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Magnetic fields in the non-masing ISM

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Abstract. Observations of the Zeeman effect in OH and H_2O masers provide valuable information about magnetic field strength and direction, but only for the very high density gas in which such masers are found. In order to understand the role of magnetic fields in the evolution of the interstellar medium and in the star formation process, it is essential to consider the maser results in the broader context of magnetic fields in lower density gas. This contribution will (very briefly) summarize the state of observational knowledge of magnetic fields in the non-masing gas. Magnetic fields in H I and molecular clouds may be observed via the Zeeman effect, linear polarization of dust emission, and linear polarization of spectral-line emission. Useful parameters that can be inferred from observations are the mass-to-flux ratio and the scaling of field strength with density. The former tells us whether magnetic fields exert sufficient pressure to provide support against gravitational contraction; the latter tells whether or not magnetic fields are sufficiently strong to determine the nature (spherical or disk geometry) of the contraction. Existing observations will be reviewed. Results are that the strength of interstellar magnetic fields remains roughly invariant at 5-10 microgauss between densities of $0.1\,\mathrm{cm}^{-3} < n(H) < 1,000\ \mathrm{cm}^{-3}$ but increases proportional to approximately the square root of density at higher densities. Moreover, the mass-to-flux ratio is significantly subcritical (strong magnetic support with respect to gravity) in diffuse H I clouds that are not self-gravitating, but becomes approximately critical in high-density molecular cloud cores. This suggests that MCs and GMCs form primarily by accumulation of matter along magnetic field lines, a process that will increase density but not magnetic field strength. How clumps in GMCs evolve will then depend crucially on the mass-to-flux ratio in each clump. Present data suggest that magnetic fields play a very significant role in the evolution of molecular clouds and in the star formation process.

Keywords. ISM: magnetic fields, techniques: polarimetric, stars: formation

1. Introduction

Observing polarization of electromagnetic radiation from the cosmos is the principal and most direct way to learn about cosmic magnetic fields. 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 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 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.

In this paper we discuss how 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 observations of magnetic fields. In §3 we briefly review polarization observational techniques for observing magnetic fields in molecular clouds and describe new observational results. In §4 we apply the tests and discuss the results. In §5 we summarize the conclusions about the role of magnetic fields in star formation, and finally in §6 suggest new observations that may answer definitively the question – what drives star formation?

2. Star formation theory – predictions and observational tests

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 two tests of the two extreme-case models.

2.1. *Test 1: mass-to-flux ratio*

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 $M_{Bcrit} = \Phi/2\pi\sqrt{G}$ (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 $\lambda \equiv (M/\Phi)_{obs}/(M/\Phi)_{crit}$. Inferring λ from observations is possible if the column density N and the magnetic field strength B are measured:

$$\lambda = \frac{(M/\Phi)_{obs}}{(M/\Phi)_{crit}} = \frac{mNA/BA}{1/2\pi\sqrt{G}} = 7.6 \times 10^{-21}\frac{N(H_2)}{B} \tag{2.1}$$

where $m = 2.8m_H$ 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 turbulent 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, $\lambda >> 1$.

2.2. *Test 2: scaling of B with ρ and σ*

The relationship between magnetic field strength and the volume density of gas is usually parameterized as $B \propto \rho^{\kappa}$. However, a dependence on the velocity dispersion σ may also be significant if turbulence plays a role in cloud support.

Consider first flux-freezing possibilities. If compression of the gas occurs parallel to the magnetic field, there will be no change in B, so $\kappa = 0$. If compression is orthogonal to the field, both the gas density and the field strength increase together, and $\kappa = 1$. Mestel (1966) showed that if the field is small enough to be dynamically unimportant, so gravitational collapse will be spherical, then $\kappa = 2/3$. Finally, if a cloud is supported parallel to the field by kinetic motions (thermal and/or turbulent) and orthogonal to the field primarily by the magnetic field, $\kappa = 1/2$ (Mouschovias & Ciolek 1999).

Ambipolar diffusion model: Clouds are subcritical before the formation of cores, with little change in B as ambipolar diffusion gradually increases the mass to magnetic flux ratio in the cloud center, forming a high-density core. Therefore κ for the cloud is small, $\sim 0.1 - 0.2$, in the early stages of evolution. Once the core becomes supercritical and rapid collapse ensues, the magnetic field is dragged inward with the collapsing gas, and κ gradually approaches 0.5; a typical value during the core collapse phase is $\kappa \approx 0.4$ (*c.f.*, Ciolek & Mouschovias 1994). The specific signature of ambipolar diffusion (as opposed to flux freezing in ideal MHD) is κ slightly less than 1/2. Little change in B takes place in the envelope during the entire process, however, so there is essentially no predicted correlation of B with ρ in the envelope.

Turbulence model: The correlation of field strength with other parameters has been discussed by several authors (*e.g.*, Mestel 1966; Padoan & Nordlund 1999; Basu 2000; Ballesteros-Paredes & MacLow 2002; Passot & Vazquez-Semadeni 2003). In the low-density case before gravity becomes important no relation is expected between the magnetic field strength and other parameters such as density. Hence, the prediction is similar to the ambipolar diffusion model, $\kappa \approx 0$. Once a clump becomes self-gravitating, neither magnetic fields (which are by assumption weak) or turbulence (which dissipates on roughly a free-fall time scale) can prevent approximately free-fall gravitational collapse; since magnetic fields are too weak to impose a preferred geometry, a spherical contraction is predicted. Flux freezing ($M \propto \Phi$, or $\rho R^3 \propto BR^2$) gives $R \propto B/\rho$, and a spherical collapse of a constant mass ($M \propto \rho R^3$) gives $R \propto \rho^{-1/3}$. Then $B \propto \rho^{2/3}$, so $\kappa = 2/3$. For the more general case of turbulent and magnetic field support, a rough equipartition of energies is achieved. Although clouds will generally not be in equilibrium, we can extract the form of the correlations if we assume virial equilibrium between gravity and turbulence ($3GM^2/5R = 3M\sigma^2/2$); then $\rho R^2 \propto \sigma^2$. Together with flux freezing, we find $B \propto \sigma\rho^{1/2}$. This is the same $\kappa = 1/2$ dependance discussed above with the inclusion of velocity dispersion term σ. In general σ varies much less than $n(H)$ among molecular clouds, so the dominant dependance would be expected to be the $B \propto \rho^{1/2}$ (but see Basu 2000).

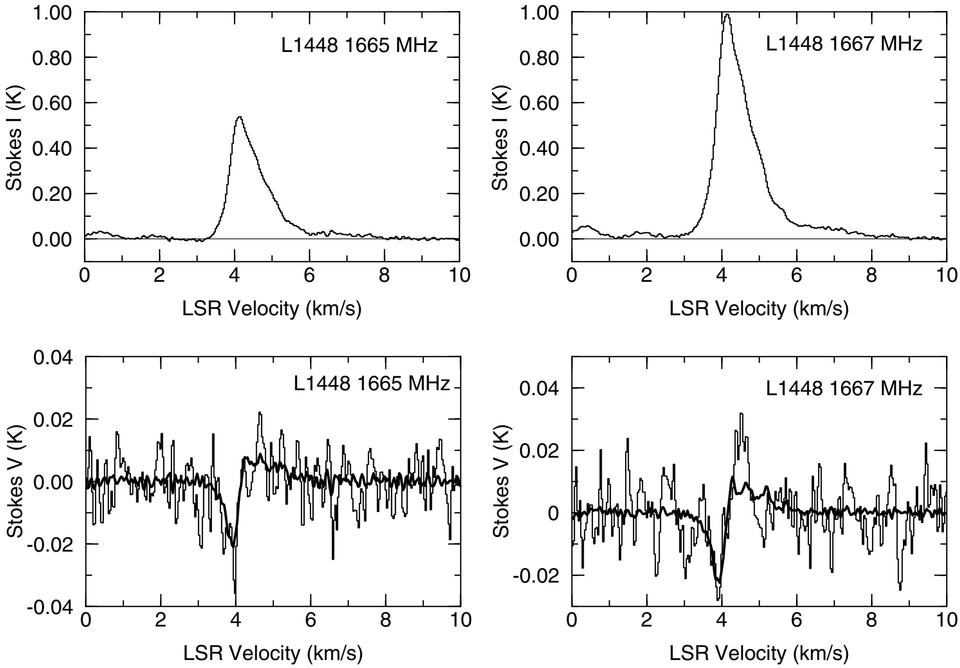

Figure 1. Arecibo Stokes I and V spectra of the 1665 and 1667 MHz lines of OH toward L1448. Observed data are histogram plots; fits to Stokes V are the dark lines. The combined result $\overline{B}_{los} = -26$ μG, together with $N(H_2) \approx 5 \times 10^{21}$ cm^{-2} inferred from the OH lines, yields a mass-to-flux ratio with respect to critical of $\lambda \approx 1.5$ (before any geometrical correction), which is nominally slightly supercritical.

3. Observational techniques and new results

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 due to the Goldreich-Kylafis (1981) effect. Space precludes detailed discussion; see Heiles & Crutcher (2005). But because maser studies of magnetic fields rely exclusively on the Zeeman effect, some brief comments about the Zeeman effect are worthwhile here. First, the normal Zeeman splitting term $\delta\nu_z$ is proportional to B_{total}, 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 $\delta\nu_z < \Delta\nu_{sl}$, the width of the spectral line, only the line-of-sight component B_{los} of **B** can be determined. This is because a radio-telescope 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 left and right circularly polarized lines will be proportional to B_{los} and not B_{total}. This is true whether the line is thermally excited or masing. See Crutcher *et al.* (1993) for details. On the other hand, if $\delta\nu_z > \Delta\nu_{sl}$, which can occur in some masers, such as OH, then the

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σ and π Zeeman components are resolved, the observed splitting is directly the Zeeman splitting $\delta\nu_z$, and B_{total} is measured.

It is possible to correct statistically for the fact that only $B_{los} = |\mathbf{B}|\cos\theta$ is what is usually measured. Averaged over an ensemble of clouds with random $\mathbf{B}$ orientation with respect to the line of sight, $\overline{B}_{los} = B_{total}/2$. If $\mathbf{B}$ is strong, clouds will have a disk morphology with $\mathbf{B}$ along the minor axis. To properly measure λ, one needs B and N along a flux tube, *i.e.*, parallel to the minor axis. For this case, $\overline{M/\Phi} = (M/\Phi)_{obs}/3$, and we define $\lambda_C = \lambda/3$. See Heiles & Crutcher (2005) for details.

Heiles & Crutcher (2005) reviewed observational results in the diffuse and molecular interstellar medium. New results have come from an extensive survey (Troland & Crutcher 2007) of the OH Zeeman effect toward 33 dark cloud core positions; there were 10 new detections. Fig. 1 shows an example of the Stokes I and V profiles, toward L1448.

4. Test results

In applying here the tests of star formation theory, I will use the following sources of data: the "Millennium" Arecibo H I, survey (Heiles & Troland 2005), the Vela cloud optical polarization survey (Pereyra & Magalhaes 2007, the Crutcher compilation (Crutcher *et al.* 1999), and the Arecibo OH cores survey (Troland & Crutcher 2007). The details of this analysis are preliminary, and additional data are available and will be added in the final analysis. Moreover, the exact values for the volume densities in the abscissa of the next two figures are preliminary estimates and will likely be modified for the final journal publication of this analysis. However, these modifications will not be systematic and will not affect the trends discussed below or the overall results and conclusions.

4.1. *Test 1 – M/Φ*

Figure 2 shows a plot of λ_C versus n(H), the volume density of protons. Error bars are not shown because they would overwhelm the figure. The n(H) have been estimated in various ways, in some cases are preliminary, and often have large uncertainties for individual points, but are not believed to be systematically in error. Although the statistical correction of 1/3 for geometrical bias has been applied to each point, so that statistically this plot should be valid, for any individual point the true λ could be higher or lower than the plotted λ_C. A large part of the scatter in figure 2 is therefore be due to geometrical projection effects. Moreover, all of the masses (column densities) have been estimated from trace constituents (dust, OH, CO, etc.); an uncertainly of ~ 2 probably exists in the mass estimates.

The results show two clear trends. Below $n(H) \sim 10^3$ cm^{-3}, the mass-to-flux ratio is clearly subcritical, with an apparent trend with density from highly subcritical to roughly critical. Because molecular clouds must form from more diffuse gas, study of λ in diffuse gas ($n < 10^3$ cm^{-3}) is relevant to star formation. Hartmann *et al.* (2001) pointed out that for the typical very diffuse ISM values $n(H) \approx 1$ cm^{-3} and $B \approx 5\ \mu$G (which would be highly subcritical), if the formation of clouds involves mass accumulation along field lines over distances greater than ~ 430 pc, eq. 2.1 implies that the resulting cloud will be supercritical. Accumulation over a flux tube with $R \approx 100$ pc and $L \approx 430$ pc would result in $\lambda = 1$ and $M \approx 3 \times 10^5\ M_\odot$ – a typical GMC mass. An intermediate step would be the formation of H I clouds, with $n(H\ I) \sim 50$ cm^{-3}. The Heiles & Troland (2005) "Millinium" survey results are for a mean $n(H) \approx 50$ cm^{-2}, and are subcritical by a factor ~ 10.

The results for $n > 10^3$ cm^{-3} are for molecular clouds. The data suggest that $\overline{\lambda} \approx 1$, or approximately critical. This agrees with the expectation for the strong magnetic field

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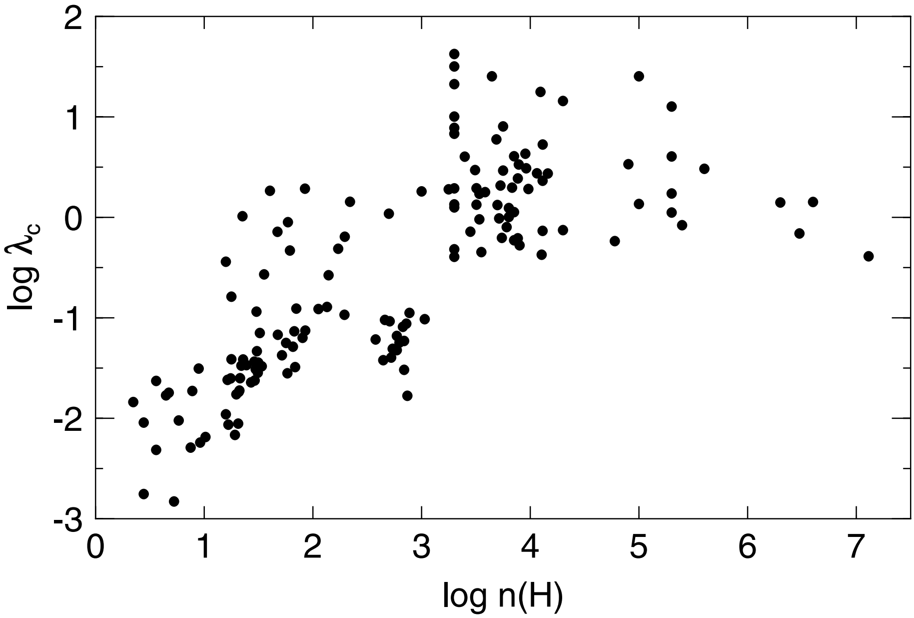

Figure 2. Observed, statistically corrected mass-to-flux ratios versus density.

model. While perhaps not fatal for the turbulence model, which predicts $\lambda > 1$ (strictly, $\lambda >> 1$), it certainly implies that magnetic fields are sufficiently strong that they cannot be neglected in models and simulations.

4.2. *Test 2 – B vs. ρ and σ*

At low densities $n \sim 0.1 - 100$ cm^{-3}, it has been clear for some time that there is no correlation of B with ρ (Troland & Heiles 1986); $\overline{B} \approx 5 - 10$ μG. At higher densities the earlier analysis (Crutcher 1999) showed that $B \propto \rho^{\kappa}, \kappa = 0.47 \pm 0.08$.

Figure 3 shows the total magnetic field strengths B_{total} versus the volume density of protons, n(H). Both the turbulence and magnetic support models predict little or no correlation between B and ρ at low densities, as observed. At higher densities, a weighted fit to the data yields $\kappa = 0.48 \pm 0.06$, consistent with the signature ($\kappa = 0.5$) of flux freezing for a cloud support by kinetic pressure parallel to the magnetic field and kinetic and magnetic pressure perpendicular to the field. The observations do not support the weak magnetic field, free-fall collapse prediction $\kappa = 2/3$. Breaking of flux freezing for the magnetically supported model by ambipolar diffusion would produce κ slightly less than 0.5; the present data are not sufficient to show whether this is the case or not.

5. Conclusions

The fact that the magnetic field strength is essentially constant ($B \approx 5 - 10$ μG) from the lowest densities in the interstellar medium up to the densities where molecular clouds are self gravitating provides a very significant clue about the formation of molecular clouds. If densities increased perpendicular to magnetic field lines, field strengths would increase linearly with density. Hence, molecular clouds must form primarily by

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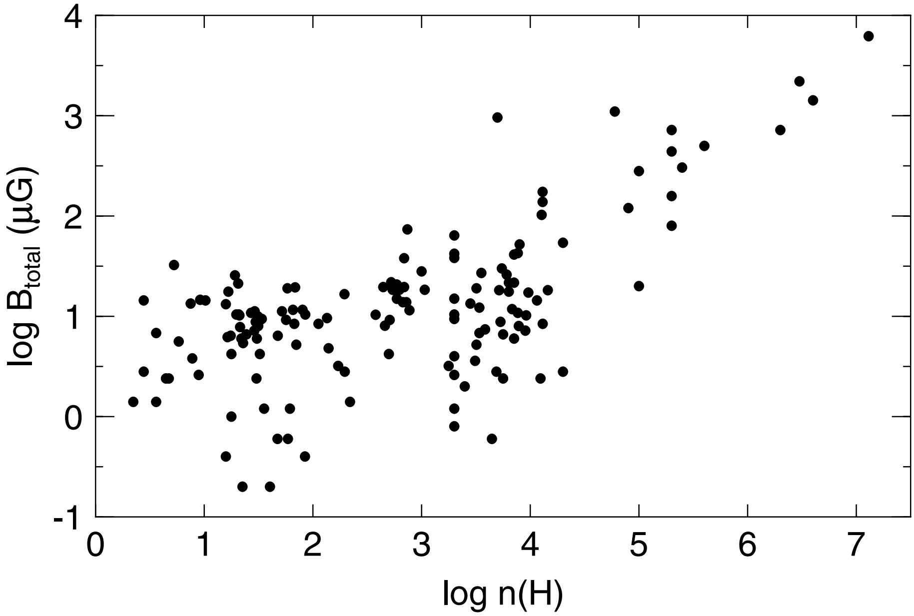

Figure 3. Observed, statistically corrected total magnetic field strengths versus density.

accumulation of matter along field lines. This process would increase densities but not field strengths.

Diffuse clouds with n(H I) $\sim$ 50 cm^{-3} are significantly subcritical ($\overline{\lambda} \approx 0.03$) but not self-gravitating. Molecular clouds are approximately critical, $\overline{\lambda} \approx 1$ (see figure 2). The change in λ from subcritical values in diffuse clouds to critical ones in molecular clouds probably takes place during the molecular cloud formation process, by material accumulating along flux tubes to form dense clouds (*e.g.*, Hartmann *et al.* 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. 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 in molecular clouds, in agreement with ambipolar diffusion. Also, the fact the κ seems to be inconsistent with 2/3 contradicts the weak field model. The available data clearly favor the strong magnetic field model of star formation.

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 (Dib 2006) appear to show that M/Φ *decreases* with density. Hence, observing the *differential* M/Φ between envelope and

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core should provide a definitive test. Even though only B_{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_{los} between envelope and core, the problem of knowing the abundance ratio [X/H] between the Zeeman species X and H is eliminated. One might suggest that [OH/H] would decrease from envelope to core due to astrochemistry, but this would not negate a test of ambipolar diffusion. A smaller [OH/H] between envelope and core would reduce the differential M/Φ between envelope and core – the opposite of the ambipolar diffusion effect. Hence, detection of an increase in the differential M/Φ in a selection of molecular clouds with cores would provide very strong support for that theory. Such an observational program has been approved. Crutcher & Troland will use the GBT to measure $N(OH)/B_{los}$ toward cores with Arecibo detections of B_{los} (Troland & Crutcher 2007) 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.

Acknowledgements

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