Triggered Star Formation in a Turbulent ISM
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Magnetic fields and star formation – new observational results

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Abstract. Although the subject of this meeting is triggered star formation in a turbulent interstellar medium, it remains unsettled what role magnetic fields play in the star formation process. This paper briefly reviews star formation model predictions for the ratio of mass to magnetic flux, describes how Zeeman observations can test these predictions, describes new results – an extensive OH Zeeman survey of dark cloud cores with the Arecibo telescope, and discusses the implications. Conclusions are that the new data support and extend the conclusions based on the older observational results – that observational data on magnetic fields in molecular clouds are consistent with the strong magnetic field model of star formation. In addition, the observational data on magnetic field strengths in the interstellar medium strongly suggest that molecular clouds must form primarily by accumulation of matter along field lines. Finally, a future observational project is described that could definitively test the ambipolar diffusion model for the formation of cores and hence of stars.

Keywords. Magnetic fields, stars: formation, ISM: clouds, ISM: magnetic fields

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. This Symposium is focused on triggered star formation in a turbulent interstellar medium. However, interstellar magnetic fields may play a significant or even dominant role in the star formation process by delaying the collapse of molecular clouds. The reduction of magnetic support through ambipolar diffusion may be an important triggering mechanism for star formation. It is therefore essential to test whether the predictions of models of star formation that include strong magnetic fields meet observational tests. In this paper we discuss how observations of magnetic fields in molecular clouds can test the strong magnetic field model of star formation, present the results of a major new study of magnetic field strengths in dark molecular clouds, summarize the conclusions about the role of magnetic fields in star formation, and suggest what new observations are necessary in order to answer more definitively the question – what triggers star formation?

2. Strong magnetic fields and star formation theory

Until recently, the prevailing view 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 flux 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 supposes that magnetic fields are too weak to dominate the star formation process, and that molecular clouds are intermittent phenomena in an interstellar medium dominated by turbulence (e.g., Elmegreen 2000; MacLow & Klessen 2004), and the problem of cloud support for long time periods is irrelevant. 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.

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 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 dependent (e.g., Mouschovias & Spitzer 1976). It is convenient to state M/Φ in units of the critical value, and to define $\lambda \equiv (M/\Phi)_{actual}/(M/\Phi)_{crit}$. Inferring λ from observations is possible if the column density N and the magnetic field strength B are measured:

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

where $m = 2.8 m_H$ 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.

In the strong field 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. 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, $\lambda > 1$.

3. The Zeeman effect

The Zeeman effect provides the only direct method for measuring magnetic field strengths in molecular clouds. Generally only those species with an unpaired electron will have a strong Zeeman splitting. This has limited detections to the the 21-cm line of H I, the 18-cm, 6-cm, 5-cm, and 2-cm Λ-doublet lines of OH, and the 3-mm N=1-0 lines of CN. The sole expectation is the 1.3-cm H_2O maser line, due to very strong line strengths and strong fields in H_2O maser regions.

Except for some OH masers, the Zeeman splitting is a small fraction of the line width, and only the Stokes V spectra can be detected (Crutcher *et al.* 1993); these reveal the sign (i.e., direction) and magnitude of the line-of-sight component B_{los}. By fitting the frequency derivative of the Stokes parameter $I(\nu)$ spectrum $dI(\nu)/d\nu$ to the observed $V(\nu)$ spectrum, B_{los} may be inferred.

It is possible to correct statistically for the fact that only one component of $\mathbf{B}$ is measured, i.e., $B_{los} = |\mathbf{B}| \cos\theta$. For a large number of clouds for which the angle θ between $\mathbf{B}$ and the observed line of sight is randomly distributed,

$$\overline{B}_{los} = \frac{\int_0^{\pi/2} |\mathbf{B}| \cos\theta \sin\theta d\theta}{\int_0^{\pi/2} \sin\theta d\theta} = \frac{1}{2}|\mathbf{B}|. \qquad (3.1)$$

If $\mathbf{B}$ is strong, clouds will have a disk morphology with $\mathbf{B}$ along the minor axis (cf, Mouschovias & Ciolek 1999). To properly measure λ, one needs B and N along a flux tube, i.e., parallel to the minor axis. Then, as noted by Crutcher (1999), the path length through a disk will be too long by $1/\cos\theta$ and N will be overestimated, while $|\mathbf{B}|$ will be underestimated by $\cos\theta$. Statistically,

$$\overline{M/\Phi} = \frac{\int_0^{\pi/2} (M/\Phi)_{obs} \cos^2\theta \sin\theta d\theta}{\int_0^{\pi/2} \sin\theta d\theta} = \frac{1}{3}(M/\Phi)_{obs}. \qquad (3.2)$$

4. Observing magnetic fields in dark clouds

4.1. *Previous work*

Most previous Zeeman detections in molecular clouds (e.g., Crutcher 1999) have been toward clouds associated with H II regions. Dark clouds offer the possibility of measuring the role of magnetic fields at an earlier stage of the star formation process. However, there have been very few Zeeman detections. Goodman *et al.* (1989) used the Arecibo telescope to observe three dark cloud cores, with one detection (Barnard 1, $B_{los} \approx 27$ μG) and two limits of ~ 10 μG. Crutcher *et al.* (1993) used the NRAO 140-foot telescope to observed 12 clouds and obtained two detections (Barnard 1 and ρ Oph, $B_{los} \approx 10$ μG) and 10 upper limits of ~ 10 μG.

4.2. *The Arecibo Dark Cloud Survey*

In order to improve our knowledge of magnetic field strengths in dark cloud cores, we have used the Arecibo telescope to carry out an extensive program to observe the Zeeman effect in the 1665 and 1667 MHz lines of OH. The project involved ~ 800 hours of allocated telescope time, of which more than 400 hours were actual on-source Zeeman integrations. Thirty-three dark cloud core positions were observed, with integration times ranging from ~ 2 to ~ 50 hours (the limited tracking range of the Arecibo telescope meant that a few positions were the only thing accessible for some periods of the day, so long integration times were accumulated). We achieved 10 detections of B_{los} at the $2-\sigma$ or better level, and sensitive upper limits on the other positions. Full details of this project will be published separately.

Figure 1 shows our Arecibo OH Stokes I and V spectra for L1448. B_{los} was inferred separately for each line, then the two results were weighted averaged to give the final result. L1448 is typical of the results for the detections. We used $2-\sigma$ as the cutoff for a detection, since our experience has shown that the random error computed from the least-squares fitting procedure underestimates the true uncertainty in Zeeman results, probably due to low-level instrumental polarization effects.

In order to compute the mass-to-flux ratio, we need an estimate for the column density of H_2. We obtain this estimate from the OH lines themselves. The Arecibo OH spectra yield N(OH). With OH/H $= 4 \times 10^{-8}$ (Crutcher 1979), we can infer N(H_2). This is not necessarily the total N(H_2) in the telescope beam, for OH does not sample the densest gas. However, N(H_2) inferred from N(OH) is the correct one to use, for it represents the

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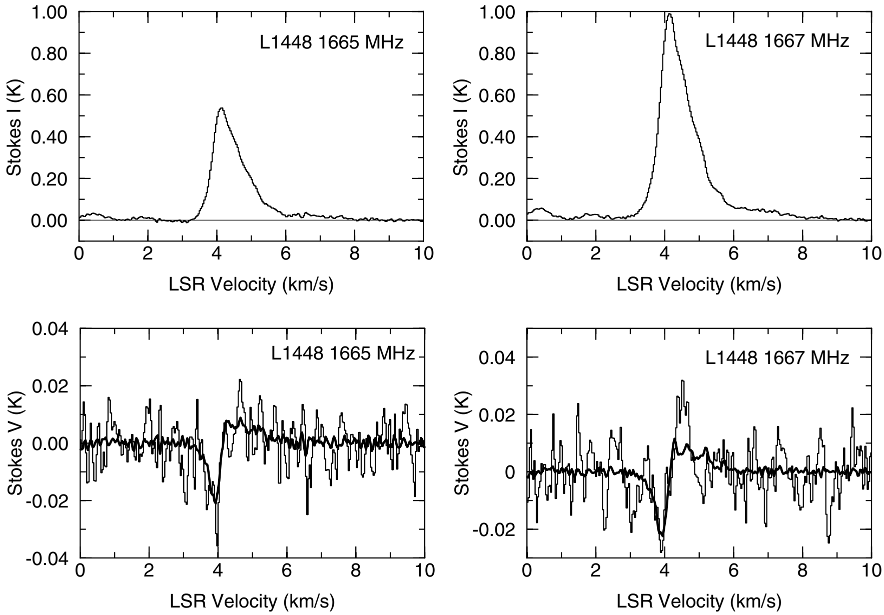

Figure 1. Arecibo Stokes I and V spectra of the OH 1665 and 1667 MHz lines of OH toward L1448. Observed data are histogram plots; fits to Stokes V are the dark lines. The respective results are $B_{los}(1665) = -25 \pm 5\ \mu$G, and $B_{los}(1667) = -28 \pm 6\ \mu$G. The combined result $\overline{B}_{los}$, together with $N(H_2) \approx 5 \times 10^{21}$ cm^{-2} inferred from the OH lines, yields a mass-to-flux ratio $\lambda \approx 1.6$ (before any geometrical correction), which is nominally slightly supercritical.

total H_2 column density within the telescope beam that is sampled by OH, and B_{los} inferred from OH represents the magnetic field in this same region.

4.3. *Arecibo survey mass-to-flux results*

Figure 2 shows all of the inferred results for B_{los} from the Arecibo survey plotted against $N(H_2)$. The importance of figure 2 is in what it can tell us about the mass-to-flux ratio in dark cloud cores. However, it must be kept in mind that all of the B_{los} results are *lower* limits to the total magnetic field strength. The statistical correction for this is given by equation 3.1. We apply this correction factor of 1/2 to equation 2.1 and plot the result as the solid line in figure 2. However, if strong magnetic fields result in a disk morphology for cloud cores, then a statistical correction for column densities along flux tubes is also necessary – equation 3.2. This prediction as plotted as the dashed line in figure 2.

5. Discussion

5.1. *The new Arecibo results*

First, note that there are no points in figure 2 that are a factor of 2 above the solid line. If the mean mass-to-flux ratio in these cores were subcritical, one would expect that a few of the magnetic fields would be pointing essentially along the line of sight, and one would see an unambiguous subcritical result without applying any statistical correction.

Second, although the detections scatter roughly equally above and below the solid line (the critical mass-to-flux line with the statistical correction for magnetic field only applied), almost all of the upper limits fall below this line. Even if every upper limit were

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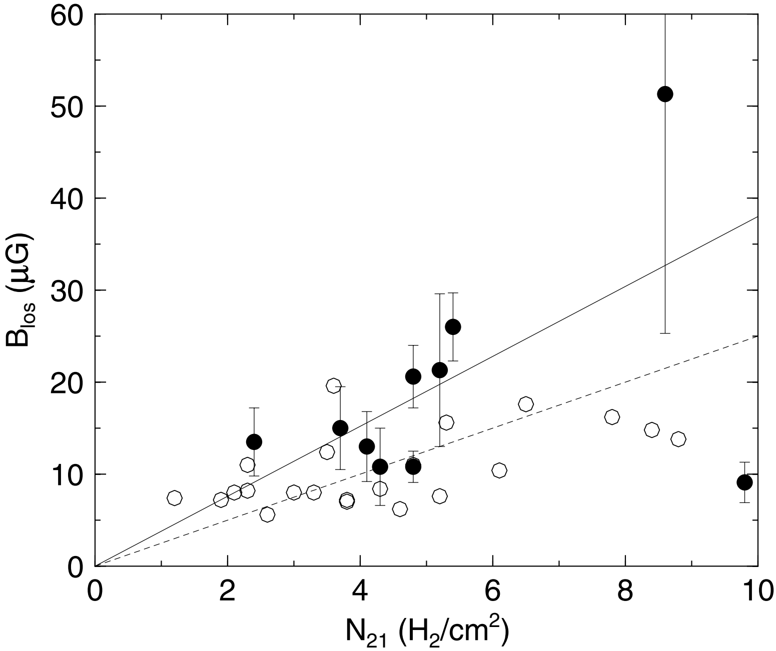

Figure 2. Results for B_{los} from our Arecibo dark cloud survey plotted against the H_2 column density ($N_{21} = 10^{-21}N$). The 10 detections are plotted as filled circles with 1σ error bars, while non-detections are plotted as open circles at the $B_{los} = 2\sigma$ positions. Straight lines are the mean predicted values of B_{los} vs. $N(H_2)$, after geometrical corrections, for a critical mass-to-flux ratio. The solid line applies only the statistical correction for measuring only one component of the magnetic vector **B**, while the dotted line applies also the correction for the column density in a disk geometry (see equations 3.1, 3.2).

later found to be a detection at the upper limit value, the conclusion would be that with no statistical correction for a disk geometry, the observed mean mass-to-flux ratio would be slightly supercritical ($\overline{\lambda} \approx 1.3$).

Finally, the detections and upper limits scatter roughly equally above and below the dotted line, where both the magnetic field and the disk geometry statistical correction (equation 3.2) have been applied. If all of the $2 - \sigma$ upper limits were detections at that level, the inferred $\overline{\lambda} \approx 0.8$, or slightly subcritical. Hence, the data are consistent with the prediction of the strong magnetic field theory – an approximately critical mass-to-flux ratio in cores with a disk morphology.

5.2. *The bigger picture*

The new data support and extend the earlier conclusion (e.g., Crutcher 1999, 2004) that the data are consistent with the strong magnetic field model of star formation. In addition, the data on magnetic field strengths in the interstellar medium lead to a strong conclusion about the formation of molecular clouds. First, diffuse clouds with n(H I) $\sim$ 50 cm^{-3} are significantly subcritical but not self-gravitating (Heiles & Troland 2005). 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

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a single dense molecular cloud. Second, magnetic field strengths have been found to be essentially invariant ($B \approx 5 - 10$ μG) over the density range $10^{-1} < n(H) < 10^3$ cm^{-3}, and to scale approximately as $B \propto \sqrt{n}$ for $n > 10^3$ cm^{-3}, when clouds may become gravitationally bound. The fact that the magnetic field strength is essentially constant from the lowest densities in the interstellar medium up to self-gravitating molecular clouds 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 accumulation of matter along field lines. This process would increase densities but not field strengths. There are possible ways out of this conclusion: magnetic reconnection, turbulence-driven ambipolar diffusion, magneto-rotational instabilities. But in studying triggered star formation, this fact about molecular cloud formation must be explained.

5.3. *The future*

The present situation is that the ambipolar diffusion model of star formation has neither been proved or disproved by observations of magnetic fields. A test that could do this is the measurement of the differential mass-to-flux ratio between the envelope and the core of clouds. The ambipolar diffusion model absolutely requires that mass-to-flux increase from envelope to core. This measurement can now be carried out by using a telescope such as the GBT to measure N(OH) and B_{los} in the envelope regions surrounding the cores where we have achieved Zeeman detections with the Arecibo telescope. Such a differential measurement would eliminate uncertainties due to geometry that we now can only account for statistically. Clear evidence for an increase in the mass-to-flux ratio from envelope to core within individual clouds would then verify the ambipolar diffusion prediction. Alternatively, if the test shows that this is not found, turbulence-driven star formation (although with dynamically important magnetic fields) would be favored.

Acknowledgements

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Discussion

VAZQUEZ-SEMADENI: Two comments: (1) Numerical simulations of MHD turbulence systematically show a lack of correlation of B with ρ. Passot & Vazquez-Semadeni (2003, A&A) gave an explanation, based on the fact that different types of nonlinear MHD waves have different scalings of B with ρ, so in a turbulent medium, where all modes coexist, there is no single preferred scaling at work. So, magnetic reconnection and nonlinear ambipolar diffusion are not the only possibilities. (2) As I'll argue tomorrow, λ is not a fixed parameter of clouds and clumps, but increases in time as the object accretes mass from its environment.

CLARKE: Your important conclusion that dark cloud cores are magnetically critical is based on the fact that both your detections and (more numerous) upper limits to B_{los} are roughly evenly distributed about the critical $\lambda = 1$ line. Higher sensitivity observations would support this conclusion only if the true λ of these non-detections was close to their current lower limit values. Given the importance of this issue, what is the prospect for converting these λ lower limits into detections?

CRUTCHER: It would be practical to improve the sensitivity of some of the non-detections where the integration time was fairly short, but this project has already involved a very large amount of observing time. In any case, some magnetic fields must lie close to the plane of the sky, so even if the total field strength were very large, the line-of-sight component B_{los} that the Zeeman observations can measure could be arbitrarily small. So it would be impossible to convert all upper limits to B_{los} (and hence lower limits to λ) into detections. The important point is that all of the Zeeman results are *lower limits* to the total magnetic field strength, even when a non-detection is an *upper limit* to B_{los}. That is why it is necessary to look at the predicted statistical fraction of detections and non-detections for a given sensitivity limit and an assumed λ in order to infer the most likely value of $\overline{\lambda}$. I think the conclusion that the mass-to-flux ratios in these dark clouds is *approximately* (within a factor of two) critical is solid; the data rule out a *mean* mass-to-flux ratio that is more than a factor of two supercritical, although of course some individual clouds without detections of B_{los} could be significantly supercritical.