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OH AND CN ZEEMAN OBSERVATIONS OF MAGNETIC FIELDS IN MOLECULAR CLOUDS

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RESUMEN

Observaciones del efecto Zeeman en OH y CN proveen información valiosa acerca del la magnitud del campo magnético y su dirección en nubes moleculares en el rango de densidad $10^3 < n(\mathrm{cm}^{-3}) < 10^6$, que estas especies muestrean. Los datos hacen posible probar las predicciones de formación de estrellas en el caso de campo débil, inducida por turbulencia y en caso de campo fuerte, inducida por difusión ambipolar. Aquí discutimos exactamente qué información pueden porporcionar las observaciones Zeeman y cómo los datos pueden ser analizados para proporcionar resultados significativos. Los datos implican que la razón media de masa a flujo en núcleos moleculares es $\sim 2-3$ veces la crítica, lo cual significa que los campos magnéticos generalemente no son suficientemente fuertes para prevenir el colapso gravitacional. Sin embargo, esta información acerca de las magnitudes medias del campo no es definitiva para excluir alguno de los dos modelos de formación estelar. Los datos actuales sugieren que los campos magnéticos juegan un papel importante en la evolución de las nubes moleculares y en el proceso de formación estelar. Finalmente, se discuten resultados muy preliminares de 2 estudios en proceso. Estos estudios tienen el potencial de ser significativamente más definitivos en probar las predicciones de la teoría de la formación estelar, y a lo mejor, discriminar entre las dos teorías.

ABSTRACT

Observations of the Zeeman effect in OH and CN provide valuable information about magnetic field strengths and directions in molecular clouds in the density range $10^3 < n(\mathrm{cm}^{-3}) < 10^6$ that these species sample. These data make it possible to test predictions of weak field, turbulence driven star formation and strong field, ambipolar diffusion driven star formation. Here we discuss exactly what information Zeeman observations provide and how those data may be analyzed to yield meaningful results. The data imply that the *mean* mass-to-flux ratio in molecular cores is $\sim 2-3$ times critical, which means that magnetic fields are generally not strong enough to prevent gravitational collapse. However, this information about mean field strengths is not definitive in excluding one or the other of the two models of star formation. Present data do suggest that magnetic fields play a very significant role in the evolution of molecular clouds and in the star formation process. Finally, very preliminary results are discussed from two in-progress studies; these studies have the potential to be significantly more definitive in testing the predictions of star formation theory, and perhaps in discriminating between the two theories.

Key Words: ISM: magnetic fields — stars: formation — techniques: polarimetric

1. INTRODUCTION

It has become increasingly clear that cosmic magnetic fields are pervasive, ubiquitous, and likely important in the properties and evolution of almost everything in the Universe, from planets to quasars, e.g., Wielebinski & Beck (2005). One area where the role of magnetic fields is far from being understood is star formation – an outstanding challenge of modern astrophysics. In spite of significant progress in recent years, there remain unanswered fundamental questions about the basic physics of star formation. In particular, what drives the star formation process? The prevailing view for most of the past 30 years has been that self-gravitating dense clouds are supported against collapse by magnetic fields, e.g., Mouschovias & Ciolek (1999). However, magnetic fields are frozen only into the ionized gas and dust, while the neutral material (by far the majority of the mass) can contract gravitationally unaffected directly by the magnetic field. Since neutrals will collide with ions in this process, there will be support against gravity for the neutrals as well as the ions. But there will be a gravity-driven drift of neutrals into the core without a significant increase in the magnetic field strength in the core; this is ambipolar diffusion. Eventually the core mass will become sufficiently large that the magnetic field can no longer support the core, and dynamical collapse and

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star formation can proceed. The other extreme from the magnetically dominated star formation scenario is that molecular clouds are intermittent phenomena in an interstellar medium dominated by turbulence, e.g., MacLow & Klessen (2004), and the problem of cloud support for long time periods is irrelevant. In this picture, clouds form and disperse by the operation of compressible supersonic turbulence, with clumps sometimes achieving sufficient mass to become self-gravitating. Even if the turbulent cascade has resulted in turbulence support, turbulence then dissipates rapidly, and the cores collapse to form stars. Hence, there are two competing models for driving the star formation process. The issue of what drives star formation is far from settled, on either observational or theoretical grounds.

The only available technique for directly measuring magnetic field strengths in molecular clouds is observation of the Zeeman effect in spectral lines that arise in molecular clouds. In this paper we discuss how Zeeman observations of magnetic fields in molecular clouds can distinguish between these models. In § 2 we describe the predictions of the two models that may be tested via Zeeman observations of magnetic fields. In § 3 we briefly review the Zeeman effect and what it actually tells us about interstellar magnetic fields, and in § 4 describe new observational results. In § 5 we discuss the results of the test of the two models. Finally in § 6 we discuss new observations and analysis techniques that may answer definitively the question – what drives star formation?

2. STAR FORMATION THEORY – PREDICTION AND OBSERVATIONAL TEST

The ambipolar diffusion and turbulence models for driving star formation have different predictions for magnetic field strength, which form the basis for tests of the two models using observations of magnetic fields. Of course, it is clear that there are both magnetic fields and turbulence in real clouds. In order to sharpen the distinctions between the two models, we will consider only turbulence models in which magnetic fields are negligibly weak and magnetic support/ambipolar diffusion models without turbulence. Here, we will discuss only the most clear-cut of possible tests of the two extreme-case models – the prediction and observation of mass-to-flux ratios.

The ratio of the mass in a magnetic flux tube to the magnitude of the magnetic flux is a crucial parameter for the magnetic support/ambipolar diffusion model. The critical value for the mass in a disk with uniform density that can be supported by magnetic flux Φ is $M_{B\mathrm{crit}} = \Phi/2\pi\sqrt{G}$ (Nakano & Nakamura 1978); the precise value of the numerical coefficient is slightly model dependant, e.g., Mouschovias & Spitzer (1976), who calculated the result for a more realistic density stratified disk model. It is convenient to state observed M/Φ in units of the critical value, and to define $\lambda \equiv (M/\Phi)_{\mathrm{obs}}/(M/\Phi)_{\mathrm{crit}}$. Inferring λ from observations is possible if the column density N and the magnetic field strength B are measured:

$$\lambda = \frac{(M/\Phi)_{\mathrm{obs}}}{(M/\Phi)_{\mathrm{crit}}} = \frac{mNA/BA}{1/2\pi\sqrt{G}} = 7.6 \times 10^{-21} \frac{N(H_2)}{B} \qquad (1)$$

where $m = 2.8 m_H$ allowing for He, A is the area of a cloud over which measurements are made, $N(H_2)$ is in cm^{-2}, and B is in μG.

Ambipolar diffusion model: Clouds are initially subcritical, $\lambda < 1$. Ambipolar diffusion is fastest in shielded, high-density cores, so cores become supercritical, and rapid collapse ensues. The envelope continues to be supported by the magnetic field. Hence, the prediction is that λ must be < 1 in cloud envelopes (models typically have $\lambda \sim 0.3 - 0.8$), while in collapsing cores λ becomes slightly > 1. Hence, this model tightly constrains λ.

Turbulence model: The turbulence model imposes no direct constraints on λ, although strong magnetic fields would resist the formation of gravitationally bound clouds by compressible turbulence. Also, if magnetic support is to be insufficient to prevent collapse of self-gravitating clumps that are formed by compressible turbulence, the field must be supercritical, $\lambda > 1$. λ may take any value > 1, although of course for the turbulence model with very weak magnetic fields that we are considering, clouds and cores will be highly supercritical, $\lambda \gg 1$.

3. THE ZEEMAN EFFECT

There are three main techniques for measuring magnetic fields that are applicable to molecular clouds: the Zeeman effect, linear polarization of thermal radiation from dust, and linear polarization of spectral-line emission (Goldreich & Kylafis 1981). See Heiles & Crutcher (2005) for a detailed discussion. Here we consider only the Zeeman effect.

First, the normal Zeeman splitting term $\delta\nu_z$ is proportional to B_{tot}, the total magnetic field strength, with the proportionality constant depending on the specific spectral line being observed. An essential point for the Zeeman effect is that if the Zeeman splitting $\delta\nu_z < \Delta\nu_{\mathrm{sl}}$, the width of the spectral line, only the line-of-sight component B_{los} of $\mathbf{B}$ can be determined. This is because a radio-telescope

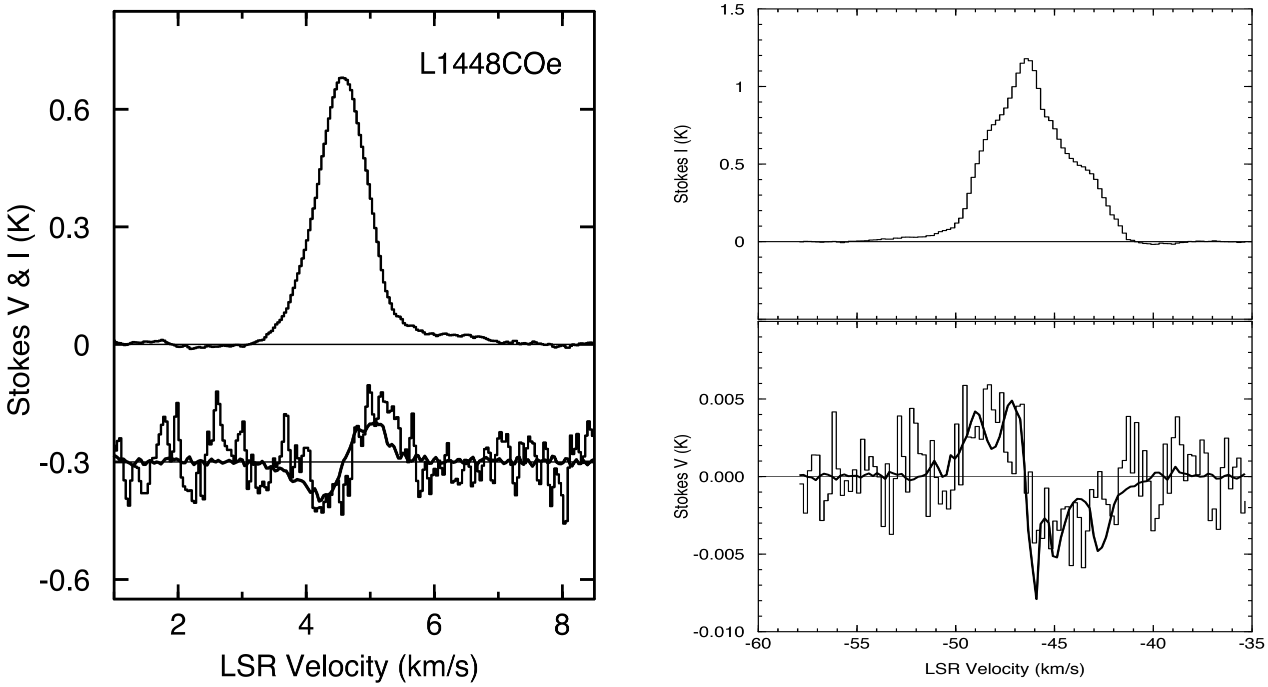

Fig. 1. Examples of the Arecibo OH (left) and IRAM CN (right) Stokes I and V spectra, toward L1448 (Troland & Crutcher 2008) and W3OH (Falgarone et al. 2008) respectively. Observed data are histogram plots; fits to Stokes V are the dark lines. In the OH figure V has been displaced by −0.3 K and multiplied by 10 for display purposes. The spectra are weighted averages of respectively the two OH main lines and the four CN hyperfine lines with strong Zeeman coefficients. The L1448 result is $\overline{B}_{\rm los} = -26\ \mu$G, while the W3OH result is $\overline{B}_{\rm los} = +1.1$ mG.

receiver sensitive (say) to left circularly polarized radiation will detect both the left elliptically polarized Zeeman σ component (which will be shifted by $\delta\nu_z$ from the rest frequency), half of the linearly polarized π (unshifted in frequency) component, and half of the linearly polarized part of the right elliptically polarized σ component (shifted in the opposite sense from the other σ component). This will "pull" the observed frequency of the "left" circularly polarized line toward the unshifted frequency; similarly for right circular polarization. The result is that the observed separation of the lines observed with receivers sensitive to left and right circularly polarized signals will be proportional to $B_{\rm los}$ and not $B_{\rm tot}$. In practice one observes the Stokes parameter V spectrum (the difference between the right and left circularly polarized line signals), with V $\propto dI/d\nu \times B_{\rm los}$. See Crutcher et al. (1993) for details. On the other hand, if $\delta\nu_z > \Delta\nu_{\rm sl}$, which can occur in some masers, such as OH, then the σ and π Zeeman components are resolved, the observed splitting is directly the Zeeman splitting $\delta\nu_z$, and $B_{\rm tot}$ is measured.

It is possible to infer statistical information about the total magnetic field strength in a sample of interstellar clouds by making assumptions. One assumption is that the direction of **B** in the clouds in the sample is random, so that the observed $B_{\rm los}$ range from zero up to the full magnitude of **B**. Another assumption concerns $\phi(B_{\rm tot})$, the probability density function (pdf) of the $B_{\rm tot}$ (the magnitude of the total strength of the 3D magnetic field) and its relation to $\psi(B_{\rm los})$, the pdf of the observed $B_{\rm los}$. Heiles & Crutcher (2005) have discussed this assumption. They considered four analytic functions to describe $\phi(B_{\rm tot})$: a Kronecker delta function, a flat distribution, a weighted Gaussian function, and a Gaussian function. The delta function is the form generally assumed (usually implicitly); this assumes that all clouds in a sample have the same $B_{\rm tot}$. Then both the mean and median values of $\psi(B_{\rm los}) = 0.50B_{\rm tot}$. One simply finds the mean or median value of the set of observed $B_{\rm los}$, and $B_{\rm tot}$ equals twice this value. The other assumed possible forms for $\phi(B_{\rm tot})$ all yield mean and median values for $B_{\rm los}$ roughly equal to $0.5B_{\rm tot}$. Hence, for purposes of inferring $B_{\rm tot}$ from a set of $B_{\rm los}$ measurements, the form of the distribution of $B_{\rm tot}$ within the set of clouds does not matter very much. This fact has made it possible to infer astrophysically meaningful results about interstellar magnetic fields from Zeeman observations.

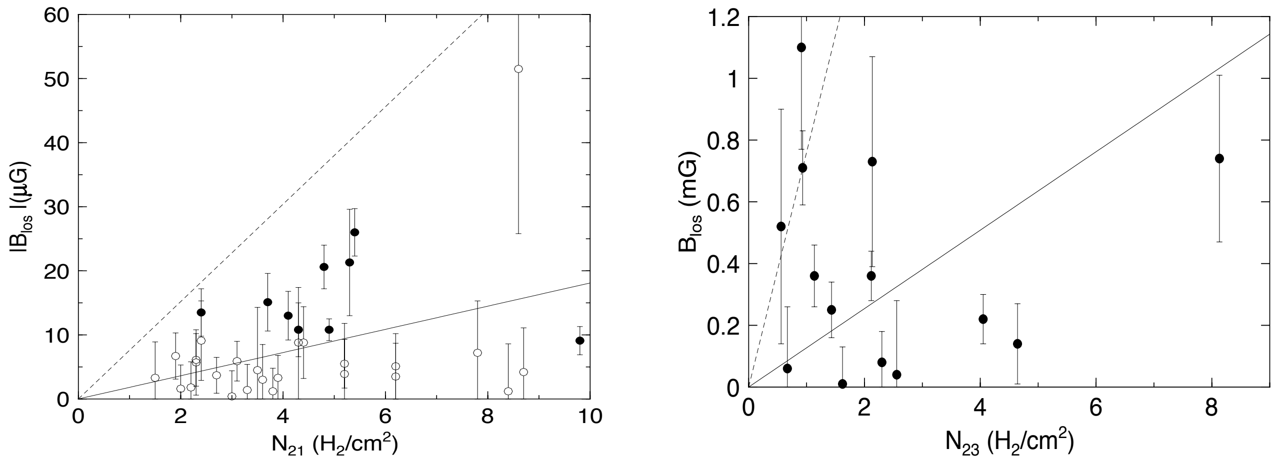

Fig. 2. Results for B_{los} from the Arecibo OH Zeeman dark cloud survey (left) and from the IRAM CN Zeeman study (right) plotted against the H_2 column density ($N_{21} = 10^{-21}N$, $N_{23} = 10^{-23}N$). Error bars are 1σ. The solid line is the weighted mean value for the mass to flux ratio with respect to the critical value, or λ, inferred from the Zeeman $B_{\rm los}$ data with no geometrical correction. For the OH data, $\lambda \approx 4.8 \pm 0.4$. After geometrical corrections (see text), $\lambda_c \approx 1.6$, or slightly supercritical. For the CN data, $\lambda \approx 6.0 \pm 0.5$. After geometrical corrections (see text), $\lambda_c \approx 2$, or again slightly supercritical. The dashed line is the critical mass to flux ratio, $\lambda = 1$.

Here, we shall discuss in detail only the information that can be extracted without knowledge of $\phi(B_{\rm tot})$. We find the mean or median value of the measured $B_{\rm los}$ and assume that $B_{\rm tot}$ equals twice this value. A further geometrical correction to the mean mass-to-flux ratio would be needed if the clouds or cores are flattened (Heiles & Crutcher 2005); this correction would decrease λ by 1.5. We have included this factor in the λ's discussed below.

4. NEW OH AND CN ZEEMAN RESULTS

Heiles & Crutcher (2005) reviewed observational results in the diffuse and molecular interstellar medium. New results have come from an extensive survey (Troland & Crutcher 2008) of the OH Zeeman effect toward dark cloud core positions, and from CN Zeeman observations (Falgarone et al. 2008) toward 14 high-mass star formation regions. Figure 1 shows an example of the Stokes I and V profiles from these two papers, and Figure 2 shows results for the mass-to-flux ratio.

The Troland & Crutcher (2008) survey of magnetic field strengths toward dark cloud cores involved ~ 500 hours of observing with the Arecibo telescope and obtained sensitive OH Zeeman observations toward 34 dark cloud cores. Nine new probable detections were achieved at the 2.5-sigma level. Their analysis included all the measurements and does not depend on whether each position has a detection or just a sensitive measurement. Rather, the analysis established mean (or median) values over the set of observed cores for relevant astrophysical quantities, such as $B_{\rm los}$. The results were that the total field $B_{\rm tot} \approx 16$ μG while the average density of the medium sampled is $n({\rm H}_2) \approx 3.2 \times 10^3$ cm^{-3}, and the mean mass-to-flux ratio is supercritical by ~ 1.6 (assuming a thin-disk geometry).

The Falgarone et al. (2008) paper reported new, sensitive CN Zeeman results and discussed these results plus earlier results, for a total of 14 star forming regions. The analysis was similar to that of Troland & Crutcher (2008). They found that the distribution of the line-of-sight field intensity, including non-detections, provided a median value of $B_{\rm los}$ that implied the total field $B_{\rm tot} \approx 0.56$ mG while the average density of the medium sampled is $n({\rm H}_2) \approx 4.5 \times 10^5$ cm^{-3}. They showed that the CN line probably samples regions similar to those traced by CS and that the magnetic field observed mostly pervades the dense cores. The dense cores are found to be critical to slightly supercritical with a mean mass-to-flux ratio $M/\Phi \sim 2$ (again assuming a thin disk geometry).

These new results essentially agree with those discussed by Crutcher (1999), especially when it is recognized that he analyzed only the 15 detected Zeeman results available at that time and did not consider the non-detections.

5. DISCUSSION AND CONCLUSION

Diffuse clouds with n(H I) ~ 50 cm^{-3} are significantly subcritical ($\overline{\lambda} \approx 0.03$) but not self-gravitating (Heiles & Troland 2005). Molecular clouds are slightly supercritical, $\overline{\lambda} \approx 2$. The change in λ from subcritical values in diffuse clouds to critical ones in molecular clouds may be the result of ambipolar diffusion, or could take place during the molecular cloud formation process, by material accumulating along flux tubes to form dense clouds, e.g., Hartmann, Ballesteros-Paredes, & Bergin (2001). Although this would not actually increase the mass-to-flux ratio in a flux tube, observers of individual H I clouds in the flux tube would infer a lower λ than would be found after H I clouds aggregate to form a single dense molecular cloud, since that would mainly increase the mass but not the flux. A combination of accumulation of matter within flux tubes, turbulence-driven ambipolar diffusion (Heitsch et al. 2004), and gravity-driven ambipolar diffusion may all be important at different stages in molecular cloud formation and collapse.

The data show that M/Φ is subcritical in H I clouds and approximately critical (slightly supercritical) in molecular clouds, in agreement with ambipolar diffusion. However, this result is not definitive, since turbulence simulations show a range in λ, from slightly subcritical to highly supercritical, and the above analysis assumes that $\phi(B_{\rm tot})$ is a delta function. But in any case, the available data clearly favor a significant role for magnetic fields in the star formation process.

6. THE FUTURE

The tests described above are limited by the fact that only one component of the three-component vector **B** can be measured, requiring statistical analysis that may not be convincing. However, there is a prediction of the ambipolar diffusion theory that is subject to a direct test, object by object. The theory absolutely requires that M/Φ *increase* from the envelope of a cloud to its core. On the other hand, "observations" of cores formed in converging turbulent flow simulations (see Dib 2006, private comm.) appear to show that M/Φ *decreases* with density. This decrease is really an artifact of how M/Φ is measured. It is never possible to measure the entire mass and magnetic flux in a flux tube. We measure and calculate M/Φ in discrete objects, such as clouds. If a uniform density gas in a flux tube fragments into multiple clouds and cores without (in this simple example) changing the field strength, the mass of a single cloud would be less than the total mass in the flux tube, but the magnetic flux would be unchanged. Hence, M/Φ would be found to decrease.

Because the turbulence simulations and the ambipolar diffusion models predict the opposite behavior of M/Φ with radius within a single cloud, observing the *differential* M/Φ between envelope and core should provide a definitive test. Even though only $B_{\rm los}$ can be measured via Zeeman observations, the angle between the regular magnetic field and the line of sight will be essentially the same between envelope and core. Moreover, if one uses the same species (such as OH) to measure $B_{\rm los}$ between envelope and core, the problem of knowing the abundance ratio [X/H] between the Zeeman species X and H is eliminated, at least to first order. Hence, detection of an increase in the differential M/Φ from envelope to core in a selection of molecular clouds with cores would provide very strong support for the ambipolar diffusion model. Such an observational program has been completed by Hakobian, Crutcher & Troland, who used ~ 250 hours of GBT observing time to obtain the requisite data for four dark cloud cores. They measured $N(OH)/B_{\rm los}$ toward four cores with Arecibo detections of $B_{\rm los}$ (Troland & Crutcher 2008) by observing at the four cardinal positions surrounding but excluding the cores. Together with the Arecibo results for the cores, the GBT results for the envelopes will yield the change in mass-to-flux ratio from envelope to core. Failure to detect the differential M/Φ predicted by ambipolar diffusion will be difficult for advocates of that theory to dismiss. On the other hand, success would provide powerful evidence for ambipolar diffusion. Very preliminary analysis appears not to yield the ambipolar diffusion prediction.

The analysis and discussion in § 4 and § 5 have used only information about the mean (or median) values of magnetic field strengths toward molecular cloud cores. However, there is now sufficient survey data that it is possible to attempt to infer the pdf of the total field strength, $\phi(B_{\rm tot})$, from the Zeeman observed pdf of the line-of-sight component, $\psi(B_{\rm los})$. Crutcher & Wandelt have begun such a study, using Bayesian analysis. The very preliminary results suggest that $\phi(B_{\rm tot})$ at a given molecular density is not a delta function, but a uniform distribution with $B_{\rm tot}$ varying from cloud to cloud from very small values to some maximum value. This would imply that the mass-to-flux ratio is also highly variable from cloud to cloud, so that the range would perhaps be from slightly subcritical to significantly supercritical. This very preliminary result would appear to agree better with the results of turbulent simulations than with the requirements for the strong field, ambipolar difusion driven model.

However, it must be kept in mind that both of the above very interesting results are preliminary ones from ongoing analyses.

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