Magnetic Fields in Dense Interstellar Clouds [and Discussion]

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Magnetic fields in dense interstellar clouds

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Evidence is presented that shows that magnetic fields pervade the entire interstellar medium including interstellar gas clouds of both low and high density. The magnetic field in the 'seed' gas from which the denser clouds form is 0.2–0.3 nT (1 T = 10^4 G). Zeeman effect measurements of neutral hydrogen show that stronger fields occur in denser clouds. These data, taken with the microtesla fields found in OH maser sources, indicate that magnetic flux is conserved during gravitational collapse of interstellar clouds from densities of *ca.* 5 to *ca.* 10^7 cm^{-3}. Magnetic fields appear to play a major role in the formation of dense interstellar clouds. Furthermore there is a strong indication that the magnetic field direction is preserved during cloud collapse.

1. Introduction

Magnetic fields pervade the Galaxy; they play a crucial role in many astrophysical phenomena. The linear polarization of starlight is produced by scattering on aligned dust grains. The pattern of alignment in the polarizations of the assembly of stars as projected on the sky indicates a systematic arrangement of magnetic fields in the nearby spiral arms accessible to optical study. On the large scale, relativistic electrons spiralling in magnetic fields generate radio-synchrotron emission, which is detected throughout the disc of the Galaxy and possibly in a weak extended halo. Similarly the Faraday rotation, in the Galactic electron and magnetic field distribution, of the linearly polarized emission of pulsars and extragalactic radio sources demonstrates the pervading nature of the magnetic field in the Galaxy. Because of the strong coupling of the magnetic field to the interstellar plasma, magnetic fields play a major role in astrophysical phenomena in the interstellar medium. These phenomena include shocks, gravitational collapse of clouds and star formation. In this paper I explore the evidence for the strength and arrangement of magnetic fields in interstellar clouds ranging in density from *ca.* 1 to *ca.* 10^8 cm^{-3}. It is concluded that molecular clouds with densities in this range contain magnetic fields whose strength is determined by the compression of the intrinsic interstellar field consequent upon cloud collapse.

I shall first describe the physical conditions within the interstellar medium from which the denser clouds ultimately form. Neutral hydrogen is mainly clumped into clouds with typical densities of 14 cm^{-3} and diameters of 7 pc; 11 such clouds are found per kiloparsec in spiral arm regions (Takakubo & Van Woerden 1966). Clouds with a range of sizes and densities have been identified; however, a significant amount of neutral hydrogen is also found in regions between clouds. Half of all the H I seen in emission from the spiral arms may be in this form, having an average density of 0.5 cm^{-3} and a kinetic temperature of 2–5000 K (Radhakrishnan *et al.* 1972); Davies & Cummings 1975). In addition, a distribution of high-density low-temperature H I clouds is seen in absorption against background radio sources. These have densities ranging up to *ca.* 100 cm^{-3} and kinetic temperatures extending down to *ca.* 30 K. Two or three such clouds are found per kiloparsec in the nearby spiral arms.

The mean electron density in the disc of the Galaxy, derived from the dispersion measure of pulsars, is 0.03 cm^{-3}. This value, combined with the observed Faraday rotation of pulsars, indicates that the magnetic field of the Galaxy is 0.2–0.3 nT (Manchester & Taylor 1977). Faraday rotation measurements of extragalactic radio sources are consistent with these values. A basic assumption in making this estimate of the magnetic field strength is that the electrons and magnetic field are similarly distributed along the line of sight to the pulsars. This assumption can be shown not to be seriously in error as follows. An independent estimate of the electron density can be derived from low radio frequency absorption measurements which give values for the emission measure in the Galactic disc. I shall show in the next section that the magnetic field in H I clouds is of the magnitude expected for fields of a few tenths of a nanotesla in the background interstellar gas composed of 'normal' clouds and intercloud gas. Thus the Faraday rotation measurements indicate that the magnetic field permeates the bulk of the interstellar gas.

2. MAGNETIC FIELDS IN H I CLOUDS

Magnetic field strengths in interstellar H I clouds can be determined from the frequency displacement of the right-hand and left-hand circularly polarized components. The observed displacements (28 Hz per millitesla) are typically one thousandth of the line width. The most readily detected magnetic fields are those in the narrow features seen in absorption against strong radio sources. (These measurements detect the line-of-sight component, $B_{\parallel}$, of the magnetic field). After successively more sensitive searches for the Zeeman effect in H I clouds, magnetic fields have now been detected unambiguously in the absorption spectra of four radio sources: Cas A, Orion A, M 17 and Taurus A. Several narrow absorption features are detected in the spectrum of each of these sources and magnetic fields can be assigned to each feature. The fields detected lie in the range 0.5–4.7 nT (see, for example, Verschuur 1970; Brooks *et al.* 1971; Reif *et al.* 1978; Davies *et al.* 1981). Significant limits with $B_{\parallel} \lesssim 0.5$ nT have been set to several other absorption features.

It is equally important to attempt to measure, or at least to set sensitive limits to, the magnetic fields in emission clouds. These are the 'normal' clouds in which the seed magnetic field of the Galaxy resides. In our picture this magnetic field is compressed and amplified in the higher-density H I clouds seen in absorption or in the OH maser clouds. Zeeman effect measurements have been made of individual emission clouds that can be isolated at intermediate latitude. Other measurements have been of the integrated emission from spiral arms as seen at low latitudes. Long integrations have given r.m.s. errors of approximately 0.1 nT.

The magnetic field for each feature can be compared with its gas density as derived from the parameters of its H I profile. H I data for the absorption clouds are available from Radhakrishnan *et al.* (1972), Davies & Cummings (1975) and Lockhart & Goss (1978). A value of H I density of 5 cm^{-3} was adopted for the emission clouds in the spiral arms. For intermediate latitude clouds the H I density is derived directly from the integrated profile and the measured cloud diameter.

Figure 1 shows all the magnetic field data from the various high sensitivity H I Zeeman experiments plotted against the hydrogen density, n(H). There is clearly a scatter in the value of $B_{\parallel}$ measured for different clouds of the same density. There are several factors that lead to

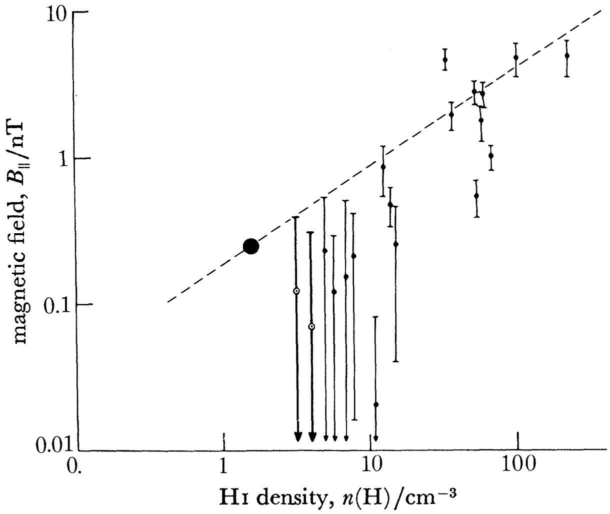

FIGURE 1. The line-of-sight component of magnetic field in H I clouds ($B_{\parallel}$) measured by the Zeeman effect plotted against the estimated H I density of the clouds ($n(\mathrm{H})$). The filled circle represents the interstellar magnetic field measured from pulsar Faraday rotation; the assigned gas density is the mean density in spiral arms. The two lowest points with heavy error bars represent the mean magnetic fields found in the Orion and Perseus spiral arms. The dashed line is the relation $B \propto n(\mathrm{H})^{\frac{2}{3}}$ expected for the isotropic collapse of a self-gravitating cloud with a frozen-in magnetic field.

this scatter. The most important is that the Zeeman effect measured in the small field clouds studied here gives a value for $B_{\parallel}$, the line-of-sight magnetic field. There is also an uncertainty in estimating $n(\mathrm{H})$ for a given cloud, particularly when there is only an absorption measurement, and values for the spin temperature and cloud diameter are required for the estimate. A further scatter may arise because of the intrinsic scatter in the magnetic field strength in the original clouds, which have subsequently been compressed; this factor will be discussed later. Also shown in figure 1 is the magnetic field derived for the interstellar medium from pulsar dispersion and Faraday rotation data. A gas density of 2 cm^{-3} has been assigned to this field strength of 0.25 nT. To make this value of the field comparable with the Zeeman measurements the latter should be increased by $\sqrt{2}$ to account for the deprojection effects mentioned above. The theoretical curve of $B \propto n(\mathrm{H})^{\frac{2}{3}}$ expected for field compression in spherically symmetric clouds is shown for comparison.

It should be emphasized that the denser clouds ($n(\mathrm{H}) \gtrsim 20\ \mathrm{cm}^{-3}$) in figure 1 contain molecules. In the direction of strong radio sources Davies & Matthews (1972) found column densities of H_2CO and OH of 2×10^{12} and $10^{14}\ \mathrm{cm}^{-2}$ respectively in typical clouds represented in figure 1. These same clouds contain detectable amounts of CH, typically at $2 \times 10^{13}\ \mathrm{cm}^{-2}$ (Rydbeck *et al.* 1976) and of HCN, typically at $4 \times 10^{11}\ \mathrm{cm}^{-2}$ (Encrenaz *et al.* 1980).

3. MAGNETIC FIELDS IN OH MASER CLOUDS

OH masers are found throughout the Galaxy associated either with regions of star formation or with circumstellar shells around evolved stars. We are concerned here with gas clouds involved in star formation, where masers characteristically emit over a range of transitions with the highest brightness temperatures (up to 10^{12} K) in the 1665 and 1667 MHz lines of the

$^2\Pi_{\frac{3}{2}}$, $J = \frac{3}{2}$ state. Long baseline interferometers show that the emission comes from maser hotspots with angular sizes of a few thousandths of a second. It is generally believed that these hotspots represent the projection of lines of sight that have above average maser gain in a restricted velocity interval. The masing molecules form part of the compact cloud of neutral gas and dust surrounding, or adjacent to, a compact H II region. Estimates of the gas density in the maser columns are subject to some uncertainty because of the uncertain state of saturation of the maser and because of the lack of knowledge about the level of population inversion in the maser. Most estimates place the hydrogen density of OH masers in the range 10^6–10^8 cm^{-3} over dimensions of 10^{16}–10^{17} cm (see, for example, Litvak 1971). Apart from the H_2O masers, for which there is no magnetic field information, the OH masers represent the highest density molecular clouds available for study. The majority of the widely studied clouds such as the Orion cloud and the dense dust clouds have hydrogen densities in the range 10^3–10^5 cm^{-3}.

Most OH maser components are strongly circularly polarized with only a small amount of linear polarization, which is largely removed by differential Faraday rotation in the source. The polarization structure is the result of Zeeman splitting of components in fields of 0.2–1.0 μT. Fields of this magnitude are sufficient to displace the left-hand and right-hand components by an amount similar to the Doppler broadening (a few kilometres per second) in the line-emitting cloud. The amplification of any particular Zeeman component will be a function of the velocity and magnetic field distributions along the line of sight (Cook 1966). As a consequence the emission spectrum will not conform to the expected Zeeman pattern nor will left-hand and right-hand components necessarily come from precisely the same position (Davies 1974). Reliable estimates of the magnetic field strengths in OH maser clouds associated with regions of star formation can be made either from the integrated (single telescope) spectra in both circular polarizations of the various transitions or from the velocity displacement of the left-hand and right-hand components identified in adjacent areas of long baseline interferometer maps. It turns out that the circular polarized spectra of the 6035 MHz ($^2\Pi_{\frac{3}{2}}$, $J = \frac{5}{2}$, $F = 3 \rightarrow 3$) transition provide the most unambiguous estimators of magnetic field strengths in OH maser clouds.

I conclude that typical OH masers have magnetic fields of 0.2–1.0 μT throughout the maser region, which has a hydrogen density of $10^{7\pm1}$ cm^{-3}. In OH masers the fields are the true intrinsic fields and not the projected line-of-sight fields as in the H I Zeeman measurements.

4. Magnetic fields in collapsing clouds

(a) *Compression of gravitationally contracting clouds*

The form of the plot of B against $n(\mathrm{H})$ in figure 1, which shows that higher density clouds have stronger magnetic fields, suggests that as the density of clouds builds up the magnetic field is also compressed. This is the situation expected to arise from the freezing of the magnetic field to the gas described in § 1. The compression of a frozen-in magnetic field during the gravitational collapse of a gas cloud has been described by several authors (see, for example, Mestel 1965); Mouschovias 1976). In a cloud that maintains its spherical shape, B is proportional to $n(\mathrm{H})^{\frac{2}{3}}$. More realistic geometries can be envisaged in which the cloud flattens under the influence of a supporting magnetic field in the plane perpendicular to the field direction. The magnetic field balances the inward pressure due to gravity and the confining gas between clouds. Mouschovias finds $B \propto n(\mathrm{H})^k$, where $\frac{1}{3} < k < \frac{1}{2}$ for various realistic models.

The above discussion is based on the assumption that the magnetic energy of the cloud is comparable with the gravitational energy. With the magnetic fields and densities given here this assumption can be justified. For example, a cloud with $n(\mathrm{H}) = 100\ \mathrm{cm}^{-3}$ and a radius of 5 pc has an equilibrium magnetic field of 0.6 nT. These cloud parameters are consistent with those given in figure 1, confirming that the magnetic field is the major support for dense clouds. It is worth noting that for cloud collapse under isotropic conditions the ratio of magnetic to gravitational energy remains constant, and hence, so long as the magnetic flux is not destroyed, the magnetic field will continue to be the major support throughout the collapse. Thermal and turbulent motions, which make up the virial energy, do not contribute significantly to the positive energy of the clouds (see, for example, Baker 1979).

The strong magnetic fields in the OH maser clouds can be considered as the result of the gravitational collapse from the lower density H I clouds. Evidently the H I clouds with masses of *ca.* $10^3 M_{\odot}$ fragment and only a small fraction (*ca.* 1–10 %) form into OH maser clouds with densities of $10^{7\pm1}\ \mathrm{cm}^{-3}$. The index k describing the magnetic field enhancement as a function of gas density is 0.47 ± 0.05 over the range of cloud densities represented by H I and OH maser measurements. This result, and the fact that the gravitational energy and magnetic energies are also comparable in OH maser clouds, indicate that very little magnetic flux is lost in the collapse, at least up to the stage where the gas density is *ca.* $10^7\ \mathrm{cm}^{-3}$.

I return finally to the question of the cloud density that supports the magnetic field of 0.2–0.3 nT measured in the pulsar data. By using figure 1 and the $\sqrt{2}$ factor to correct the H I Zeeman measurements to intrinsic magnetic field strengths, an intrinsic field of 0.25 nT would correspond to a density of $2\ \mathrm{cm}^{-3}$. This density corresponds to a mixture of the lowest density H I clouds and of the medium between clouds described in § 1.

Zeeman measurements can be made of the molecules with Zeeman splittings comparable with those of H I. Such paramagnetic molecules are OH, CH, CN and SO. Clark *et al.* (1978) have set an upper limit of 2.5 μT for SO molecules in the Orion cloud, which has a density of $2 \times 10^5\ \mathrm{cm}^{-3}$. This upper limit is consistent with the extrapolation of figure 1 to OH maser densities; a magnetic field of 40 nT is expected in a cloud of this density.

(*b*) *Magnetic field alignment on a small scale*

I now consider the amount of field twisting and tangling that occurs in interstellar clouds. Evidently the tangling in H I clouds is not sufficient to reduce the magnetic field strength, as plotted in figure 1, appreciably below that expected from the pulsar measurements. Individual H I clouds would appear to have very few, if any, field reversals across their diameters. Similarly the OH master clouds associated with star formation have microtesla fields throughout the bulk of their volume; this is a consequence of the general rule that these masers are strongly circularly polarized. Long-baseline interferometers show that, at least in the small number of OH masers mapped in sufficient detail, the field direction is uniform over the face of the cloud. These lines of evidence indicate that in both the H I and the OH maser clouds the magnetic field is dominating the structure and motion of the clouds.

In the picture of a distinct cloud in an isotropic medium we would expect the cloud to flatten into a plane perpendicular to the magnetic field. It is unclear whether such flattening can be distinguished in the complex environment of a region of star formation, where such processes as shocks could modify the geometry of the situation. It turns out that the W 3 OH maser cloud is elongated perpendicular to the Galactic plane, which is the direction of alignment of

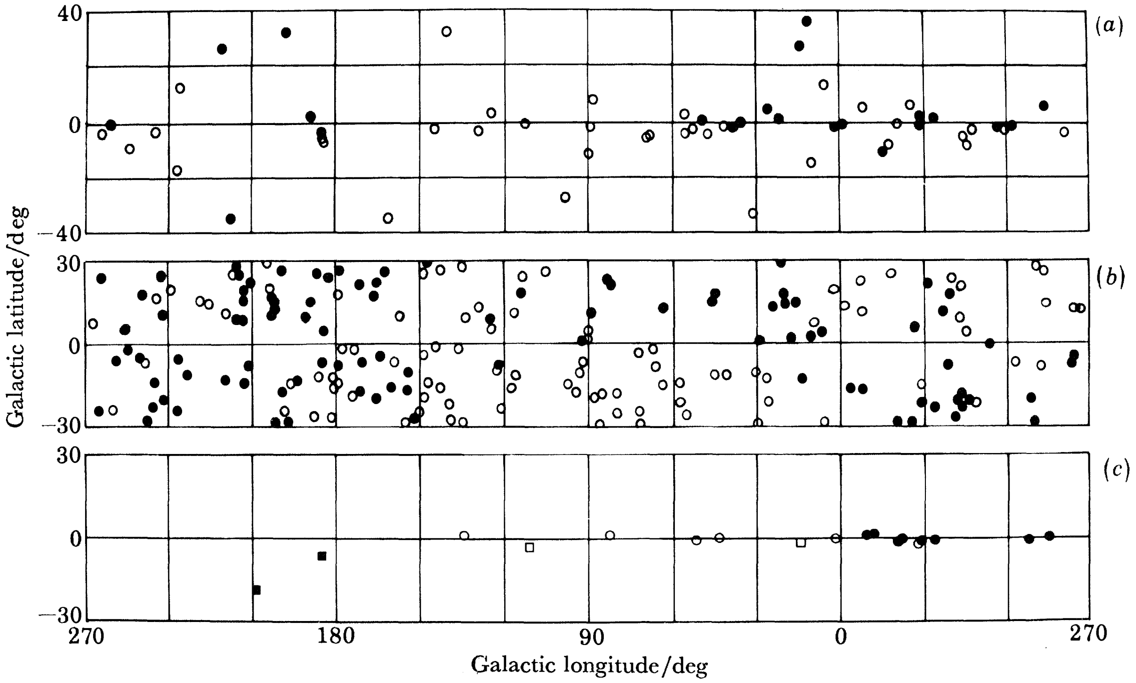

FIGURE 2. A plot of the distribution near the Galactic plane of magnetic field directions derived from four types of measurement. Filled symbols represent fields directed towards the observer; open symbols are fields away from the observer. (*a*, *b*) The field directions determined from Faraday rotations in the line of sight to pulsars and to extragalactic radio sources; note that there is both a source and a Galactic component in the Faraday rotation of extragalactic sources. (*c*) The field directions determined from the Zeeman effect for H I clouds (squares) and for OH maser sources (circles).

the magnetic field in this part of the sky. Any conclusion about the general applicability of this single result must await the mapping of more OH maser sources.

(*c*) *The large-scale alignment of cloud magnetic fields*

It is of interest to consider whether the magnetic field alignment in gas clouds follows that of the general magnetic field direction in the Galaxy. The simplest test is to examine whether the field sense (either towards or away from the observer) is consistent with the Faraday rotation data for pulsars and extragalactic radio sources (Davies 1974). Figure 2 (*a*, *b*) shows the sense of the fields derived from Faraday rotation data. The H I Zeeman and the OH maser field directions are shown in figure 2 (*c*). The Faraday rotation data appear complex at first sight. It should be remembered that there is Faraday rotation within the extragalactic sources themselves, which complicates the picture shown in figure 2; there is thought to be no internal Faraday rotation in pulsars. We accordingly make the detailed comparison of the gas cloud fields with the pulsar Faraday rotations.

The pulsar data show a consistent field direction between $l = 50°$ and $160°$; this corresponds to a magnetic field directed away from the observer. This is also a region of good field alignment in studies of polarized starlight. In this sector of the Galactic plane the fields in gas clouds have the same direction. The gas cloud fields in the sector $l = 180°–350°$ are predominantly directed towards the observer. The pulsar field directions are not so consistent, although it should be noted that the pulsars nearest the Galactic equator give the same field sense as the gas clouds.

The consistency in the field directions of the gas clouds, whether low-density H I or high-density OH, in adjacent parts of the sky indicates that the magnetic field direction is preserved during the gravitational collapse of the clouds. This again underscores the important role of magnetic fields in the formation of dense molecular clouds.

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Discussion

A. W. WOLFENDALE, F.R.S. (*Physics Department, Durham University, U.K.*). Those clouds with high H I densities presumably also have significant H_2 densities. In so far as the H_2 has come from H I, should it not be added? The high densities will be increased still further and the fit to $B \propto n(\mathrm{H})^k$ improved.

R. D. DAVIES. At the highest densities ($n(\mathrm{H}) = 100\ \mathrm{cm}^{-3}$) studied in the H I Zeeman measurements the densities would be increased by 50 % by the addition of the H_2 contribution. At one tenth of this H I density the correction is less than 1 %. Professor Wolfendale is correct; the correlation is improved when the H_2 densities are added to the H I densities in figure 1.