OBSERVATIONAL ASPECTS OF MAGNETIC FIELDS IN MOLECULAR CLOUDS

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ABSTRACT. A small but growing body of observational information now exists regarding magnetic field strengths in molecular regions. Most of these data come from study of the Zeeman effect in 18 cm OH lines. The field is strong enough in many such regions to be dynamically important.

1. QUESTIONS TO BE ADDRESSED BY OBSERVATIONAL STUDIES

Observational studies of the magnetic field strengths can address several crucial questions. For example, is the field strong enough to be dynamically important in molecular clouds? If the field is dynamically important, does field strength scale with other cloud parameters such as volume density and total mass in ways predicted by theory? Under what conditions do the effects of ambipolar diffusion become significant in a contracting cloud?

The most fundamental of these questions concerns the dynamical importance of the field. No theory can take this as a given, it must be established empirically. A simple criterion given in Mouschovias (1987) is

$$B_{crit} \approx 5 \times 10^{-21} N_p \ (\mu G),$$

where N_P is the average proton column density through the cloud. If $B \geq B_{crit}$, the field is capable of stabilizing the cloud against self gravitation irrespective of external pressure. Such a cloud is said to be *subcritical* (*e.g.* Shu, Adams, and Lizano 1987), and it can contract only on the timescale established by ambipolar diffusion. If $B < B_{crit}$, the field cannot support the cloud. The cloud is *supercritical*, and it undergoes a magnetically-diluted gravitational collapse.

2. OBSERVATIONAL METHODS

Techniques for measuring the interstellar magnetic field have been recently reviewed by Heiles (1987) and by Crutcher (1988). All involve the measurement of polarization of radiation emitted by or passing through magnetized regions. Virtually all techniques reveal either the position angle of the transverse field component on the plane of the

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sky, or else the magnitude and sign of B_R, the radial field component. In either case, information is missing about one component of the field. Moreover, the different techniques sample different locales in the clouds so that comparison of results is complicated. We briefly review Zeeman effect techniques below, see the citations above for details.

2.1. The Zeeman Effect in Molecular Clouds

The only existing method for measuring magnetic field strengths in molecular clouds is the Zeeman effect in radio frequency spectral lines. This effect usually amounts to a small frequency offset between the right and left circularly polarized components of the line (offset ≈ 10^{-3} of the line width). In such a case, the frequency offset is proportional to the magnitude and sign of B_R[1]. If the right circular component (IEEE convention[2]) is observed at higher frequency than the left, the field points toward the observer and is negative.

Zeeman effect observations are useful in studying the interstellar magnetic field not only because they provide an estimate of the field strength, but also because they sample relatively localized regions along the line-of-sight where the spectral line originates. These advantages are partly offset by the fact that only the radial component of the field is normally measured, and field reversals within the telescope beam can lead to cancellation of the observed effect.

Neither of these limitations can be entirely overcome. However, statistically significant information about the total field strength B can be inferred from an ensemble of measurements of B_R if the angles of the field relative to the line-of-sight are randomly distributed, since in this case $B = 2\langle B_R \rangle$. Also, aperture synthesis techniques can sometimes provide higher spatial resolution of the Zeeman effect, mitigating the problem of field cancellation across the beam of a single dish. Irrespective of these limitations, the Zeeman effect in radio frequency spectral lines (where detected) provides a strict lower limit to B. Moreover, since the Zeeman effect is the *only* available technique to probe field strengths in molecular clouds, its limitations must be accepted as the fundamental current limitations upon our ability to observationally specify the field strengths in these regions.

2.2. Choice of Spectral Lines for the Zeeman Effect

Only a few radio frequency spectral lines arising in molecular regions are suitable for Zeeman effect measurements. One such transition is the 21 cm line of HI. Although HI is rare in molecular clouds, the 21 cm Zeeman effect may provide useful information about field strengths in molecular regions in certain circumstances. These include cases of HI

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[1] If the Zeeman frequency offset is comparable to or greater than the line width, the offset is proportional to the *total* field strength.

[2] Electric vector rotates clockwise as it propagates away from the observer.

self absorption toward molecular clouds and HI absorption against HII regions. In the latter case, the absorbing HI may be dissociated but otherwise undisturbed gas at the HII region boundary, and magnetic fields in the HI may be representative of those in the adjacent molecular gas.

Other radio frequency spectral lines originating in molecular clouds come from molecules, and the Zeeman effects in molecular lines are almost always undetectably small. This circumstance follows from the fact that most molecules are in $^1\Sigma$ ground states and do not posses electronic angular momentum. Therefore, their Zeeman interaction energies (per unit field strength) are only of order the nuclear magneton. A very few molecules found in molecular clouds are *not* in $^1\Sigma$ ground states. Their Zeeman interaction energies are of order the Bohr magneton, about 10^3 times greater. Examples are OH, SO, CN, CH, C_2H, C_4H, C_3N, and CCS.

A second factor affecting the Zeeman suitability of a molecular transition is the line frequency ν_o, with lower frequency transitions favored for comparable field strengths. An empirical relation found by this author to be useful in predicting the standard deviation $\sigma(B_R)$ in derived magnetic field for a given Zeeman effect observation is

$$\sigma(B_R) \approx 0.8\ \nu_0{}^{1/2}(d/z)(T_{sys}/T_L)(\Delta v/\tau)^{1/2} \quad (\mu G).$$

In this equation ν_0 is the line frequency (GHz), z is the Zeeman coefficient (Hz μG^{-1}, *e.g.* 2.8 Hz μG^{-1} for HI), T_{sys} is the system temperature, T_L is the line temperature, Δv is the full line width at half power (km s^{-1}), τ is the integration time (hours) assuming both circular polarizations are simultaneously received, and d is the noise degradation factor associated with signal digitization in an autocorrelation spectrometer ($d \geq 1$). Since the Zeeman coefficient is of order unity for transitions at all radio frequencies, lower frequency lines are preferred, especially since system temperatures at centimeter wavelengths are often as much as an order of magnitude lower than those at millimeter wavelengths.

2.3. The Zeeman Effect in 18 cm OH Lines

All factors considered, the 1665 and 1667 MHz lines of OH are the most sensitive known probes of the Zeeman effect in molecular clouds. This is especially true for OH lines seen in absorption against strong continuum sources, and virtually all Zeeman effect detections to date in molecular clouds have come from OH absorption lines.

Unlike lines of many other molecules, the OH lines are not strongly density sensitive since astrochemical models suggest that the fractional abundance of OH is relatively stable over the density range 10^2 to 10^5 cm^{-3} (Graedel, Langer, and Frerking 1982). Moreover, the 18 cm lines appear to have only modest optical depths. Therefore, the OH Zeeman effect samples a rather broad range in density along the entire path length through a molecular cloud (emission lines) or along the path length to the continuum source (absorption lines). For this reason, OH is less useful for studying the relationship between field strength and gas density, but it is more useful for studying the overall role of magnetic fields in cloud support since the field strength criterion of § 1 is cast in terms of the average field through the cloud as a whole.

3. OBSERVATIONAL RESULTS

3.1. OH Zeeman Results

At present, single-dish 18 cm OH Zeeman effect observations have yielded detections at 13 positions, and upper limits to the field of order 15 μG or less at 12 other positions. These results are given in Table 1 along with other relevant information. As noted by Crutcher, Kazès, and Troland (1987), OH Zeeman results apply to two different types of molecular clouds, those associated with OB star formation (warm clouds) and those that are not (cold clouds). The latter class includes nearby optically visible dark clouds. Results for the two types of clouds are listed separately in the table. Note that Zeeman results in the table for W22, W22 B, W49 B, and W51 apply to cold foreground clouds, not to the molecular clouds associated directly with the continuum sources. The ρ Ophiuchi cloud has been somewhat arbitrarily placed in the cold cloud category despite the presence of several embedded B stars, and the DR23 absorption line is listed with the warm clouds even though its association with the HII region is not clearly established.

Although statistics are sparse, it is clear that a systematic difference exists in field strengths measured for the two types of molecular clouds. The average of the (absolute) values of B_R for the warm clouds is about 75 μG, while that for the cold clouds (including non-detections) is only 9 μG. This difference almost certainly reflects a systematic difference in *sampled* density in the warm and cold clouds.

Zeeman effect detections in the warm clouds have all been made in OH absorption lines. These lines sample angular scales limited (by the sizes of the HII region continuum sources) to a few arc minutes or less. Moreover, lines of sight to the continuum sources are likely to pass through the densest regions of the molecular clouds near the sites of recent star formation. Conversely, most of the Zeeman effect observations (and low upper limits) in the cold clouds have been made in emission lines with the NRAO 43 m telescope having a beam width of 18′. These observations mostly sample lower density envelope gas, and they may be affected by partial cancellation of the Zeeman effect within the telescope beam.

The possibility of partial cancellation of the field within an 18′ beam is suggested by several factors. For one, cold cloud observations made in absorption (*e.g.* W22, W22 B, and W49 B) and in emission with the small Arecibo beam (*e.g.* B1, B1 SW) have generally resulted in the detection of higher fields than those allowed by the upper limits from the NRAO 43 m data. Also, aperture synthesis studies of the Zeeman effect in OH absorption lines toward S106 (Loushin, Crutcher, and Troland in preparation and elsewhere in this volume) have revealed a field reversal across the source on an angular scale of about 30".

TABLE 1. Field strengths derived from the 18 cm OH Zeeman Effect

Source	l^{II}	b^{II}	$B_R \pm \sigma$	Limit	Notes		Ref
Warm Clouds (*i.e.* with OB Stars)							
W40	28.79	3.48	-14 ± 3		A	NA	5
S88B	61.48	0.10	69 ± 5		A	NA	5
S106	76.38	-0.62	137 ± 17		A	GB	6
DR23	81.62	0.02	-60 ± 8		A	NA	8
W3	133.71	1.22	73 ± 7		A	NA	3
NGC 2024	206.54	-16.35	38 ± 1		A	NA	1
Orion A	209.04	-19.33	-125 ± 20		A	NA	4
Cold Clouds (*i.e.* without OB Stars)							
L 134	4.15	35.76	-3 ± 3	<13	E	GB	8
L 183	6.00	36.74	1 ± 5	<16	E	GB	8
W49 B	43.25	-0.18	21 ± 5		A	NA	5
W51	48.93	-0.29	-1 ± 3	< 9	A	NA	10
L 889	78.57	0.10	-1 ± 2	< 7	A	GB	5
Cas A	111.74	-2.12	9 ± 2		A	HC	2
B1	159.21	-20.12	-27 ± 4		E	AO	7
B1 SW	159.20	-20.19	-12 ± 5	<25	E	AO	11
L 1495	168.07	-16.55	5 ± 3	<13	E	GB	8
Taurus cloud	168.70	-15.59	1 ± 2	< 7	E	GB	8
L 1521	172.60	-14.50	0 ± 3	< 9	E	GB	8
Taurus cloud	173.91	-15.95	8 ± 3	<16	E	GB	8
TMC-1	174.43	-13.44	-2 ± 4	<13	E	GB	8
Orion cloud	212.13	-19.19	5 ± 4	<15	E	GB	8
ρ Oph core	353.08	16.66	-10 ± 3		E	GB	9
ρ Oph NE	353.33	16.80	1 ± 4	<14	E	GB	9
W22	353.15	0.66	18 ± 1		A	NA	3
W22 B	353.17	0.89	-32 ± 9		A	NA	5

Notes: A = absorption line, E = emission line. NA = Nançay Observatory 200 x 35 m, GB = Green Bank 43 m, AO = Arecibo Observatory 300 m, HC = Hat Creek Observatory 26 m.

References: (1) Crutcher and Kazès 1983; (2) Heiles and Stevens 1986; (3) Kazès and Crutcher 1986; (4) Troland *et al.* 1986; (5) Crutcher *et al.* 1987; (6) Kazès *et al.* 1988; (7) Goodman *et al.* 1989; (8) Crutcher, Troland, Goodman, Myers, Kazès, and Heiles, in preparation; (9) Troland, Heiles, Crutcher, and Kazès, in preparation; (10) Kazès, Troland, and Crutcher, in preparation; and (11) Goodman *et al.*, in preparation.

3.2. HI Zeeman Results

While not normally considered directly relevant to molecular clouds, HI Zeeman observations can have a bearing upon magnetic fields in these regions (§ 2.2). One of the very earliest Zeeman effect detections was in the HI absorption line towards Orion A. At 50 μG, this was long the highest field strength known in the interstellar medium outside maser regions. Subsequent aperture synthesis observations of the HI Zeeman effect toward Orion A (Troland, Heiles, and Goss 1989) established that B_R reaches 100 μG toward this source. More recent HI aperture synthesis observations reveal that B_R toward W3 exceeds 100 μG and even reverses direction over an angular scale of about one arc minute (Troland *et al.* 1989; van der Werf and Goss 1989). Field strengths of this order are never found in HI emission regions (Heiles 1987, 1988), they are comparable to those detected in the warm molecular clouds (including the OH absorbing region toward Orion A). A plausible conclusion is that the HI Zeeman effect toward these two sources is an indirect probe of magnetic field strengths in the molecular clouds from which the HII regions have formed.

3.3. Other Molecules

For reasons outlined in § 2.2, molecules other than OH have provided little information to date about the magnetic field in molecular regions. Two interesting and recent exceptions to this rule involve detection of the Zeeman effect in H_2O masers and in a 3 cm transition of CCS in the Taurus dark cloud region (Fiebig and Güsten 1989, Güsten and Fiebig in this volume, and Moran in this volume). Note that H_2O has no electronic angular momentum, yet the Zeeman effect is detected since the maser lines are so strong and the field strengths so high ($B_R \approx 0.1$ G).

4. IMPLICATIONS OF MAGNETIC FIELD OBSERVATIONS

4.1. The Dynamical Importance of the Field

The most fundamental question about magnetic fields in molecular clouds is the extent to which they are dynamically important (§ 1). The present results suggest that they often are important, and that many of these regions may be supported by the field in a subcritical state. For example, $N_p \approx 8 \times 10^{22}$ cm^{-2} for each of the clouds associated with S106 and S88B (Bally and Scoville 1982, Evans, *et al.* 1981), requiring a field of about 400 μG for support. Fields this high are known to exist in the S106 cloud from aperture synthesis studies (Loushin *et al.* in preparation). The single dish field for S88B is about a factor of six weaker. However, uncertainties in estimating N_p, and the possibility of field reversal in this cloud (as in S106), make the possibility of magnetic support very real. In the direction of the B1 core $N_p \approx 10^{22}$ cm^{-2} (Goodman, *et al.* 1989), requiring 50 μG for support. This figure is close to the value $B_R \approx 30$ μG actually measured for the region. In the envelopes of dark clouds $N_p \approx$ few x 10^{21} cm^{-2}, requiring supporting fields of order 10 μG. Present sensitivity limits preclude detection of fields this weak in most of these regions. However, 21 cm Zeeman effect observations establish that the field in HI regions associated with molecular clouds are of this order (Heiles 1987, 1988).

A possible counter example to this trend of magnetic support is the ρ Ophiuchi core. The $C^{18}O$ map of Wilking and Lada (1983) suggests $N_p \approx 10^{23}$ cm^{-2} over the region sampled for the Zeeman effect, hence a field of order 400 μG is necessary for support. The measured field is only of order 10 μG. In principle, a uniform 400 μG field could exist in the ρ Ophiuchi core so nearly in the plane of the sky that $B_R \approx 10$ μG. However, the *a priori* probability of so close an alignment is only 0.025. It is also possible that the field is quite tangled over the region sampled for the Zeeman effect. If so, this itself is a signal of the dynamical insignificance of the field. It seems very likely that the ρ Ophiuchi core is *not* supported by magnetic effects. Therefore, this region may be in a state of supercritical collapse as suggested by Shu *et al.* (1987).

A further indication of the dynamical importance of the magnetic field in many molecular regions comes from the analysis of Myers and Goodman (1988). They consider 14 molecular clouds (including cold clouds, warm clouds, and OH maser regions) for which Zeeman effect measurements exist, and they estimate the field strength required in each of these clouds for equilibrium between magnetic, kinetic and gravitational energies. They find good agreement between the estimated equilibrium fields and fields derived from the Zeeman effect studies.

4.2. Field Strengths and Gas Densities

The observed relationship between field strength and gas density cannot yet be sufficiently quantified to warrant detailed comparison with theoretical predictions. However, it is clear from the Zeeman results in warm and cold clouds that field strengths do tend to increase with increasing gas density. A very general comparison between observations and theory can be made from the work of Mouschovias. (See Mouschovias 1987.) These studies of magnetized self-gravitating clouds with dynamically important frozen-in fields suggest the following relationship for the magnetic fields B_c in the cloud *cores*:

$$B_c \approx 0.11\ [B_o/3\mu G]^{1/4}\ M^{1/4}\ n_c{}^{1/2}$$

In this equation B_o is field strength in the gathering cloud at the time it became self gravitating, M is the cloud mass in $M_\odot$, and n_c is the core density. B_o is essentially the average interstellar field strength, uncertainties in the value of B_o are of little relevance because of the weak dependence of B_c upon B_o. Taking representative values of $M \approx 10^{3.5} M_\odot$ and $n \approx 10^3$ cm^{-3} for the cold clouds and $M \approx 10^{4.5}$ $M_\odot$ and $n \approx 10^4$ cm^{-3} for the warm clouds, the equation predicts $B \approx 25$ μG for the former and $B \approx 150$ μG for the latter. The figure for warm clouds is quite consistent with observations for which $\langle B_R \rangle \approx 75$ μG and for which several measurements of B_R are greater than 100 μG.

The predicted field strength for cold clouds appears to be higher than allowed by observations. Indeed, limits set upon the field in many cold clouds are comparable to field strengths measured in HI regions. (See above.) However, the low limits set for field strengths in the cold clouds need not suggest a discrepancy with theory for several reasons. For one, the equation above applies to cloud *cores*, whereas observations of the OH Zeeman effect in emission sample primarily the envelopes around these cores. Also, reversal of the field may play a role in the OH emission measurements for which the beamwidth is large compared to scale sizes in the cold clouds. Finally, many of the regions studied for the OH Zeeman effect are in the Taurus-Orion region. If the field in this region lies primarily along the line-of-sight (as it might if it is parallel to the spiral arm), then existing Zeeman effect results for cold clouds might be biased toward low values.

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