Interstellar Magnetic Fields via Zeeman Splitting at Arecibo

Timothy Robishaw[1], Carl Heiles[2], James A. Green[3], Gabriele Surcis[4], Wouter Vlemmings[5],
A. M. S. Richards[6], Sandra Etoka[7]
[1]National Research Council Canada; [2]University of California at Berkeley; [3]SKA
Organization; [4]Joint Institute for VLBI in Europe; [5]Chalmers University of Technology;
[6]Jodrell Bank Centre for Astrophysics; [7]Hamburger Sternwarte

1. Introduction

Interstellar magnetic fields, together with turbulent pressure and gravity, are the three major forces on interstellar gas. Despite their huge dynamical importance, the fields are very weak—strengths of microgauss for the diffuse ISM and milligauss for star-forming regions and shocks in molecular gas. The Zeeman effect provides the only way to measure the actual magnetic field strength. But the weak fields are hard to measure because, in all cases except typical OH masers, they produce Zeeman splitting that is much smaller than the line width ($\Delta\nu_Z \ll \delta\nu$). This makes Zeeman splitting observations sensitivity limited.

For a given field strength, the line splitting $\Delta\nu_Z$ depends on whether the atom or molecule has electronic angular momentum. Species with electronic angular momentum, such as H I and OH, have splitting proportional to the Bohr magneton, i.e. $\Delta\nu_Z \propto (e\hbar/2m_e c)$; for species without, such as CH_3OH and H_2O, it's the nuclear magneton that counts, i.e. $\Delta\nu_Z \propto (e\hbar/2m_n c)$, which is thousands of times smaller. For the diffuse ISM, the microgauss field strengths lead to splittings of no more than tens of Hz for H I and OH; with line widths of tens of kHz, this leads to Zeeman splitting signatures of a few tenths of a percent. For star-forming regions, the milligauss field strengths lead to comparable splittings for species *without* angular momentum like CH_3OH; so for comparable line widths—as exist for the 6 GHz CH_3OH masers—we also have Zeeman signatures of a few tenths of a percent.

Fortuitously, the ratio of the Bohr to the nuclear magneton, ~ 2000, is comparable to the ratio of the field strengths in dense gas and diffuse gas. Accordingly, successful Zeeman splitting measurements for strong lines are made for both the diffuse gas (OH and H I) and, also, molecular gas with strong lines (CH_3OH masers). Tables of all known Zeeman coefficients for species with angular momentum can be found in Heiles et al. (1993) and Robishaw (2008). Suitable species for Arecibo (with line frequencies < 12 GHz) include H I, Radio Recombination Lines, OH, CH, C_4H, and C_2S. Examining different species is useful because they sample different regimes of density; one usually expects the magnetic field strength to increase with density. Zeeman coefficients for CH_3OH are currently uncertain but are presently being determined by a team of theoretical chemists and astrophysicists; the final results will be published by the end of 2014.

For the case $\Delta\nu_Z \ll \delta\nu$, Zeeman splitting is detectable in the Stokes V spectrum, which is the difference between the two circular polarizations. The V spectrum has the shape of the first derivative of the line profile (the Stokes I spectrum) with an amplitude $\propto B_{||}$, where $B_{||}$ is the line-of-sight component of the field. The Zeeman effect exhibits itself only in terms of this frequency difference; intensity differences between the two circular polarizations are irrelevant. In contrast, for narrow lines in high-density regions we can have $\Delta\nu_Z \geq \delta\nu$; this occurs for many OH masers. In this case, the splitting is proportional to the total field strength rather than the line-of-sight field (Crutcher et al. 1993).

2. CH_3OH Masers Near Young Stellar Objects (YSOs)

The role of magnetic fields during the formation of high-mass stars ($M > 8M_\odot$) is still a matter of debate, even in the face of many recent investigations, both theoretical and observational (Seifried et al. 2012; Surcis et al. 2013). Recent magnetohydrodynamical simulations show that the collimation of outflows and the formation of accretion discs strongly depend on the strength of magnetic fields (Seifried et al. 2012). In addition, simulations show that magnetic fields also prevent fragmentation, reduce angular momentum, and determine the size of H II regions (Peters et al. 2011; Hennebelle et al. 2011; Seifried et al. 2012). The simulations take into account only relative values of magnetic field strengths obtained considering ratios of magnetic energy with other types of energies (e.g., gravitational energy). Therefore, no real values of magnetic field strengths are currently used in the theoretical calculations. To provide observational measurements of magnetic field strengths close to the massive YSOs is of great importance.

The best probes of magnetic fields at small scales close to YSOs are masers, in particular 6.7 GHz methanol masers. Methanol masers, which are the most numerous massive star formation maser species, are playing a crucial role in determining the magnetic field morphology (Vlemmings et al. 2010; Surcis et al. 2012, 2013). Moreover, Vlemmings et al. (2006b, 2011) showed that at arcsecond resolution, methanol masers also display significant circular polarization. In fact, 70% of their total Effelsberg+Parkes flux-limited (>50 Jy) sample (51 sources) show circularly polarized emission. Excited OH masers are also useful but are located further away (Vlemmings et al. 2006a; Surcis et al. 2011, 2013, 2014).

A larger set of Zeeman-splitting detections towards high-mass star-forming regions is needed in order to provide inputs for numerical simulations of massive star formation.

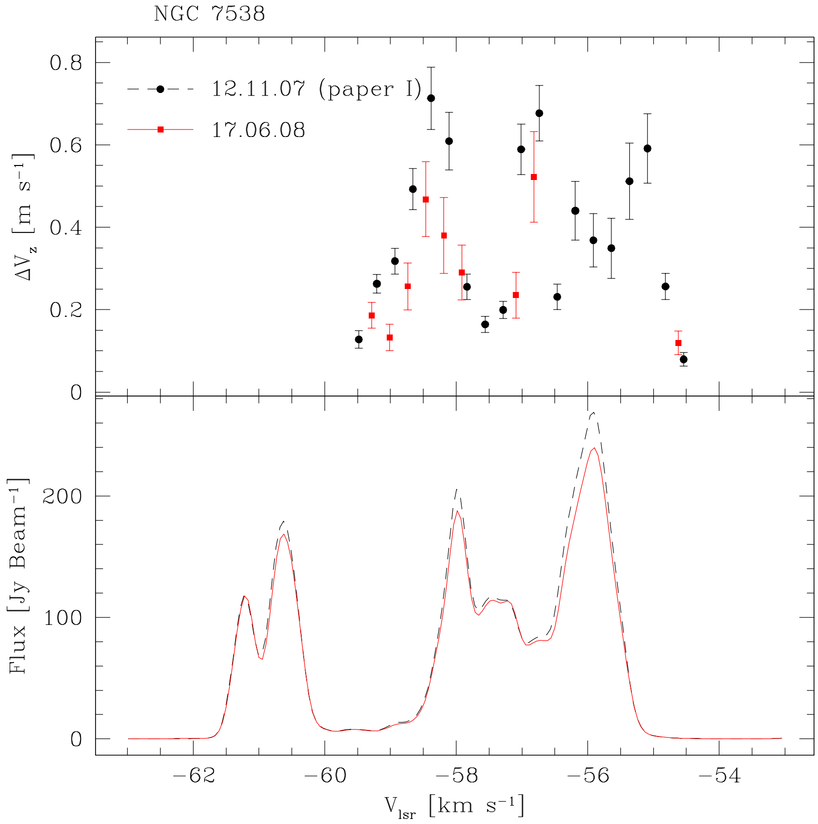

Fig. 1.— 6 GHz CH_3OH maser emission in G111.43+076 (NGC 7538). (*Bottom panel*) Stokes *I* emission. (*Top panel*) Zeeman splitting velocity separation for different maser componets. Red and black denote observing dates as labelled in legend. From Fig. 2 of Vlemmings et al. (2011).

Arecibo, with its huge collecting area, is uniquely suitable for this work. Masers having flux density exceeding ~ 4 Jy provide antenna temperatures that exceed the system temperature, the condition under which integration times are independent of flux density. Reaching the necessary 3σ limits of $\sim 0.1\%$ in Stokes V/I takes only a few hours for such cases. This makes hundreds of Galactic massive star-forming regions available for magnetic field measurements.

3. OH Masers in Circumstellar Envelopes (CSEs)

Evolved OH/IR stars commonly exhibit OH maser emission that probes the outer part of their CSEs where ordered magnetic fields with strengths of a few milligauss are detectable (Etoka & Diamond 2010, 2004). Such observations can trace fields even at the proto-planetary nebula stage (Etoka et al. 2009). Although they start their lives as spherically symmetric objects, a large fraction of planetary nebulae are asymmetrical objects. Whether the change of symmetry is linked primarily to binarity, the organized magnetic fields detected at the distances where OH masers operate in the CSEs seem to indicate the possible role of magnetism in this morphological development.

While VLBI gives us a snapshot of the magnetic field structure at a given time, single dish monitoring is the only way to follow the structural evolution of the magnetic field. Such monitoring can reveal abnormally strong polarization and the signature of magnetic field reversals, which are directly related to the stage of evolution (Etoka & Le Squeren 2004; Szymczak et al. 2001). Such studies are completely limited by the beam size, spectral resolution, and sensitivity achievable, meaning that only a handful of instruments around the world can perform such studies. Arecibo, with the smallest beam size currently available, its high spectral resolution, and unrivaled sensitivity, can prove invaluable in the study of magnetic fields in CSEs.

4. Carbon Radio Recombination Lines

Carbon Radio Recombination Lines (RRLs) sample dense photodissociation regions, where the hydrogen is molecular but the carbon is singly ionized. Natta, Walmsley, & Tielens (1994) find that the carbon RRLs in Orion come from very high density regions, $n_{\mathrm{H}_2} \sim 10^6$ cm^{-3}, with rather high temperatures, $T \sim$ 500–1000 K; the pressures are enormous. In the S 140/L 1204 complex, where the carbon RRL is weaker, the densities are only $\sim 10^4$ cm^{-3} (Smirnov, Sorochenko, & Walmsley 1995).

Zeeman splitting of the carbon RRLs offers a unique probe of the magnetic field in dense regions. Sensitivity is, of course, a serious issue; but an ameliorating situation is the ability to measure many RRLs simultaneously. For example, preliminary measurements by Robishaw & Heiles (private communication) find 3σ detections for S 88B and S 235 at the few-hundred μG level. Longer integration times would produce better sensitivity, but more likely is that spatial structure in the field reduces the beam-averaged field relative to values seen with higher angular resolution; detections should be followed up at the VLA.

5. Zeeman Splitting of H I in Shocks and Filaments

Heiles (1989) measured Zeeman splitting of Galactic H I in emission that was located in nearby walls of shells (shocks) and filaments and found field amplification, as is expected for shocks on theoretical grounds. Supershells and worms exist over a large range of Galactocentric radius and some of the most prominent objects have been identified (Heiles, Reach, & Koo 1996). Supershell and worm walls have swept up the gas and field from the interiors and such swept-up gas should constitute an important fraction of the CNM. Arecibo has the angular resolution required to isolate the gas in distant worm walls; the lines are fairly bright and the field strengths should be detectable in a few hours of integration. The distant objects may reflect the variation of field strength and direction with Galactocentric radius.

6. H I Absorption Lines against Background Continuum Sources

The magnetic field in the cold neutral medium (CNM) can be probed via the absorption of continuum emission from compact sources at 21 cm. This method was successfully used by Heiles & Troland (2004, 2005) at the Arecibo telescope to make the unprecedented "Millennium" survey of the CNM towards 41 radio-loud sources; 20 magnetic field components were detected throughout the Milky Way. 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 superAlfvénic. These observations supply 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 Millennium survey covered only about 1/3 of the total number of sources for which it could obtain useful results. Complete coverage of the Arecibo sky down to a limiting flux density of 2 Jy would supply about 150 additional sources for the expenditure of $\sim$ 2000 hours of telescope time.

7. OH Masers Tracing the Galactic Magnetic Field

Davies (1974) found the amazing result that the magnetic field measured in OH masers seemingly traces the large-scale field that the masers are embedded in. The "MAGMO" survey (Green et al. 2014) was launched at the Australia Telescope Compact Array (ATCA) in order to examine this enticing correlation and potentially map out the magnetic field in the Galactic plane by searching for Zeeman splitting in OH masers. MAGMO observations achieved a sensitivity of 50 mJy in 30 min of ATCA observing with an $8''$ beam, and consisted of targeted follow-up of positions where 6.7 GHz methanol masers were detected. This species of maser is an exclusive tracer of high-mass star formation and as such traces the key structural features of the Galaxy, the spiral arms, 3-kpc arms and bar interaction. The combination of structure and magnetic field information can be a very powerful tool for understanding the dynamics and evolution of the Milky Way.

VLBI observations of OH masers at the highest resolutions have demonstrated that maser Zeeman splitting shows field directions and magnitudes which are largely coherent (e.g. Fish et al. 2003; Vlemmings & van Langevelde 2007). The splitting is often replicated in the lower resolution single-dish studies (Fish et al. 2005; Szymczak & Gérard 2009). Following the work of Davies (1974), several authors have investigated the concept of maser Zeeman splitting tracing the Galactic magnetic field (e.g. Reid & Silverstein 1990; Fish et al. 2003; Han & Zhang 2007), finding fields consistent across kiloparsec scales. These studies consisted of samples of masers collated from a range of heterogeneous observations; the largest set of systematic observations were those of Fish et al. (2003), but these were limited to only 40 star-forming regions, all visible from the northern hemisphere, and with only a few masers per spiral arm. Despite these limitations, there is an implication that the magnetic fields traced by the masers are tied to the large-scale Galactic magnetic fields, such as those traced by rotation measures (e.g. Brown et al. 2007; Van Eck et al. 2011). The MAGMO project (Green et al. 2014) built on these with a systematic survey. A logical extension of the MAGMO project would be an Arecibo-complete survey for OH masers in the Galactic plane.

8. Zeeman Splitting in Extragalactic Megamasers

Masers have the highest luminosity per unit frequency of any radio source, so it is natural to use Zeeman splitting in these beacons to measure magnetic fields in distant galaxies. With Arecibo's sensitivity, OH megamasers are the prime targets. Megamasers have been detected in hundreds of galaxies at $z \sim 0.1$, and, with the aid of lensing, as far away as $z = 2.6$ (Castangia et al. 2011).

The most exciting use of OH megamasers has been the measurement of *in situ* magnetic fields by Robishaw et al. (2008) and McBride & Heiles (2013), who used the high spectral resolution of Arecibo to separate multiple Zeeman components and compared these with VLBI and MERLIN total-intensity lower-resolution spectra extracted from spatially-discrete regions. The inferred magnetic field strengths of 0.5–80 mG provide an energy density comparable to the hydrostatic gas pressure in the masing regions, likely to be active star formation sites. The results from OH megamasers also suggest that magnetic fields are dynamically important throughout the central starburst region, whereas weaker magnetic fields are inferred from radio synchrotron measurements assuming equipartition. The OH megamaser-derived estimates are consistent with the linearity of the far-infrared-radio correlation (McBride et al. 2014).

McBride (private communication) has recently been able to image the Zeeman splitting in the OH megamaser emission inside the interacting cores of Arp 220 using the High Sensitivity Array. This combines the NRAO Very Long Baseline Array, the NRAO Green Bank Telescope, the phased NRAO Jansky Very Large Array, and Arecibo. This powerful supertelescope can be used to map the fields throughout nearby starburst galaxies exhibiting OH megamaser emission, but this can currently only be done if Arecibo is included because of the sensitivity that it provides.

9. H I Absorption in Damped Lyα Absorbers

Damped Lyα absorbing systems (DLAs) are a class of quasar absorber in which hydrogen remains mostly neutral. The neutral gas content of the Universe is dominated up to redshift 5 by DLAs and the H I layers producing the absorption are considered to be the progenitors of modern galaxies. DLAs are perhaps the best and only sample of an interstellar medium in the high-redshift Universe (Wolfe et al. 2005). As such, the possibility of measuring Zeeman splitting in the 21 cm line absorption in these systems would allow us to test the importance of the role of magnetic fields in galaxy formation and evolution and constrain dynamo models for the generation and amplification of magnetic fields in the early Universe.

Wolfe et al. (2011, 2008) describe GBT observations of a DLA at $z = 0.692$ towards 3C 286. No Zeeman signature was detected in the Stokes V spectrum at 839.40 MHz down to a 3σ sensitivity of 17 μG. However, the integration time was only 12.6 hours. As explained in the original paper, when absorption lines are observed against a continuum source such as 3C 286, use of "self-calibration" to determine the system's polarization properties (i.e., the Mueller matrix) virtually eliminates instrumental errors, and integration times can be pushed to arbitrary limits. The only obstacle to obtaining physically meaningful limits for the field strength (say, ~ 1 μG) in a selection of sources is the willingness of the TAC to provide a few thousand hours of time!

REFERENCES

Brown, J. C., Haverkorn, M., Gaensler, B. M., Taylor, A. R., Bizunok, N. S., McClure-Griffiths, N. M., Dickey, J. M., & Green, A. J. 2007, ApJ, 663, 258

Castangia, P., et al. 2011, A&A, 529, A150

Crutcher, R. M., Troland, T. H., Goodman, A. A., Heiles, C., Kazes, I., & Myers, P. C. 1993, ApJ, 407, 175

Davies, R. D. 1974, in IAU Symp. 60, Galactic Radio Astronomy, ed. F. J. Kerr & S. C. Simonson (Dordrecht: Reidel), 275

Etoka, S., & Diamond, P. 2004, MNRAS, 348, 34

Etoka, S., & Diamond, P. J. 2010, MNRAS, 406, 2218

Etoka, S., & Le Squeren, A. M. 2004, A&A, 420, 217

Etoka, S., Zijlstra, A., Richards, A. M., Matsuura, M., & Lagadec, E. 2009, in Astronomical Society of the Pacific Conference Series 404, The Eighth Pacific Rim Conference on Stellar Astrophysics: A Tribute to Kam-Ching Leung, ed. B. Soonthornthum, S. Komonjinda, K. S. Cheng, & K. C. Leung, 311

Fish, V. L., Reid, M. J., Argon, A. L., & Menten, K. M. 2003, ApJ, 596, 328
Fish, V. L., Reid, M. J., Argon, A. L., & Zheng, X.-W. 2005, ApJS, 160, 220
Green, J. A., Gray, M. D., Robishaw, T., Caswell, J. L., & McClure-Griffiths, N. M. 2014, MNRAS, 440, 2988
Han, J. L., & Zhang, J. S. 2007, A&A, 464, 609
Heiles, C. 1989, ApJ, 336, 808
Heiles, C., Goodman, A. A., McKee, C. F., & Zweibel, E. G. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: Univ. Arizona Press), 279
Heiles, C., Reach, W. T., & Koo, B.-C. 1996, ApJ, 466, 191
Heiles, C., & Troland, T. H. 2004, ApJS, 151, 271
———. 2005, ApJ, 624, 773
Hennebelle, P., Commerçon, B., Joos, M., Klessen, R. S., Krumholz, M., Tan, J. C., & Teyssier, R. 2011, A&A, 528, A72
McBride, J., & Heiles, C. 2013, ApJ, 763, 8
McBride, J., Quataert, E., Heiles, C., & Bauermeister, A. 2014, ApJ, 780, 182
Natta, A., Walmsley, C. M., & Tielens, A. G. G. M. 1994, ApJ, 428, 209
Peters, T., Banerjee, R., Klessen, R. S., & Mac Low, M.-M. 2011, ApJ, 729, 72
Reid, M. J., & Silverstein, E. M. 1990, ApJ, 361, 483
Robishaw, T. 2008, Ph.D. thesis, University of California at Berkeley
Robishaw, T., Quataert, E., & Heiles, C. 2008, ApJ, 680, 981
Seifried, D., Banerjee, R., Pudritz, R. E., & Klessen, R. S. 2012, MNRAS, 423, L40
Smirnov, G. T., Sorochenko, R. L., & Walmsley, C. M. 1995, A&A, 300, 923
Surcis, G., Vlemmings, W. H. T., Curiel, S., Hutawarakorn Kramer, B., Torrelles, J. M., & Sarma, A. P. 2011, A&A, 527, A48
Surcis, G., et al. 2014, ArXiv e-prints
Surcis, G., Vlemmings, W. H. T., van Langevelde, H. J., & Hutawarakorn Kramer, B. 2012, A&A, 541, A47
Surcis, G., Vlemmings, W. H. T., van Langevelde, H. J., Hutawarakorn Kramer, B., & Quiroga-Nuñez, L. H. 2013, A&A, 556, A7
Szymczak, M., Błaszkiewicz, L., Etoka, S., & Le Squeren, A. M. 2001, A&A, 379, 884
Szymczak, M., & Gérard, E. 2009, A&A, 494, 117
Van Eck, C. L., et al. 2011, ApJ, 728, 97
Vlemmings, W. H. T., Diamond, P. J., van Langevelde, H. J., & Torrelles, J. M. 2006a, A&A, 448, 597
Vlemmings, W. H. T., Harvey-Smith, L., & Cohen, R. J. 2006b, MNRAS, 371, L26
Vlemmings, W. H. T., Surcis, G., Torstensson, K. J. E., & van Langevelde, H. J. 2010, MNRAS, 404, 134
Vlemmings, W. H. T., Torres, R. M., & Dodson, R. 2011, A&A, 529, A95
Vlemmings, W. H. T., & van Langevelde, H. J. 2007, A&A, 472, 547
Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2005, ARA&A, 43, 861
Wolfe, A. M., Jorgenson, R. A., Robishaw, T., Heiles, C., & Prochaska, J. X. 2008, Nature, 455, 638
———. 2011, ApJ, 733, 24