A SURVEY OF RECENT MAGNETIC FIELD MEASUREMENTS IN H I FEATURES OF THE GALAXY

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ABSTRACT: More than 300 measurements of magnetic field strengths in H I regions now exist. Interpretation of about 100 shows that magnetic pressure either is comparable with or dominates other pressures near at least some dark clouds and in at least some H I shells. There appears to be direct evidence for Alfvén waves, but this needs to be confirmed by additional examples. In many regions the field is highly uniform, but in other regions it varies considerably over 30 arcminutes or less. The field directions derived from Zeeman splitting and from Faraday rotation do not correlate well.

Great strides have been made in recent years in the derivation of magnetic field strengths in H I regions from measurements of the Zeeman splitting of the 21-cm line. The number of measurements now exceeds 300, although most remain to be published.

In this review I would like to concentrate on five particular topics. First (section 1) is a brief history, which also contains several key references from which the entire literature can be accessed. Next (section 2) are systematic effects, which can be serious and are the limiting factor in many measurements, especially of weak fields. Third is a particular aspect of a magnetic map of the environment of the dark cloud L204: correlations between $B_{||}$, velocity, and velocity width can be interpreted in terms of a strong field and the presence of large-amplitude Alfvén waves. Fourth is a brief review and update of a published data on shells, showing that the magnetic field is dynamically dominant but that small-scale structure may imply that it is less dominant than appears at low angular resolution. Finally, I review Verschuur's recent contribution, which tends to confirm previous data and shows that the measured field strength can vary 'rapidly' with position.

1. Historical review

Magnetic field strengths in H I regions can be derived from measurements of the Zeeman splitting of the 21-cm line. The measurement is difficult for several reasons, one of which being that the splitting is very small compared to the linewidth. This necessitates long integration times, and without the digital integration techniques we now take for granted this is very difficult to accomplish. The early attempts at the first measurements are somewhat checkered, with some claims followed by retractions; the history is reviewed by Verschuur (1979).

Verschuur (1969) himself, using one of the early digital autocorrelators, was the first to discover the Zeeman splitting of interstellar H I; it was seen in absorption against Cas

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A. He followed this soon after with several other measurements in absorption against the strong sources, some of which were confirmed by others; again, see Verschuur (1979) for details.

Going beyond the strong sources requires either measurements of absorption against weak sources or measurements in emission. The former requires interferometric techniques, and up until now such techniques have been applied to mapping the magnetic field structure against strong sources instead of measuring weak sources. The latter brings in a host of instrumental effects related to the polarized sidelobe structure. Understanding these effects was a major effort, so that additional progress did not occur for many years.

Troland and Heiles (1982a, b) and Heiles and Troland (1982) used the 85-foot telescope of the Hat Creek Radio Observatory (HCRO) to make the first measurements in emission, and discussed the instrumental effects in some detail. Heiles (1988, 1989) followed with about 100 measurements, one set near the dark cloud L204 and another in interstellar shells. Verschuur (1989) made 7 additional detections, which tend to confirm the validity of the HCRO results and add information on the small-scale structure of the field. Some of the recently published work has been reviewed (before its publication) by Heiles (1987).

2. Instrumental effects

2.1. General characteristics.

An external magnetic field splits the upper level of the 21-cm line into three levels. The splitting between the highest and the lowest levels is $2.8B_{tot}$ Hz, where B_{tot} is the *total* field strength in μG. In all diffuse clouds, this splitting is much smaller than the typical line width. In this limiting case, the *observed* splitting is $2.8B_{\|}$ Hz—proportional only to the *parallel* component of magnetic field.

To detect the splitting, one observes the difference between the two circular polarizations. This difference is the frequency derivative of the line profile with an amplitude proportional to $(B_{\|}/\delta\nu)$, where $\delta\nu$ is the line width. Thus high frequency resolution is not required.

Polarized sidelobes represent a serious instrumental effect because the difference between the two polarizations becomes equivalent to a difference between positions on the sky. The H I velocity changes with position. Thus polarized sidelobes generate a fake Zeeman splitting by an amount depending on the velocity structure of the H I that happens to lie in the polarized sidelobes. Note that polarized sidelobe effects are not restricted to measurements of Zeeman splitting: they affect all types of measurements of angularly extended polarized emission.

There are four basic types of polarized sidelobes. The first is 'beam squint', in which the two circular polarizations point in slightly different directions, resulting in a 'first-derivative' pattern on the sky. It is caused by the feed not pointing exactly at the vertex of the paraboloid. This pointing error changes with time owing to gravitational and thermal deflection. At HCRO we remove it with a servo system activated by the error signal from a laser, located at the vertex, reflecting from the feed onto a quadrant detector.

The second is a 'second-derivative' pattern on the sky. It is caused by imperfect circular polarization, *i.e.* a residual component of linear polarization, together with the impossibility of constructing a linearly-polarized feed whose illumination pattern is perfectly cylindrically symmetric. The solution is to adjust the polarization to be accurately circular.

The third is distant conically-shaped sidelobes resulting from scattering off of the feed legs. The polarized pattern for the HCRO telescope is given by Troland and Heiles (1982a), and I have been told that the pattern for the Green Bank 140-foot telescope is similar. We have had some success with reducing the amplitude of these sidelobes by placing absorbing material on the top 3 meters or so of the feed legs. In addition, the sidelobe contribution can be calculated and removed.

The fourth is a random jumble of near-in sidelobes caused by scattering from surface irregularities. These are extremely difficult to measure, and probably change with time with gravitational and thermal deflections. The best solution may be to pray to one's favorite diety.

In fact, in all of these matters it never hurts to pray.

2.2. Experimental determination.

The circularly polarized sidelobes have less structure in the 'radial' direction, away from the center of the main beam, than they do in the 'azimuthal' direction, around the center of the beam. This means that a sufficient experimental proof that polarized sidelobes are not important consists of observing a position using more than one orientation of the telescope with respect to the sky. Alt-az telescopes do this routinely, and are thus the telescopes of choice for measurements of Zeeman splitting.

Equatorially mounted telescopes can do this only at a celestial pole. In the north, we are blessed by a nice H I shell with a strong magnetic field at the pole. Heiles (1989) has reported the results obtained by allowing the telescope to sit at the north pole without moving, letting the sky turn with respect to the telescope through the day. The derived $B_{||} = +10.6 \pm 1.7$ μG (1σ). The quoted error is an overestimate because of the limited integration time for each contribution to the average. Also, it may be larger than typical errors in the sky because the velocity gradient at the north pole is rather large, about 0.7 km/s per degree. I am in the process of studying these effects in more detail.

3. The Environment of L204

Heiles (1988) mapped the field in 27 position near the elongated dark cloud L204. The average of these 27 positions is best represented by one emission and one self-absorbed component having $B_{||} = +4.2$ and $+7.6$ μG, respectively. The associated magnetic pressure is about ten times larger than the gas thermal pressure, and is probably somewhat larger than the 'turbulent' pressure calculated from the line width.

For the emission component, $B_{||}$ is reasonably well correlated with the measured velocity V_{lsr}. We argue that this correlation is consistent with the field dominating the dynamics, as follows. Both V_{lsr} and $B_{||}$ are projections of total vectors onto the line of sight. If the field dominates the dynamics and the total field strength is roughly constant throughout the region, then variations in $B_{||}$ result from geometry: a small $B_{||}$ results from the field lying nearly across our line of sight. If the field dominates the dynamics, the gas can only flow along the field, and thus V_{lsr} should be correlated with $B_{\|}$.

$B_{\|}$ is also correlated with the velocity width FWHM, although the correlation is not as nice as the correlation with V_{lsr}. The correlation is in the sense of a larger FWHM being associated with a smaller $B_{\|}$. This could be a result of Alfvén or magnetosonic waves, in which the material moves perpendicular to the field lines, so the line-of-sight gas velocity associated with the waves is largest when the magnetic field is perpendicular to the line of sight. The implied velocity of matter associated with the waves it about 8 km/s, somewhat smaller than the Alfvén velocity.

4. Field Enhancement in H I Shells

Heiles (1989) measured $B_{\|}$ for 73 positions located both in morphologically distinct H I shells and in a comparison region. $B_{\|}$ is typically $\sim 6.4\ \mu$G in morphologically prominant filaments and smaller elsewhere. If there is no small scale structure in the H I filaments, then magnetic pressure dominates thermal and turbulent gas pressures by factors of ~ 70 and 10, respectively, and line widths are ~ 1.8 times smaller than the Alfvén velocity.

However, there may be small-scale structure of the H I. The best example of a shell lies near the north celestial pole, because it is the only Galactic object along the entire line of sight. Accordingly, its IRAS image is very clear. The 100 μm IRAS image exhibits a beautiful, intricate network of very thin filaments having angular widths < 5 arcmin. If the H I lies primarily in these filaments, then the thermal gas pressure is much larger than we had originally estimated and the magnetic pressure is no longer much larger than the thermal pressure. We are currently studying this object and hope to definitively resolve this question in the near future.

Heiles (1989) also compared the field directions derived from Zeeman splitting and Faraday rotation. Some of the rotation measures were obtained from extragalactic sources and some from the diffuse Galactic synchrotron emission. There was no apparent correlation. This is apparently a general truism. The fact that Zeeman splitting and Faraday rotation sample different regions is elegantly illustrated by the observational results towards the Crab nebula, against which Zeeman splitting has been detected in H I absorption, and the associated pulsar, for which the Faraday rotation has been measured. Zeeman splitting shows a field directed towards the Earth, while Faraday rotation shows the opposite.

The two techniques sample different kinds of region. Zeeman splitting favors high H I column density and narrow line width, so it samples the cold H I clouds. Faraday rotation samples ionized regions, the same as sampled by pulsar DM's; these are produced mainly by the Warm Ionized Medium (see Kulkarni and Heiles 1987, 1988; Heiles and Kulkarni 1987).

5. Verschuur's Recent Work

Until very recently, the only measurements of Zeeman splitting of the 21-cm line in emission were obtained at HCRO. Verschuur (1989) has just published a number of emission measurements obtained with the 140-foot NRAO telescope. His measurements are important for two reasons: one, they provide a valuable check on the HCRO data; and two, they exhibit substantial variations on half-degree angular scales in some regions.

Verschuur observed four positions that had been previously observed at HCRO: $(l,b) = (206.9°, -49.6°)$, $(156.8°, -49.3°)$, $(209.6°, -20.0°)$, and $(210.4°, -20.0°)$. The results for the first three positions are in excellent agreement, while those for the last disagree: Verschuur obtains $B_{\parallel} < 3.3$ μG and Heiles and Troland (1982) obtain +10 μG. The constrast of this discrepancy with the excellent agreement of the first three positions leads me to believe that it is the result of an experimental blunder by one or both of the observers. Alternatively, it is conceivable (but unlikely in my opinion) that the discrepancy is a result of angular structure, because the beamwidths of the telescopes are 21 arcminutes (NRAO) and 36 arcminutes (HCRO).

Verschuur also observed closely-spaced position. In two cases he found significant angular structure over distances of about 30 arcminutes. Such variations are definitely not universal, because Heiles (1989) observed very systematic fields over large angular areas in several shells (see his Figures 2, 3, 4b, and 5). But there seems to be unmistakable evidence for variations near $(l,b) = (37°, 44°)$ and $(207°, -50°)$; near the first position, Heiles (1989) also has closely-spaced measurements and the results agree with Verschuur's. A more complete understanding of the situation requires maps and careful analysis of both the velocity and field structure.

6. Summary

We have begun to understand something of the magnetic field in H I regions. Magnetic pressure either is comparable with or dominates other pressures near at least some dark clouds and in at least some H I shells. There appears to be direct evidence for Alfvén waves, but this needs to be confirmed by additional examples. Finally, in many regions the field is highly uniform, but in other regions it varies considerably over 30 arcminutes or less. Comparing our current knowledge with that of ten years ago reveals tremendous progress, but there remains much to be learned. Understanding these questions requires not only measurements of magnetic field strength but also structural studies of the H I at arcminute and somewhat larger scales.

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SHUKUROV: There are two basic sources of random magnetic fields in interstellar gas: (1) tangling of the regular field by turbulence and (b) a fluctuation dynamo which generates magnetic ropes. Thus, the presence of two distinct components is expected: a smooth, gaussian component and a concentrated one which can give rise to sharp gradients of magnetic field. Your data seem to fit this picture. Is this right?

HEILES: I don't know. I have always interpreted the shells as being shocks which have compressed the ambient field. In many cases the field seems quite uniform, but not all. I don't know how to relate to theory in any more detail at the present time.

MOUSCHOVIAS: Couldn't you make your answer to the previous question a lot stronger? That is, don't your observations as well as optical and infrared polarization observations show (1) that there is an amazing regularity of the magnetic field from scales of ~1 kpc to ~10^{-2} pc; and (2) that the magnetic field direction in dense clouds correlates well with that of their more diffuse envelopes? One can, of course, have *local* disturbances (e.g. due to expanding supernova remnants and HII regions, stellar winds etc.), but this does not detract from the point that the interstellar magnetic field seems to be, perhaps surprisingly so, rather regular in character.

HEILES: Speaking purely from the empirial standpoint, it is difficult to detect the fluctuating component. Some clouds exhibit lots of different directions of optical polarization, and in some cases field reversals are measured from the Zeeman effect. This doesn't necessarily mean the field is being pushed around by random gas motions, because gravity may be important in these objects. But fluctuations are observed sometimes. Because the uniform component is what we usually measure and we cannot easily get information on the fluctuating component, we don't discuss the fluctuating component very much.

SPANGLER: With regard to your possible observation of Alfvén waves in L204, the observed width of the line should be less than or equal to the Alfvén speed in the cloud. Is this the case?

HEILES: Yes, the observed line width is less than the Alfvén velocity, but not by a high factor. In other words, the waves are of large amplitude.