OBSERVATIONS AND MODELS OF MAGNETIC MOLECULAR CLOUDS

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1. Introduction

In the last few years our knowledge of the strengths and directions of magnetic fields in molecular clouds has increased significantly. This paper briefly reviews observations of magnetic field strength and direction, compares such observations with equipartition models, and discusses the implications of these comparisons for the typical internal structure of the field in a molecular cloud.

2. Equipartition among Magnetic, Kinetic, and Gravitational Energy

Figure 1 summarizes 14 measurements of magnetic field strength B_{obs}, based on the Zeeman effect in lines of OH and H, and the equipartition field strength B_{eq}, compiled by Myers and Goodman (1988*a*, hereafter MG*a*). The equipartition field strength is calculated by assuming equality among the magnetic, kinetic, and gravitational energy densities, respectively $\mathcal{M}$, $\mathcal{K}$, and $\mathcal{G}$, for a uniform sphere with radius R, column density N, and FWHM velocity dispersion Δv. An equivalent statement of the equipartition is that the Alfven speed, velocity dispersion, and free-fall speed are equal. This three-way equipartition implies

$$B_{eq} = \frac{3}{8 \ln 2}\left(\frac{5}{G}\right)^{1/2}\frac{\Delta v^2}{R} = \frac{C\Delta v^2}{R}, \tag{1}$$

where G is the gravitational constant and $C \equiv 15\ \mu\text{Gkm}^{-2}\ \text{s}^2$ (Myers and Goodman 1988*b*, hereafter MG*b*). This expression for B_{eq} is consistent with that derived from the less restrictive, two-way equipartition $\mathcal{M} = \mathcal{G}$,

$$B_{eq} = 3\pi m\left(\frac{G}{5}\right)^{1/2} N = DN, \tag{2}$$

where m is the mean molecular mass and $D \equiv 4.2 \times 10^{-21}\ \mu\text{G cm}^2$ (*e.g.,* Chandrasekhar and Fermi 1953). Eq.(2) is better-known than eq. (1), but its comparison to observations is more difficult than for eq. (1) because regions of high density and field strength have column density N uncertain by a factor 10 or greater, while their line width Δv and the map size R are each usually uncertain by a factor less than 2.

Figure 1 shows that $B_{obs} = B_{eq}$ within a factor of about 2 for a range of three decades in field strength, from $\sim 10\ \mu$G to ~ 10 mG. Of the three new measurements of field strength reported at this meeting, two (in Barnard 1 and NGC 2024) appear consistent with B_{eq} within a factor 2, while one (in TMC-1C) is less certain because the field strength deduced from the Zeeman effect depends on molecular constants for the molecule CCS, which have not yet been verified by laboratory measurement.

3. Equipartition Field Strengths in Molecular Clouds

The line width Δv and cloud size R have been measured for hundreds of molecular clouds in numerous molecular lines, so one can estimate the equipartition field strength B_{eq} for many clouds

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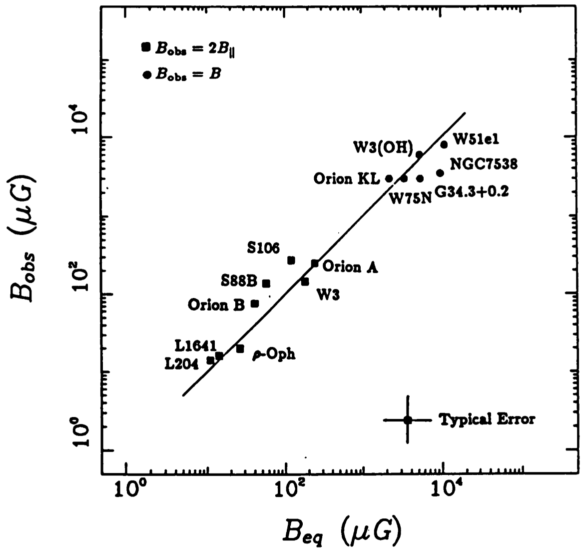

Figure 1: Magnetic field strengths observed (B_{obs}) and predicted (B_{eq}) in 14 molecular clouds and molecular cloud cores. B_{obs} is equal to either twice the line-of-sight component, $2B_{\|}$ (*filled squares*), or the total field strength, B (*filled circles*). The solid line indicates $B_{obs} = B_{eq}$; the error bars indicate estimated uncertainty of a factor of 2. From MG*a*.

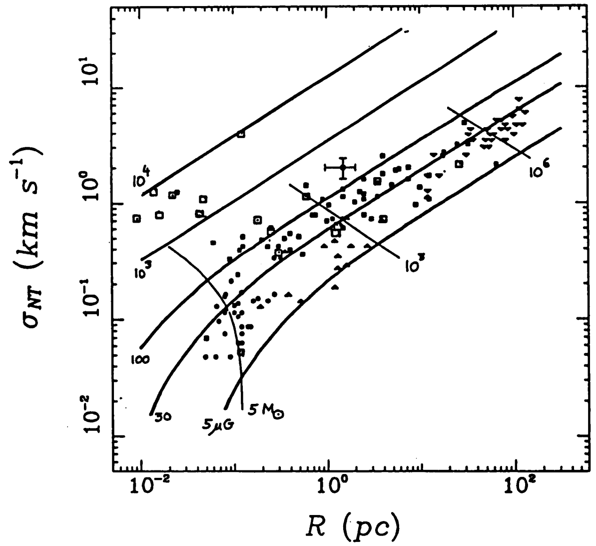

Figure 2: Nonthermal velocity dispersion *vs.* size for molecular clouds and cloud cores observed in several molecular lines. Curves show predictions of the model of equipartition among K, M, and G for a uniform sphere with temperature 10 K. *Heavy curves*, constant field strength as labeled; *light curves*, constant cloud mass as labeled. Adapted from MG*b*.

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using eq. (1), or a slightly more general version which distinguishes thermal and nonthermal kinetic energy (MG*b*). For this estimate we use the nonthermal part of the velocity dispersion,

$$\sigma_{NT} = \left(\frac{\Delta v^2}{8 \ln 2} - \frac{kT}{m}\right)^{1/2}, \qquad (3)$$

where k is Boltzmann's constant and T is the kinetic temperature. This allows for the relatively few clouds whose nonthermal line widths are small enough to be comparable to their thermal line widths: then the nonthermal and total line widths differ, and only the nonthermal part is attributed to magnetic origins.

Figure 2 shows the relation of σ_{NT} and R for more than 100 clouds observed primarily in lines of ^{12}CO, ^{13}CO, and NH_3(MG*b*). The values of σ_{NT} and R appear correlated, approximately according to $\sigma_{NT} \propto R^{1/2}$, as was first discussed by Larson (1981). The solid lines in Figure 2 show predictions of the three-way equipartition model for various field strengths B_{eq}. The data for the 14 clouds in Figure 1, which also have estimates of B_{obs}, are shown as open squares.

Most of the clouds represented in Figure 2 have equipartition field strengths within a factor 2 of 30 μG. If their true field strengths are generally close to their equipartition values, the relative variation of B is then small compared to the relative variation of R, and the correlation evident in Figure 2 is easily understood from eq. (1).

4. Spatial Structure of Magnetic Fields in Molecular Clouds

The apparent consistency of the equipartition field strength, derived from observed line widths, and the observed field strength, derived from the Zeeman effect, carries implications for the spatial structure of the field in molecular clouds. If the field were highly uniform, so that the mean field strength B were typically much greater than the characteristic spatial fluctuation in the field strength δB, then the observed velocity dispersion would arise solely from thermal and nonmagnetic turbulent motions. Its similarity to the Alfven speed, evident in Figure 1, would then be an unlikely coincidence. On the other hand, if the field were highly tangled, so that $\delta B \gg B$, then one would not expect to detect the Zeeman effect, which requires a nonzero component of the field along the line of sight; and one would not expect to observe the highly correlated field directions from point to point in dark clouds, deduced from the position angles of optical polarization of background stars (*e.g.,* Vrba, Strom, and Strom 1976; Goodman *et al* 1990, this volume). Thus it appears more plausible that $B \approx \delta B$, *i.e.* the mean and fluctuating component of the field are typically of the same magnitude.

If $B \approx \delta B$, the question of whether the typical self-gravitating cloud is supported by its magnetic field or by its internal "turbulent" motions becomes somewhat academic: the turbulent motions are primarily magnetic, and both sources of support are present, with about the same energy density. The origin of the fluctuations still requires explanation, and hydromagnetic waves appear to offer a plausible account, if their excitation is sufficiently energetic (*e.g.,* Arons and Max 1975; Shu, Adams and Lizano 1987).

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POUQUET: 3 methods of measuring B (Δv_{NT}; Zeeman; dust grain) lead you to conclude that $\vec{B}$ is slightly tangled. But at what scale, compared, for example, to the scale of velocity and/or density of clumps? On what range of scales does this argument (slight entanglement) hold?

MYERS: The apparent equality of B_{eq}, based on random motions, and $B_{\parallel}$, based on Zeeman effect, has been on scales ranging from about 10^{16} cm in clouds associated with masers and compact HII regions, to about 10^{19} cm in extended dark clouds. In L1641 and in S106 there is also some evidence for $B_{eq} \approx B_{\parallel}$ from scale to scale within each cloud. As your question suggests, it is important to establish the range of scales over which $B_{eq} \approx B_{\parallel}$ and at which scales it breaks down.

MOUSCHOVIAS: I would like to caution that using molecular line widths and masses of cores to infer magnetic field strengths is dangerous (especially at densities $\gtrsim 10^5$ cm^{-3}). Our results show that (1) ambipolar diffusion is in progress at these densities, and (2) the field strength is not due to the self-gravity of a core but due to that of the cloud as a whole.

To illustrate the latter point, consider a thought experiment: Remove the matter of the core and leave an empty cavity there, and ask what the field strength will be in the cavity. If the core's mass confined the field, the field would drop to zero (or at least to the intercloud value of ~3 μG). That cannot happen because the very large mass of the molecular cloud envelope confines the field, and its value in the cavity would be that which is appropriate to the *total* mass and the density of the cloud surrounding the core (see review by Mouschovias 1987, in *Physical Processes in Interstellar Clouds*, eds. G. Morfill and M. Scholer, Reidel, Dordrecht, p. 453, for the proper interpretation of line width as caused by hydromagnetic waves).

RUZMAIKIN: What is the physical meaning for the relation $B_{eq} \sim (\Delta v)^2/R$? It looks like a contradiction to the equipartition relation $B_{eq}^2 \sim n(\Delta v)^2 \sim (\Delta v)^2/R$ when $n \sim R^{-1}$.

MYERS: $B_{eq} \sim (\Delta v)^2/R$ arises from both (1) "virial" equilibrium $\Delta v \sim (GM/R)^{1/2} \sim \sqrt{\rho}\, R$ and (2) "magnetic" equilibrium $\Delta v \sim B/\sqrt{\rho}$. Eliminating ρ, the mass density, gives $B \sim \Delta v^2/R$. Eliminating Δv gives $B \sim \rho R$. In your question, $n \sim R^{-1}$ should read $n \sim BR^{-1}$, then $B \sim (\Delta v)^2/R$ follows. Physically, these assumptions represent an equipartition among kinetic, magnetic, and gravitational energy densities; or equivalently, an approximate equality of the line width, the Alfvén speed, and the gravitational escape speed.

MOUSCHOVIAS: For magnetically-supported self-gravitating clouds, the Alfvén speed is comparable to the free-fall speed (almost by definition). That is $v_A \approx V_{ff} \approx (GM/R)^{1/2} \approx (\pi G\sigma R)^{1/2}$, where $\sigma \equiv M/\pi R^2$, so that virialized line widths are naturally expected in such clouds. In other words, the motions responsible for supersonic line widths in molecular clouds are most likely *long-wavelength* hydromagnetic waves, which resemble large-scale oscillations (vibrational or rotational) within a cloud

(Mouschovias, 1975, in *Ph.D. Thesis*, Univ. of California at Berkeley) and which damp essentially on the ambipolar diffusion time scale (see review 1987, in *Physical Processes in Interstellar Clouds*, eds. G. Morfill and M. Scholer, Reidel, Dordrecht, p. 453, section 2.2). It is thus clear that $\Delta v \propto R^{1/2}$, but the proportionality "constant" is not constant at all! It depends on the column density σ (in g/cm^2). In fact, the scatter seen on $\log(\Delta v)-\log(R)$ plots may be just due to variations of σ from object to object; this should be looked into by our observer colleagues. The reason, I believe, the scatter about the $\Delta v \propto R^{1/2}$ line is not much larger than that observed, is due to the fact that the background magnetic field does not depart much from ≈3 μG and, for magnetically-supported clouds, $\sigma \propto B$ (see equation (3c) in the review cited above).

MYERS: One might expect the relation $B \propto \rho^{1/2}$ to apply to *non*-self-gravitating clouds, in addition to self-gravitating clouds. If the line width is comparable to the Alfvén speed then $B \propto \Delta v\, \rho^{1/2}$. Now in all known interstellar clouds the range of Δv is about two orders of magnitude, while the range of $\rho^{1/2}$ is about five orders of magnitude. Then the smaller range of Δv will appear as a constant of proportionality and $B \propto \rho^{1/2}$ will result.

DOGIEL: Two comments:
1. Besides the influence of an ambipolar diffusion inside molecular clouds on the structure of magnetic field the processes of magnetic field amplifi-ations by gas turbulence need to be taken into account. According to our calculations the last process can provide magnetic field fluctuation spectra which differ from those expected from the equilibrium conditions, especially in the subsonic scale range of gas motions.
2. I would like also to notice the importance of the results presented by Dr. Myers. If small-scale magnetic field fluctuations are of an order of large-scale magnetic field in clouds, the CR propagation there differs from that previously supposed.

SHUKUROV: We have heard today about a nice agreement between theory and observations of magnetic clouds. Nobody feels comfortable with this unusually good agreement. I'd like to try to add a problem. As Dr. Dogiel has mentioned, there should be chaotic magnetic fields within the clouds whose strengths are comparable with the regular field strength. This chaotic field cannot be revealed by Zeeman measurements but it contributes to magnetic pressure and ambipolar diffusivity (the latter quantity can suffer a change by the factor of 4). Is this chaotic field included in equilibrium and dynamic models of interstellar clouds?

HEILES: In order to measure both $B_\parallel$ and $B_\perp$ from the Zeeman effect, we must measure not only circular but also linear polarization. The linear polarization comes from the π components. These are not easily measured in the case of line splitting $\delta\nu \ll$ the line width $\Delta\nu$. In this case, the Stokes V spectrum is left-right circular $\propto \delta\nu/\Delta\nu$. In contrast, the Stokes Q and U spectra $\propto (\delta\nu/\Delta\nu)^2$. If $\delta\nu/\Delta\nu \sim 10^{-3}$, then it requires $\sim 10^6$ times more integration time simply for detection. The sensitivity requirements are prohibitive unless $(\delta\nu/\Delta\nu)$ is not too small.

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