at approximately logarithmically-spaced intervals. Since it is difficult, for an arbitrary distribution of sources in the Galaxy, to interpret directly the output of the correlation function, or even to decide what constitutes a "high" degree of correlation, similar correlations were calculated for randomly-generated simulated data at the same source positions. Table 1 shows a comparison of the real data correlations to the randomly generated ones for 5×10^7 trials.

Since most pairs of H II regions included in this study are separated by less than 10 kpc, the low degree of correlation at 10 and 20 kpc indicates that the numbers of sources with clockwise and counterclockwise magnetic fields are nearly equal, as mentioned above. However, a kiloparsec-scale field correlation does seem to occur, as indicated by the paucity of trial runs showing a greater correlation at 1 kpc. Indeed, small clumps of sources exhibiting the same line-of-sight field direction are readily seen, for example, in the Crux (near $\Theta = -1$, $\Pi = -3$ kpc) and Sagittarius ($\Theta = 2$, $\Pi = -2.5$ kpc) arms in Figure 1. Despite occasional field reversals between sources located in the same association, such as the Sgr B2 sources near the Galactic center, a large majority of source pairs with separations around 1 kpc have mutually-consistent magnetic field directions.

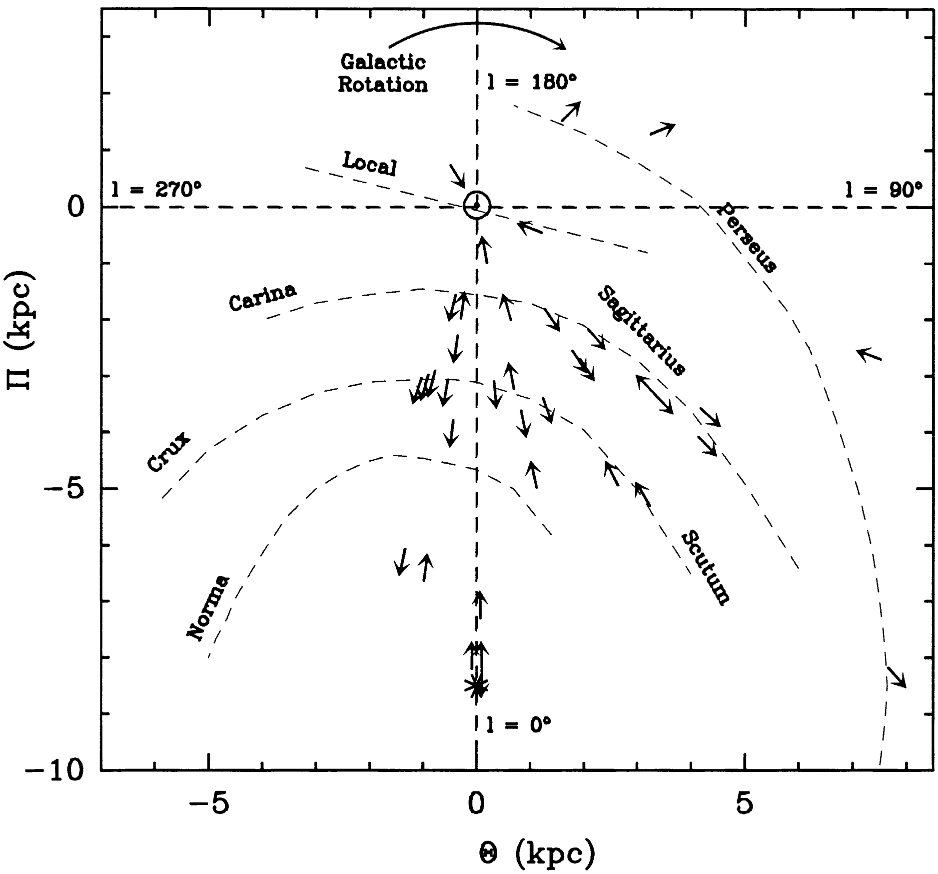

Figure 1. Line-of-sight magnetic field directions on a plot of the Galaxy. Approximate spiral arms are sketched in. The positions of the Sun, ⊙, and the Galactic center, ∗, are indicated, as is the direction of Galactic rotation.

3. Future Considerations

While this initial study was restricted to maser sources in the VLA survey by Argon et al. (2000) to reduce bias and ensure homogeneity, further studies will incorporate sources from other surveys as well. Since many UCH II regions in the third and fourth Galactic quadrant are observable only from the southern hemisphere, the VLA survey alone is inadequate to cover the entire Galactic

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Separation (kpc)	Less Correlated	More Correlated
0.5	90%	5%
1.0	98%	1%
2.0	89%	9%
5.0	56%	39%
10.0	19%	72%
20.0	11%	80%

Table 1. Two-point correlation results. The percentages of trial runs of randomly-generated data showing a lesser and greater degree of correlation than the real data for a given maximum source separation are shown. Since some trial runs indicated equal correlation as the real data, the "less" and "more" correlations do not sum to 100%.

plane. VLBI mapping may also be crucial to understanding magnetic fields deduced from UCH II regions. Preliminary VLBA maps of several sources indicate a reversal of field direction across the source in approximately half the sources mapped so far. Thus, a field direction based on only one or two Zeeman pairs, as is the case for many of the VLA sources, may be misleading. Furthermore, the distances to many of the VLA sources are unknown. Measuring H I absorption against the H II continuum should resolve the kinematic distance ambiguity for the sources with bright continuum emission. While this ambiguity does not have a direct impact on the large-scale Galactic field, its resolution will further refine kiloparsec-scale correlation results. Finally, there remains to interpret OH Zeeman results in the context of more complicated Galactic field morphologies. Results of pulsar rotation measure studies (e.g., Han, Manchester, & Qiao 1999) suggest field reversals between spiral arms. This could explain both the lack of Galactic-scale consistency of OH maser source field directions (since most source pairs at large separation cross arm boundaries) and the consistency of field directions on kiloparsec (i.e., intraarm) scales. A larger sample of OH Zeeman sources may be useful in confirming this hypothesis.

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