THE DOMINANT, NEGLECTED FOURTH FORCE: THE INTERSTELLAR MAGNETIC FIELD

Carl Heiles

1. INTRODUCTION

1.1. Science Background

The four major forces on interstellar gas are gravity, gas pressure, cosmic ray pressure, and magnetic pressure *and tension*. The magnetic field is like a glue because it couples cosmic rays and itself to the gas—and the gas to itself. But the field is unique because the forces it exerts—tension along the field lines, pressure perpendicular to the lines—are *anisotropic*—just like the gas structures we observe. Our implication—that the anisotropies are related—is certainly not universally true, but it is often true. Optical polarizations of thousands of stars reveal the large-scale structure of the interstellar magnetic field and, in specific regions, small-scale details; and Zeeman splitting measurements of the 21-cm HI and 18-cm OH lines provide field strengths. These measurements show conclusively that the field is not only *an* important player, but sometimes *the* important player in the gas dynamics.

This document describes a few specific examples of diffuse interstellar gas structures for which magnetic field measurements are crucial. It is a small sample; the sky is full of such structures, and to understand their magnetic properties we need to sample a reasonable number.

The magnetic field is not well studied because it is notoriously difficult to measure. For the neutral gas our methods include optical polarization of background stars, infrared polarization of the dust emission, and Zeeman splitting. Zeeman splitting is uniquely informative because it provides an *in situ* effect that refers only to the specific locale where the spectral line is being produced. It's hard to measure because it's weak. It requires long integration times (up to tens of hours per position) and careful attention to systematic effects.

1.2. Instrumentation

The primary scientific requirement is to measure Zeeman splitting for a well-defined and sufficiently large statistical sample of interstellar structures. Such structures include both individual macroscopic objects, such as the writhing supersonic filamentary structures that were recently discovered with the GALFA project at Arecibo; and, also, structures related to the scale-invariant fractal structures of interstellar turbulence.

For typical line strengths this sensitivity needs some tens of hours of telescope time with a filled aperture. Arecibo is the only filled aperture telescope with enough angular resolution to do the job. Interferometric arrays such as the VLA have hopelessly inadequate surface brightness sensitivity. However, if the Allen Telescope Array is built out to its intended goal of 350 telescopes, it will be superb because it will *map* the magnetic field over a 2.5 degree region with angular resolution of about 1 arcminute, much better even than Arecibo. *These two telescopes—Arecibo and the ATA—are what's required for measuring magnetic fields in the diffuse interstellar medium.*

2. THE HI SKY AT ARCMIN RESOLUTION

2.1. Sheets and Filaments, Supersonic and Not

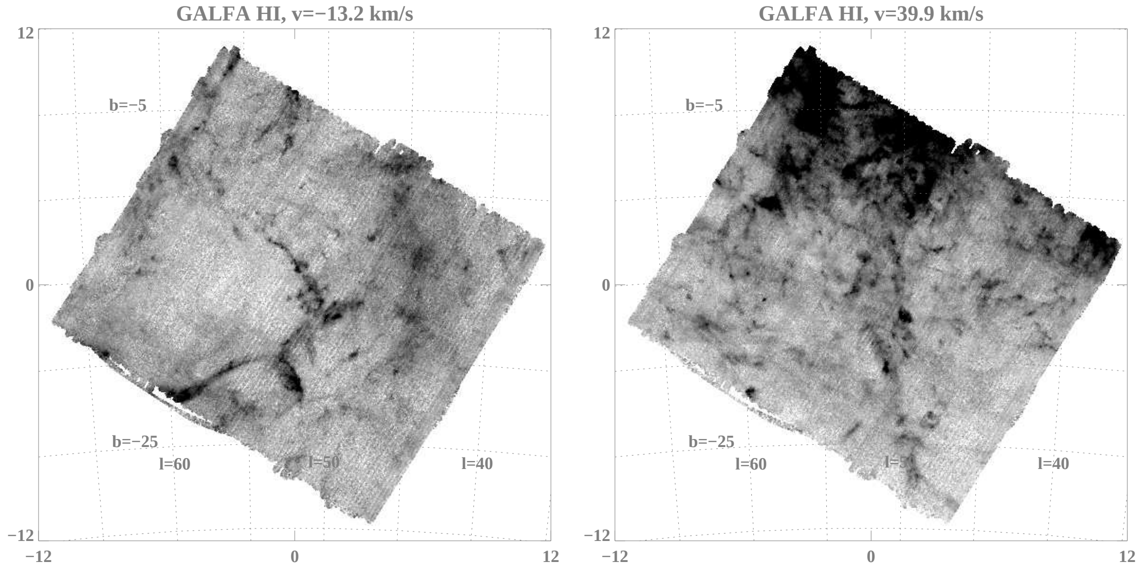

Fig. 1.— GALFA maps of a ~ 500 deg^2 area centered near $(\ell, b) = (50°, 0°)$ at two velocities, –13.2 km s^{-1} and +39.9 km s^{-1}. The data are shown in the underappreciated stereographic projection, which is one of the very few projections that is *conformal*, which means that shapes are locally preserved.

Figure 1 shows a GALFA map of a somewhat arbitrarily-chosen ~ 500 deg^2 area at two velocities, –13.2 and +39.9 km s^{-1}. The enhanced detail afforded by GALFA's unique combination of angular resolution and surface-brightness sensitivity is the difference between a blobby mush and the clarity required to discern the kinematical and morphological details.

At the $v = -13.2$ km s^{-1} of the left-hand panel, the HI is local and lies in the negative-velocity tail of the profiles. The most prominent HI structures are long, thin filaments with some blobby substructure, giving the impression of shocks. Being on the tail, these filaments have lots of kinetic energy per unit mass and their appearance gives feeling that the energy comes from some external source (stellar winds? supernovae?)—as opposed to simply being a result of intermittency in turbulence.

At the $v = +39.9$ km s^{-1} of the right-hand panel, Galactic rotation puts the distance at ~ 2.9 kpc. The HI structure breaks up into discrete clouds, some of which are connected by weaker filaments; at the center of the map these clouds lie 750 pc off of the Galactic plane. We strongly suspect these clouds to be the counterparts of Lockman's (2002) discrete halo clouds, and eagerly anticipate studying their statistics.

This morphology is common—clouds and filamentary or sheet-like structure, and often one is embedded in the other. This combination of observed sheets/filaments and clouds is familiar to theorists who perform numerical simulations. Such structures result from compressed regions in colliding clouds that undergo thermal instabilities with concomitant amplification of magnetic fields (e.g. Audit & Hennebelle 2005). These simulations confirm speculations that stringy interstellar structures are probably intimately related to interstellar magnetic fields.

2.2. The Helical(?) Magnetic Field around the Orion Molecular Cloud

Figure 2 (left single panel) shows an image of CO emission from the Orion molecular cloud. The two vertical strips of white circles on the right side of the filament are the positions at which we have made HI Zeeman-splitting detections using the GBT. Figure 2 (right double panel) shows the results for the strip at $\ell = 209^\circ.7$. The left subpanel clearly shows that the magnetic field makes a sharp reversal across the central axis of this filament; the right subpanel shows that the velocity structure is more complicated, so that the magnetic field and velocity do not behave identically. At lower angular resolution, Heiles (1997) found that this reversal occurs all the way along the Orion molecular cloud's axis, but could not pinpoint the location as the filament's axis.

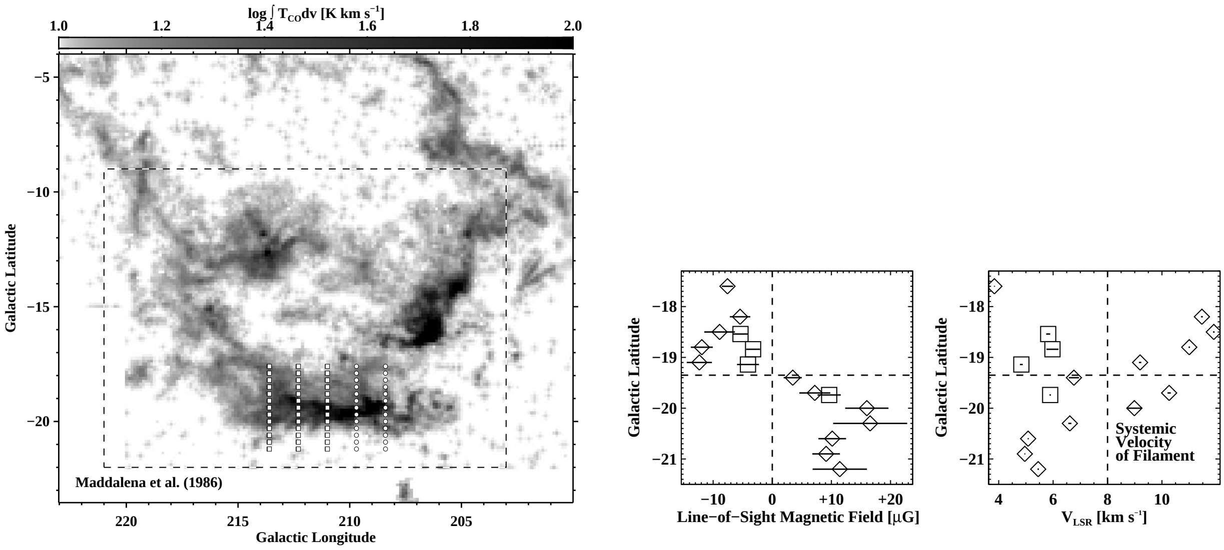

Fig. 2.— *Top:* ^{12}CO emission in the Orion molecular cloud. The columns of white symbols are positions for Zeeman splitting; see text. *Bottom:* Results along the column at $\ell = 209^\circ.7$. *Left,* $B_{||}$ shows a sharp reversal. The squares and diamonds represent different velocity components. *Right,* component velocities.

Observations of starlight polarization suggest a quasi-uniform tilted field. All this led both Heiles (1987) and Bally (1989) to conclude that a helical magnetic field is wrapped around the molecular cloud. Much recent theoretical work has been focused on the creation of helical and toroidal fields in filamentary molecular clouds; in particular, Fiege & Pudritz (2000) point to the Orion molecular cloud as the canonical case. The Orion Molecular Cloud is our nearest example of massive star formation. It seems clear that the magnetic field is playing an important role.

Currently, the reversal's angular scale is limited by the angular resolution of the GBT for HI. More resolution is needed, and moreover we need to map the field over a larger area comparable to the size of the Orion Molecular Cloud itself. The best—in fact, the *only* feasible instrument for this job—will be the Allen Telescope Array after it has been built out to its complement of 350 telescopes.

2.3. The North Celestial Pole (NCP, or Ursa Major) Region

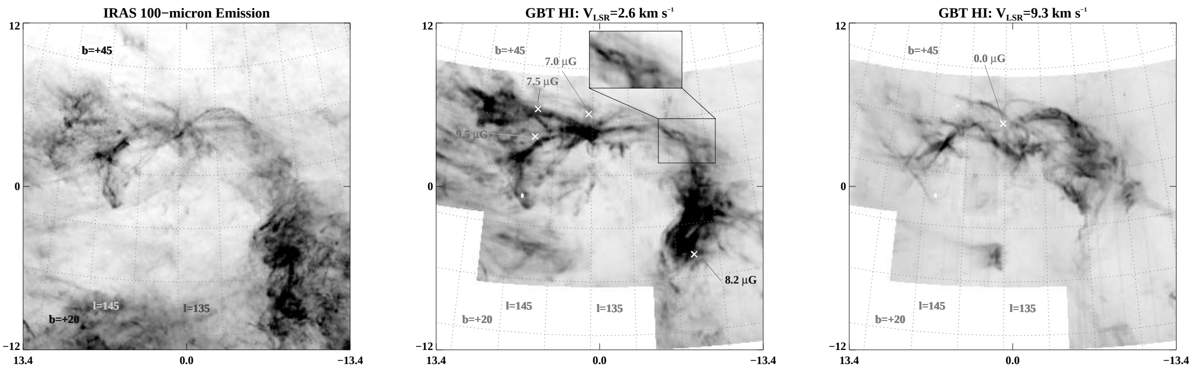

Fig. 3.— *Left:* 100 μm IRAS image of the North Celestial Pole Loop. *Center:* 21-cm line (2.6 km s^{-1}) GBT image. *Right:* 21-cm line (9.3 km s^{-1}) GBT image. All images are negatives, in which black means higher intensity.

The Ursa Major loop, or North Celestial Pole (NCP) loop, is a giant HI structure of diameter 30° that encircles the NCP. It is perhaps the foremost example of individual filaments being part of a coherent structure, probably produced by a point-source energy source such as supernova or stellar wind. Central to a proper analysis is the existence of data. However, only one data set—the IRAS 100 μm image—has adequate resolution to see the filaments. The best HI maps we have are from the Green Bank Telescope (GBT; Robishaw & Heiles, in preparation).

Figure 3 shows three images. With the 4 arcmin IRAS resolution on the left panel, the shell is clearly resolved into intertwining filaments. With the 10 arcmin angular resolution of the GBT, these filaments are blurred; the Allen Telescope Array, when built out to completion, will be the only telescope that can properly map this structure—in particular, to map the *magnetic field strength* using Zeeman splitting.

The comparison of the two GBT HI maps at 9.3 and 2.6 km s^{-1} suggests that the top horizontal portion of the loop is a radially expanding cylindrical structure whose axis lies close to the plane of the sky. At 2.6 km s^{-1}, the HI lies in a few horizontal filaments that concentrate near $b \sim 38°$. At 9.3 km s^{-1}, the filaments remain more-or-less horizontal but split into two concentrations that are vertically separated by about 3°. The change of size with velocity is a classic mark of an expanding structure. Expanding spherical *shells* produce *circles* that change diameter with velocity; at the shell's edge, the gas moves across the line of sight so it has no Doppler motion. Expanding *cylinders* produce *lines* instead of circles.

Cylindrical expansion suggests an anisotropic pressure that resists expansion. The only known source of anisotropic pressure is the magnetic field. This region does, indeed, have systematically strong magnetic fields (Heiles 1989). Myers et al. (1995) map the field strength in the small 25 deg^2 CO-containing area; the field is strong throughout. The HI gas, especially at 2.6 km s^{-1} (middle panel), is distinguished by strong line-of-sight magnetic fields in the 6-9 μG range as measured with the GBT (Robishaw & Heiles, in preparation).

These are strong fields! For a 10 μG field, the magnetic pressure $\frac{P}{k} \sim 3 \times 10^4$ cm^{-3} K—almost ten times the typical CNM thermal pressure and comparable to the total hydrostatic pressure of the ISM. The fields are probably confined to the filaments, so when we resolve them with the ATA we will probably observe field strengths that are even higher (and closer to reality). Our ATA map will provide a fully sampled map of HI and OH column densities, velocity, and magnetic field over the whole structure. This will be a unique example of a magnetically dominated shock as part of an explosively produced shell.

The current sparse GBT data suggest that the HI filaments are flux tubes, in which the field follows the filament axis or is helically wrapped around the axis as in Solar prominences. We can hope to confirm this picture by correlating filament column density and measured field strength. Zeeman-splitting measurements provide the line-of-sight component of the field. Thus, when the filament bends such that it runs more nearly parallel to the line of sight, both the apparent column density and field strength increase, and the correlation should be detectable with enough samples.

3. REFERENCES

Audit, E., & Hennebelle, P. 2005, "Thermal condensation in a turbulent atomic hydrogen flow", A&A, 433, 1-13

Bally, J. 1989, "The Structure and Kinematics of Star Forming Clouds", in proceedings of the ESO Workshop on Low Mass Star Formation and Pre-main Sequence Objects, ed, Bo Reipurth, European Southern Observatory

Fiege, J. D., & Pudritz, R. E. 2000, "Helical fields and filamentary molecular clouds - I", MNRAS, 311, 85-104

Heiles, C. 1987, "Interstellar magnetic fields", in *Interstellar Processes*, eds. D. J. Hollenbach & H. A. Thronson Jr. (Dordrecht: Kluwer), 171-194

Heiles, C. 1989, "Magnetic fields, pressures, and thermally unstable gas in prominent H I shells", ApJ, 336, 808-821

Heiles, C. 1997, "A Holistic View of the Magnetic Field in the Eridanus/Orion Region", ApJS, 111, 245-288

Myers, P.A., Goodman, A.A., Güsten, R., & Heiles, C. 1995, "Observations of magnetic fields in diffuse clouds", ApJ, 442, 177-185

Lockman, F.J. 2002, "Discovery of a Population of H I Clouds in the Galactic Halo", ApJ, 580, L47-L50