# Magnetic Fields and Polarization in the Diffuse Interstellar Medium

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## 1. ABSTRACT

Magnetism is one of the most important forces on the interstellar medium (ISM), anisotropically regulating the structure and star formation that drive galactic evolution. Recent high dynamic range observations of diffuse gas and molecular clouds have revealed new links between interstellar structures and the ambient magnetic field, but deciphering them requires high-resolution measurements of the magnetic field: linear polarization of starlight and dust emission, and Zeeman splitting. These measure different components of the magnetic field, and crucially, Zeeman splitting is the only way to directly measure the field strength in the ISM. We advocate a statistically meaningful survey of magnetic field strengths using the 21-cm line in both absorption and emission.

Finally, we report on the currently-unconfirmed serendipitous discovery of linear polarization of the 21-cm line, which demands both theoretical and observational follow-up.

## 2. Introduction

The 'neutral' interstellar medium (ISM) is ionized to a small degree, $\sim 10^{-4}$, enough for the gas to be tightly coupled to the magnetic field. Magnetic forces are fully competitive with gravity, turbulent pressure, and cosmic ray pressure in the dynamics of the gas. Magnetic forces are anisotropic and are transmitted from the rare electrons to the plentiful neutral Hydrogen (HI) by collisions and cosmic-ray coupling, both of which become ineffective at small length scales and high volume densities (Hennebelle & Falgarone 2012; McKee & Ostriker 2007; Stanimirović & Zweibel 2018). These magnetically-related phenomena not only make the ISM a fascinating entity in itself, but also lead to the multifaceted process of star formation—and, by extension, galactic and cosmological evolution.

## 3. Observing Magnetic Fields in the ISM

Magnetic fields reveal themselves most obviously in linear polarization of starlight and of infrared dust emission, both of which are produced by magnetically-aligned dust grains; these polarizations trace the orientation of $B_\perp$, the plane-of-the-sky component, but provide no information on magnetic field strength. Zeeman splitting produces circular polarization that provides the line-of-sight magnetic field strength and direction $B_{||}$; the splitting is very small compared to the line width, which makes the measurements sensitivity limited.

## 4. Building an Unbiased Sample of Magnetic Field Strengths in the CNM Using the H I Line in Absorption

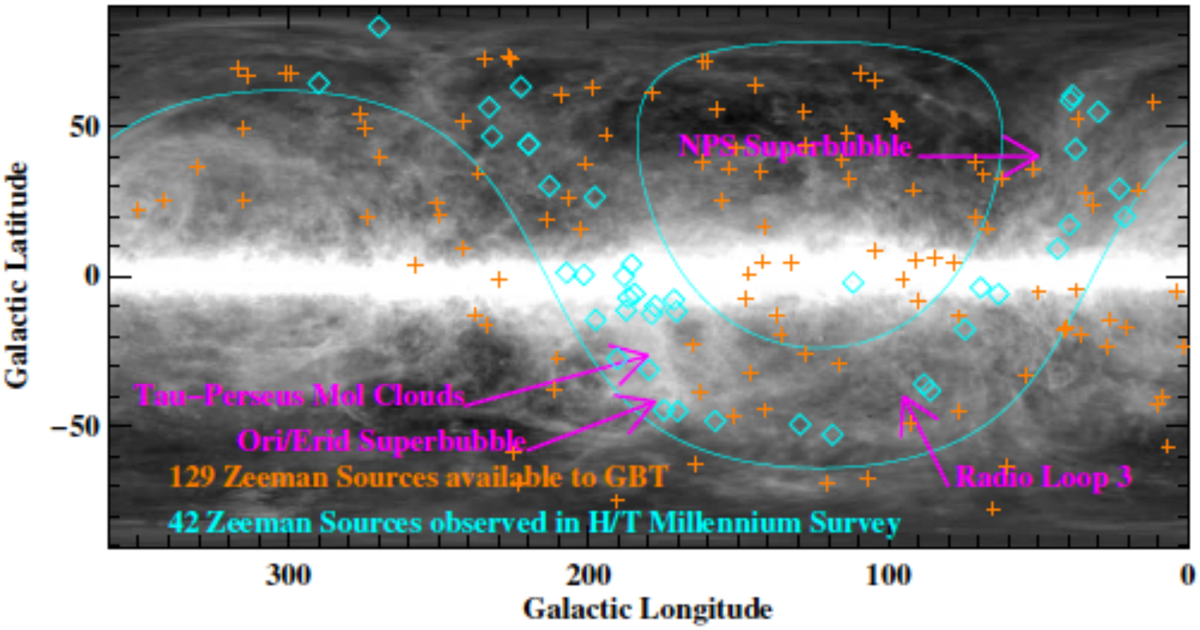

Fig. 1.— *Left:* the 42 Millennium survey sources (cyan diamonds) and the 566 sources exceeding 1 Jy (orange crosses) within the Arecibo declination range (cyan lines), superposed on a grey-scale image of H I. *Right:* Magnetic field signs from Zeeman splitting of H I emission lines. Pluses are positive, crosses negative, and diamonds are nondetections, superposed on a grey-scale image of the H I line in a portion of the Orion/Eridanus superbubble. $|B_{||}|$ ranges from 4 to 11 $\mu$Gauss.

The line-of-sight component of the magnetic field strength ($B_{||}$) in the CNM can be probed via the absorption of continuum emission from compact background sources, which are distributed randomly on the sky. This method was successfully used by Heiles & Troland (2004, 2005) at the Arecibo telescope to make the unprecedented "Millennium" survey of the CNM towards 42 radio-loud sources. The unique products of such observations include not only the field strength, but also accurate kinetic temperatures—and, from the line width, the degree of turbulence and whether it is supersonic and/or super-Alfvénic. This is a unique combination of physical conditions in the CNM.

While these results are important and widely referenced, the number of actual detections is, from a statistical standpoint, pitifully small. The cyan diamonds in Figure 1 show the 42 sources. The Arecibo sky contains four important and distinguishable interstellar structures: Perseus, the northern portion of the Orion/Eridanus superbubble, the northern portion of the North Polar Spur superbubble (a.k.a. the Radio Loop 1 superbubble), and the Radio Loop 3 superbubble. Each of these entities is sampled by only a handful of sources. This is simply inadequate to develop a statistically reliable picture of the magnetic field and its fluctuation within each structure.

Moreover, we need to sample more representatuve areas to reveal the diversity of the ISM.

The orange plus symbols in Figure 1 show the sources for which the GBT can provide reliable results (flux densities exceeding 4 Jy). There are 129 sources, three times more than the entire number that have been measured so far. This represents an substantiual increase in our data and knowledge base!

## 5. Sampling Magnetic Field Strengths in Shocks and Filaments Using the HI Line in Emission

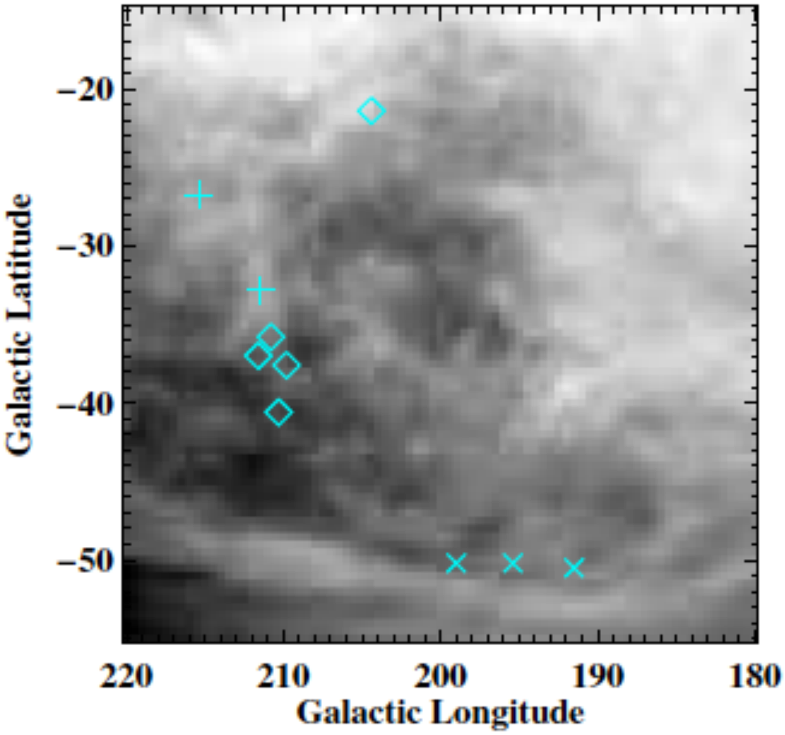

Fig. 2.— Magnetic field signs from Zeeman splitting of HI emission lines. Pluses are positive, crosses negative, and diamonds are nondetections, superposed on a grey-scale image of the HI line in a portion of the Orion/Eridanus superbubble. $|B_{||}|$ ranges from 4 to 11 $\mu$Gauss.

Heiles (1989) measured Zeeman splitting of Galactic HI in emission, targeting compressed supershell walls and filaments. Figure 2 shows the results for a portion of the Orion/Eridanus superbubble. Three things stand out from this image: 1. The HI is swept up from the interior into shell walls, which themselves have considerable spatial structure that sometimes looks filamentary. 2. The observational sampling is totally inadequate relative to the structural details of the HI. 3. There is an apparent large-scale field reversal across the superbubble. However, the sampling is so coarse that no statistically firm statement about field reversal can be made—at *any* scale. The

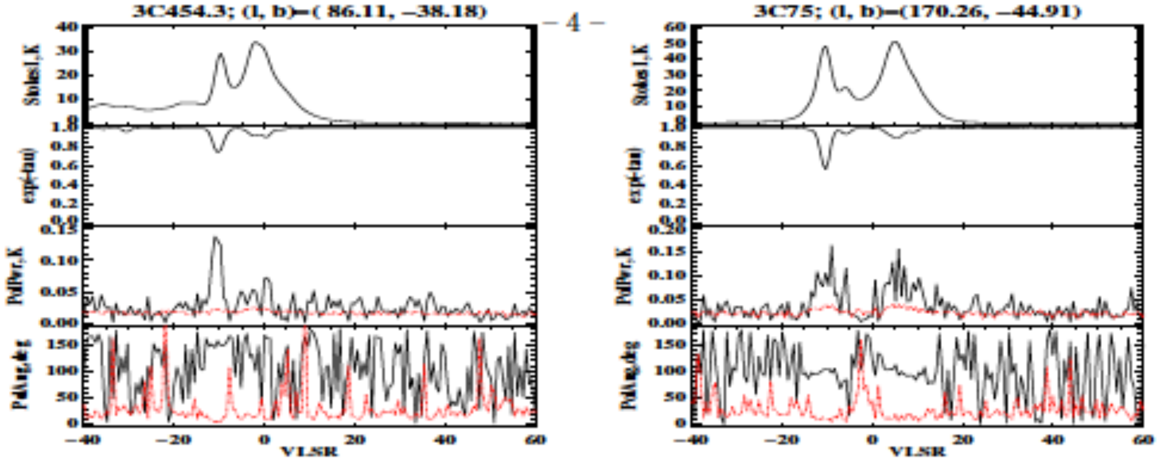

Fig. 3.— Each of two sources has the four panels: top, Stokes I emission spectrum; next, the optical depth spectrum $\exp(-\tau)$; next, the total linear polarization power $(Q^2 + U^2)^{1/2}$; bottom, the position angle of linear polarization $\frac{1}{2}\text{atan}(Q/U)$. The solid (black) line is the spectral quantity and the red (dashed) line its statistical uncertainty.

advantage of emission over absorption measurements is that one can choose interesting positions based on ISM structure; one is not limited to the arbitrary positions of background continuum sources. Heiles (1989) sampled 73 positions in superbubble walls, , which are compressed by shocks. The result from this limited sample is that their field strengths are about twice those of the randomly-selected positions of §4. These emission measurements were all made with the Hat Creek 85-foot telescope, which sadly collapsed during a major windstorm in January 1993.

## 6. A Serendipitous Discovery: Linear Polarization of the 21-cm Line

Some years ago, for technical reasons we wanted to observe a set of test sources known to be unpolarized. We expected the 21-cm line to be unpolarized because its 2 level system is populated overwhelmingly by collisions. We used the Heiles & Troland Millennium survey (2003) data because of their long integration times and careful polarization calibration. We studied a subset of 18 sources and found, much to our surprise, that 13 of these 18 sources exhibit detectable linear polarization at levels 0.14% to 0.35%. The linear polarization appears to be astrophysical, and we are currently trying to confirm or refute the finding.

Figure 3 shows two examples, 3C75 and 3C454.3. The top panel exhibits the emission line and the absorption line. The bottom panels exhibit the linearly polarized power and the position angle; the black lines are the profiles and the red their uncertainties. Figure 3 shows that the polarization is not exclusively associated with either the absorption profiles (the CNM) or the emission profiles (both the WNM and the CNM).

How can the collisionally-dominated two-level system show linear polarization? While we idealize the hyperfine levels of the H I atom as a 2-level system, this is not strictly true. Ly-$\alpha$ radiation is an important populating agent for the 21-cm levels (Murray et al. 2014), and could conceivably differentially populate the magnetic sublevels, particularly if it is anisotropic in either physical or frequency space. Indeed, we were surprised to learn that linear polarization of the 21-cm line was predicted by Yan & Lazarian (2007).

## 7. How does all this relate to ALPACA?

Measuring circular polarization (§4, §5) and linear polarization (§6) require obtaining not only the four on-source HI Stokes parameter spectra, but also the emission spectrum that would be observed at the position of the continuum source if the source had zero flux (this is commonly called the 'expected profile'). This requires sensitive and accurate measurements of the HI profile, which can only be done with a large single dish telescope; interferometric arrays cannot measure the spatially extended emission brightness-temperature spectra with high sensitivity. Arecibo used to be the best telescope for these measurements. FAST has set the new standard, but access is *extremely* tight because the telescope is under extremely high demand for many other projects by a huge community of mainly Chinese users.

The GBT comes next. The GBT has a broader beam and is less sensitive for point sources, but being equipped with the ALPACA feed with its multiplicity of synthesized beams means that when measuring absorption lines against continuum sources, the off-source emission data come 'for free'. The 38 off-source beams provide excellent sky sampling so that the expected profile and its uncertainty can be derived from analyzing the spatial structure of the emission. ALPACA is beautifully matched to making these measurements accurately and efficiently.

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