Revealing Magnetic Fields in the Neutral ISM: Outlook and Goals for the Next Decade

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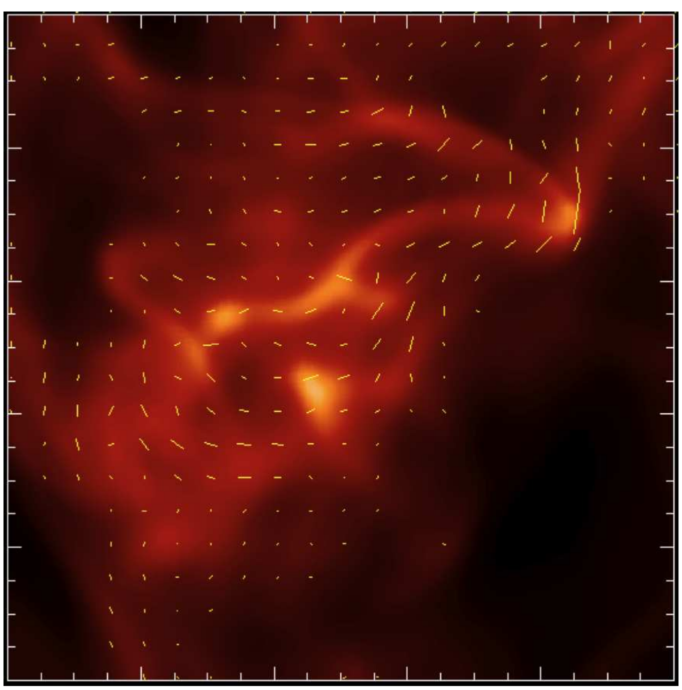

Figure 1: Simulated far-IR flux density and polarization map from 512^3-element numerical model of the turbulent, magnetized ISM (Falceta-Gonçalves et al. 2008). Simulations such as these have shown that the mean magnetic field strength can be derived from high-quality maps of polarization with accuracy as good as $\sim$20% . Measuring such polarization maps and therefore revealing the magnetic fields in neutral interstellar clouds is a high priority for the next decade and beyond.

1. Scientific Context

Magnetic fields are the direct cause of a wide variety of astrophysical phenomena on scales from radio galaxy jets to sunspots. A comprehensive observational and theoretical study of magnetic fields is an essential component of future research in astrophysics; such a study should address the origin of seed magnetic fields in the early Universe; their amplification in the first and subsequent generations of stars and galaxies through the dynamo effect; diffusion of magnetic fields into the interstellar medium (ISM); and their influence on the structure that we observe today on galactic, (proto-)stellar, and sub-stellar size scales.

Outside the Solar System, astrophysical magnetic fields are notoriously difficult to measure, and the inclusion of magnetic fields adds significant obstacles to theoretical modeling of gas flow. We can therefore expect that magnetic field work will challenge technological limits into the next decade and beyond.

In this white paper, we narrow our focus to magnetic fields in the neutral interstellar medium – the key phase for the assembly of clouds and star-forming cores. Despite some past observational and theoretical progress, we still cannot claim to know the role played by magnetic fields over the life cycle of interstellar clouds. Several pieces of evidence point to a rough equipartition of gravitational, magnetic, and turbulent (probably MHD-based) energies. Without the research program described here, we cannot hope to understand star formation and the nature of the ISM.

Techniques for measuring magnetic fields in atomic and molecular gas are relatively few. Zeeman splitting at radio wavelengths, and continuum polarization from absorbing and emitting magnetically-aligned dust at infrared/submm wavelengths, are proven techniques. First detections of the Goldreich-Kylafis effect, in which polarized molecular line emission traces magnetic fields, have been made in the last fifteen years. Recently, Houde et al. (2002) and Li & Houde (2008) have used small differences in velocity profiles of coexistent neutral and ionized molecules to infer information about magnetic fields constraining the ions. A new technique which should be explored is the theoretical expectation of polarized emission and absorption by atoms and ions aligned by anisotropic radiation and magnetic fields (Yan & Lazarian 2008).

2. Recommendations/Executive Summary

Our findings are summarized here and justified in the remainder of the text.

- Observational and theoretical studies of magnetic fields remain a vital component of interstellar research into the next decade.
- Engineering philosopy for telescopes, instruments, and detectors must include provision for measuring weak polarization signals.
- Expanded capability at UV through radio wavelengths is critical for measuring magnetic fields. In particular, we highlight:
  - exploratory UV measurements of polarized radiation from aligned atoms, potentially giving new information about interstellar magnetic fields,

- large surveys of optical/near-IR starlight absorption polarimetry, probing the magnetic field in entire diffuse or moderately dense clouds[1],
- advanced polarimeters on SOFIA, balloon-borne far-IR telescopes, and high-elevation submm telescopes, to measure magnetic field strengths in Galactic clouds via the Chandrasekhar-Fermi technique, map magnetic field structure on arcminute size scales, and test field models of the Galactic center,
- at millimeter wavelengths: increased emphasis on accurate dust polarimetry and Zeeman measurements with interferometers like CARMA and ALMA, as well as new single-dish facilities and instruments (GBT and LMT), for the purpose of measuring arcsecond-scale structure in the magnetic field,
- strong consideration of the serendipitous science return from the high-frequency channels of CMB polarimeters which measure magnetic field structure on arcminute and degree size scales and test grain alignment theory,
- at centimeter wavelengths, continuing improvements in sensitivity, angular resolution, and accuracy of Zeeman measurements using thermal absorption lines (H I, OH), as well as key maser lines of OH, H_2O, and methanol which allow the highest possible resolution polarization measurements using the EVLA and VLBA.

- We highly recommend continued theoretical investigations of magnetic fields, turbulence, and grain alignment, which have made tremendous progress in the past few decades, but are still limited by computing power and human insight.

3. The Energy Density of Magnetic Fields in the ISM

The magnetic field energy density is a key element in the stability and evolution of galactic clouds, along with self gravitation, internal velocities, and outside forces. This fact has motivated difficult measurements in the optical/NIR, far-IR/submm, and radio designed to measure the strength of the magnetic field.

Progress Within the Past Decade: Crutcher (1999), Troland & Crutcher (2008), and Falgarone et al. (2008) summarized Zeeman measurements (typically along single lines of sight) of self-gravitating clouds: observations in H I and OH thermal lines reveal magnetic fields of 10's of μG in the lower density ($n \sim 10^{3-4}$ cm^{-3}) envelopes, and observations in CN find typical fields of $\sim$0.5 mG in the dense ($n \sim 10^{5-6}$ cm^{-3}) cores. Judging by the mean value of the mass-to-flux ratio inferred for the observed samples, the clouds are supercritical by a typical factor of 2, meaning that static magnetic fields alone are insufficient for support against gravity. However, magnetic and kinetic energies are approximately equal, suggesting support from a combination of static fields and MHD waves.

The past 20 years have seen increasing use of spatially-resolved structure in the magnetic field in the plane of the sky to measure the strength of the field by its resistance to gas motion. This technique, first applied by Davis (1951) and Chandrasekhar & Fermi (1953) to low-density gas in the local spiral arm, has now been extended to far-IR/submm measurements of dense cloud cores, resulting in field strength estimates that fall within the broad range

[1]This topic is discussed in detail in the white paper submitted by Clemens and Andersson to this same Galactic Neighborhood panel.

expected from Zeeman work (e.g., Crutcher et al. 2004; Curran & Chrysostomou 2007). We eagerly await future gains in sensitivity and accuracy which will improve the reliability of the field strength measurements and broaden the range of sources which can be mapped.

Goals for the Next Decade: Numerical simulations (e.g., Figure 1 on cover) show that for the assumption that all grains are well aligned, modified Chandrasekhar-Fermi (C-F) formulae can recover the magnetic strength with the accuracy of about 20% (Falceta-Gonçalves et al. 2008 and references therein). The theory of grain alignment predicts that grains must be well aligned at least in diffuse gas (Lazarian 2007), paving the way for reliable application of the C-F technique for these environments. Application of the C-F technique for dense clouds requires more modeling, which takes a partial suppression of grain alignment into account.

Given these theoretical tools, the next decade promises a breakthrough in precision measurement of magnetic field strengths in interstellar clouds. Modern far-IR polarimeters on SOFIA and other meter-class suborbital telescopes would offer an order of magnitude leap in polarization sensitivity compared to what has been done before (e.g., Vaillancourt et al. 2007), as would a polarimeter on a large submillimeter telescope on a very high and dry site. In addition to allowing new measurements away from the densest cores, this new capability would improve the statistical power of the C-F technique, with the number of polarization detections per object increasing by as much as two orders of magnitude.

The VLA has provided the best opportunity to *map* magnetic fields via Zeeman measurements on 0.1 pc scales in H I and OH absorption (e.g., Brogan & Troland 2001). Maps of more regions and on a range of size scales are critical to a robust statistical compilation of field strengths that will provide important input to theoretical models of star formation. The receiver and electronics upgrades on the the EVLA will provide greater sensitivity to thermal Zeeman studies. However, the number of sources that can be mapped in this way is limited by favorable source geometries, and, moreover, these species do not trace the very high densities where stars actually form. To access magnetic fields on the smallest scales will require higher density probes like CN, CCH, and SO with CARMA and ALMA (arcsecond scales). The very highest possible angular resolution Zeeman data (milliarcsecond scales) will be afforded by observations of 1.6 GHz OH, 6.7 GHz CH_4OH, and 22 GHz H_2O maser lines with the EVLA and sensitivity enhancements to the VLBA (North American Array).

4. Connecting Large- and Small-Scale Interstellar Fields

The role played by magnetic fields in cloud assembly and star formation has remained controversial, only weakly constrained by the limited available measurements. At one extreme of the theories is that magnetic fields control the formation and evolution of the molecular clouds from which stars form (Mouschovias & Ciolek 1999). The other extreme is that magnetic fields are unimportant, with molecular clouds forming at the intersection of turbulent supersonic flows in the interstellar medium (Mac Low & Klessen 2004).

Progress Within the Past Decade: Past attempts to link large and small scales have resulted in inconclusive results (e.g., Ménard & Duchêne 2004; Fish & Reid 2006). One interesting, recent observation is that the magnetic field directions on 100 pc scales (sampled by optical polarimetry) appear to correlate strongly with directions on 1 pc scales (sampled by 350 μm polarimetry; H. Li et al. 2009, submitted). Data sets larger by an order of magnitude are needed to test this and other possible correlations.

Goals for the Next Decade: New instruments will be needed to provide the crucial link between large- and small-scale magnetic fields – essential to understand the role of magnetic fields in cloud evolution and star formation. On the largest scales, large area starlight polarization surveys (see Clemens & Andersson white paper) and Planck 850 μm polarization maps at $5'$ resolution will map out the structure of the interstellar magnetic field on Galactic and molecular cloud scales. Higher resolution maps (e.g., with SOFIA) will make it possible to study structure of cores relative to large-scale magnetic fields. Some predicted phenomena that require the correlation of the large- and small-scale maps of magnetic field structures include collapse of mass along field lines to form flattened cores, magnetic braking of cores that twist the fields as angular momentum is transferred outward from cores to envelopes, and bipolar outflows from protostars with magnetic fields being parallel to the outflows. On the smallest scales ($<$ few arcseconds), ALMA will image protostars, protoplanetary disks, and the inner parts of protostellar outflows. Combining ALMA and SOFIA polarization maps will probe the full spatial structure of these phenomena and allow testing of star formation theory.

Arcsecond-resolution maps of magnetic fields in the dense ISM of nearby spiral galaxies would offer valuable perspective on molecular cloud assembly, but the ultrasensitive far-IR/submm polarization measurements required are unlikely to be available before 2020.

5. The Turbulent ISM

The interstellar medium has been known for decades to be turbulent from the scales of 100 pc to 1000 km (Armstrong et al. 1995). Even with ionization of the order 10^{-4}, which is typical for diffuse gas, turbulent motions of gas and magnetic fields are inseparable, apart from very small scales. Magnetized turbulence plays a crucial role in the evolution of clouds, star formation, formation of structures at hundred-AU scales, suppression of large scale instabilities, transport of heat and polarized radiation, etc. Turbulence also heats the ISM and is intricately involved with cosmic rays: scattering, trapping, and accelerating them while experiencing strong feedback from them (Cho et al. 2003; Elmegreen & Scalo 2004; McKee & Ostriker 2007).

Progress Within the Past Decade: During the past decade, turbulence has been accepted as a major agent reshaping the interstellar medium. Numerical simulations played a very important role in changing the paradigm (Mac Low & Klessen 2004). Increases in computational speed have, for instance, allowed the Goldreich & Sridhar (1995) model of turbulence to be extended to describe a compressible interstellar medium (Cho & Lazarian 2002, 2003), resolving many existing puzzles, e.g., related to the origin of the fast decay of turbulence.

Goals for the Next Decade: Testing improved theoretical models of turbulence requires better observations. Interpreting the statistics of 2D polarization maps in terms of the underlying statistics of the 3D magnetic fields is becoming tractable with modern theoretical work on radiative transfer, grain alignment, and turbulence, even in the case of inhomogeneous clouds containing dense clumps and clusters of embedded stars (Bethell et al. 2007). With maps of polarized emission having sufficient resolution, dynamic range, and spectral coverage, it will be feasible to determine characteristics of the magnetic fields such as the ratio of fluctuating to mean components, the energy spectrum, and the distribution of magnetic field strengths and thereby to test predictions of turbulent vs. static star formation.

6. Dust Grain Alignment and Composition

Understanding the nature of dust grain alignment is a key requirement for applying the

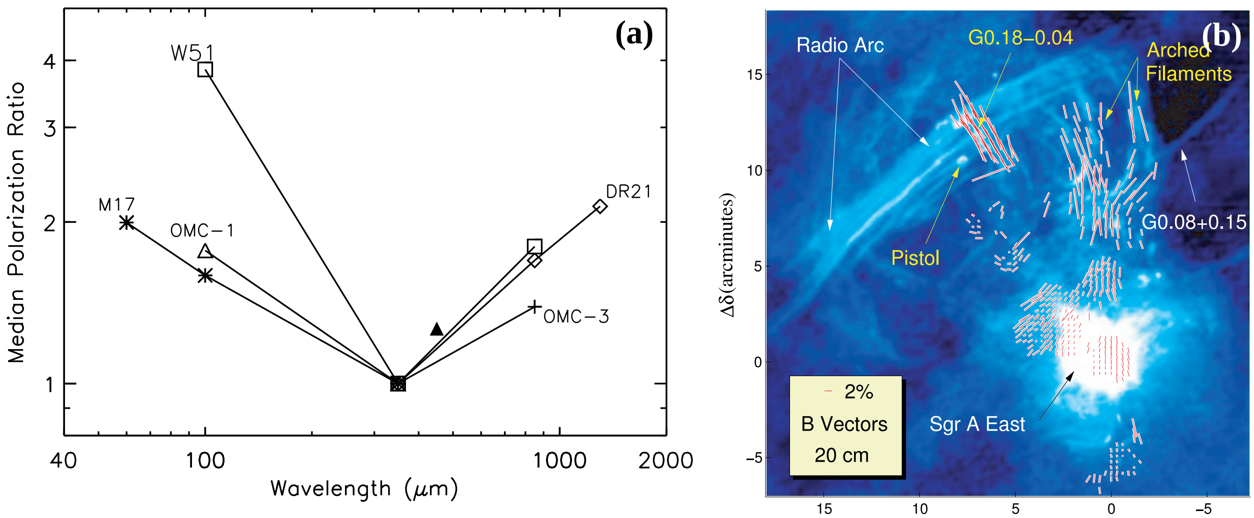

Figure 2: (a) Far-IR/submm polarization spectra of several different Galactic molecular clouds (Vaillancourt et al. 2008). Polarizations have been normalized at 350 μm within each cloud. This spectral dependence is thought to result from a mixture of two grain species with different polarization efficiency and different emissivity index and/or temperature.
(b) FIR/submm polarimetry vectors superposed on a 20 cm continuum VLA image of the Galactic Center (Chuss et al. 2003). The far-IR magnetic field vectors trace the thermal arched filaments, while the magnetic field in the molecular cloud associated with G0.18-0.04 is perpendicular to the field traced by the non-thermal filaments of the Radio Arc.

Chandrasekhar-Fermi technique and other magnetic field modeling to far-IR/submm polarization maps. The journey from the first detection of aligned dust grains in the 1940's to our present understanding of the importance of alignment by radiative torques (Lazarian 2007) has been a long and indirect one. However, one key result – that grains tend to be aligned with long axis perpendicular to the local magnetic field – has been essentially unchanged. On the other hand, our expectation for the degree of alignment has undergone several revisions but is now ripe for detailed observational test.

Much work has been done in the UV through near-IR to investigate the alignment – or not – of various interstellar grain materials via the polarization of their solid-state absorption features. The polarization spectrum has been extended (albeit with very low resolution) to the far-IR/submm in the past decade (Hildebrand et al. 1999; Vaillancourt et al. 2008). (See also Figure 2a.)

An important test for the next decade is the effect of environment. Current sensitivities in the far-IR/submm have limited polarization measurements to dense cloud cores[2]. In the next decade, the order of magnitude sensitivity gains of SOFIA and balloon-borne observatories operating in the far-IR can permit polarimetry of cloud envelopes, with the polarization of $A_V \approx 1$ dust detectable in hour-long integrations. Some predictions have been made for the diffuse polarization (Hildebrand et al. 1999), having a different spectral dependence than in the cloud centers in Figure 2a. In addition to broad-band work, it will be interesting to use

[2]The subclass of prestellar cores deserves special mention: submillimeter polarization has been detected from several, indicating that grains are aligned even in well-shielded environments (Crutcher et al. 2004), and suggesting further that the near-IR and submillimeter provide complementary sampling of exposed and shielded grains, respectively, in these sources.

low-resolution spectropolarimetry of infrared solid-state emission features as a diagnostic of the abundance and alignment of particular species. This work will have broader application beyond the study of magnetic fields.

Further orders of magnitude of improvement in polarization sensitivity can be achieved with cold space telescopes (Dowell et al. 2007), but this is likely a priority for the decade 2020-2030, in the form of high-frequency channels on CMBPOL or a polarimeter on the far-IR mission after SPICA. Spectral coverage through the far-IR and submm is key.

7. The Galactic Center

Our proximity to the Galactic Center provides a unique opportunity to study the physics of a galactic nucleus in great detail. It seems likely that magnetic fields play a key role in the dynamics of this region, as evidenced by the prominent Radio Arc and other polarized non-thermal filaments (Yusef-Zadeh et al. 1984).

Progress Within the Past Decade: The radio non-thermal filaments are thought to trace lines of magnetic flux in the hot ionized gas. Although fainter filaments have a variety of orientations (Yusef-Zadeh et al. 2004; Nord et al. 2004), the brightest are oriented perpendicular to the Galactic plane, suggesting a *poloidal* field.

On the other hand, submillimeter polarimetry has indicated that the magnetic field in the molecular gas layer is predominantly *toroidal*. This dichotomy is perhaps most striking at G0.18-0.04 (the 'Sickle'), where along the same line of sight the magnetic field in a molecular cloud is almost exactly perpendicular to the field in the brightest system of radio filaments (Figure 2b). New observations suggest that the morphology of the G0.18-0.04 molecular cloud is a direct response to channeling of gas motion by the toroidal field (Morris et al. 2009).

The toroidal nature of the field in the dense gas layer can be understood as a consequence of gravity dominating magnetism in this layer, which will be true as long as the field strength is below several mG (Novak et al. 2000). However, the possible connection between toroidal and poloidal fields remains largely unexplored. Chuss et al. (2003) argue that their submm polarimetry data show a transition from toroidal to poloidal as one moves to less dense regions (Figure 2b), but such an effect was not seen in a near-IR stellar polarization survey with SIRPOL (Nishiyama et al. 2009). The two techniques are complementary, and both are poised for dramatic increases in sensitivity due to improvements in instruments and facilities.

Goals for the Next Decade: Immediate outstanding questions concerning the Galactic center magnetic field are:

- Are the toroidal fields in the molecular gas layer linked in any way to the large-scale polodial fields? A synergistic study including near-IR, submm, and especially far-IR observations (which isolate the warmer Galactic center dust) is needed to answer this question.

- Are there sharp bends in the magnetic field in regions where the molecular clouds appear to interact with the radio nonthermal filaments? Is magnetic reconnection a likely source of acceleration of the electrons illuminating the filaments? (See Morris 2006.) Arcsecond resolution is necessary to isolate the interaction sites.

- Is the magnetic field strength in the neutral gas sufficient for magnetic support of any of its constituent structures?

In the next decade, Chandrasekhar-Fermi analysis of large new far-IR/submm polarization databases should be able to constrain the field strength in Galactic center molecular clouds. Suborbital far-IR platforms such as SOFIA and balloon observatories, and proposed large, high-elevation submillimeter telescopes, offer an order of magnitude better sensitivity to extended emission compared to what has been done in the past (Figure 2b) as well as $\sim 5''$ resolution, which is necessary to measure the dispersion within individual clouds.

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