Zeeman observations: Measuring magnetic fields in the atomic and molecular ISM.

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Abstract

Magnetic fields are believed to play an important role in the dynamics of the ISM. The Zeeman effect in the 21 cm HI line, as well as in several molecular lines, can be used to characterize the magnetic fields in the interstellar medium and in circumstellar envelopes. Feasible Zeeman measurements are presently restricted to maser observations and few cases of strong thermal lines. The significant increase of sensitivity of the SKA telescope will allow us to carry out Zeeman measurements in different environments in a systematic way. However, special care should be taken to characterize and correct the instrumental polarization.

1 Introduction

In Astrophysics, the only way to directly measure magnetic fields is through polarimetric observations. In the case of interstellar medium (ISM) studies, the polarization can be detected from the following mechanisms (see [27] for a description of these mechanisms): synchrotron radiation, thermal dust emission, interstellar absorption (by dust particles) of background stars, Faraday rotation of ionized radiation, and spectral line emission. Under the presence of a magnetic field, the spectral transitions of molecules and atoms split into magnetic sub-levels (this is the so-called Zeeman effect). There are two different processes generating polarized emission of spectral lines as a consequence of this splitting. One is the so-called Goldreich-Kylafis effect [22] that produces linear polarization in molecular rotational transitions. This polarization arises when the magnetic sub-levels of the rotational have an unequal population. In order to have significant polarized emission, some special conditions should be fulfilled such as: anisotropic radiation, moderate optical depths, the excitation of the observed transition should not be dominated completely by collisions. By measuring the Goldreich-Kylafis effect, one obtains the direction of the magnetic field projected in the plane of the sky, but it does not provide information of the magnetic field strength. The second process is related with the fact that the different magnetic sub-levels have slightly different

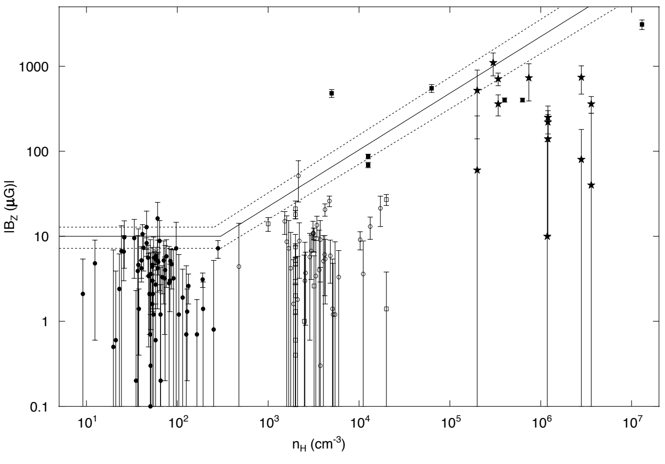

Figure 1: Set of diffuse cloud and molecular cloud Zeeman measurements of the line-of-sight component B_z of the magnetic field strength, plotted as a function of the volume density of H I (Figure 1 from [11]).

energies. Observationally, the resulting atomic and molecular transitions are partially circularly polarized. The circular polarized emission depends on the magnetic field strength along the line-of-sight and on the magnetic dipole moment. Only H I and molecules with an unpaired electron in the outer layer (i.e, radicals such as OH, CN, C_2S, C_2H) have magnetic moments high enough to the circular polarization to be detectable at radio wavelengths under the typical ISM magnetic field strengths. Masers are the exception, where their emission is so strong that the circular polarization can be relatively easily detected.

Here on, we focus on the science goals that can already be achieved with the SKA1 phase. The relevant feasible polarization mechanisms measurable with SKA1 are synchrotron radiation (see the chapter by Perez-Torres et al., this book), Faraday rotation (see the chapter by Battaner et al., this book) and the Zeeman effect. We note that we cannot discard that the Goldreich-Kylafis effect could be detected with SKA1 in some molecules with rotational transitions within the SKA1 frequency range (e.g. HC_3N). The polarization level of the interstellar radiation is, in most cases, very low (a few percent of the total intensity). These low polarization levels are comparable (and in some cases even lower) to the instrumental polarization produced in the radio telescopes (including aperture synthesis arrays). This requires an accurate determination and removal of this instrumental contribution from the telescope, making polarization observations difficult. As a result, and although the magnetic field is one of the main ingredients in the ISM, the studies of the interstellar magnetic fields have been relatively limited [23].

At radio wavelengths the Zeeman splitting has been measured in a small number of atomic and molecular lines (e.g., H I 21 cm line, OH 18 cm lines). The Zeeman observations provide a direct measurement of the magnetic field strength in the neutral atomic and molecular phases of the ISM. The studies based on the different polarimetric techniques have shown that magnetic fields are dynamically important in the evolution of the atomic and molecular

ISM, as well as in the star formation process (e.g., [23, 11, 10, 17, 18]). Figure 1 shows a recent compilation of magnetic field strengths as a function of the ISM volume density (measured from Zeeman observations of H I, OH and CN, [11]). Note that most of the measurements are upper limits and done with time-expensive observations, mainly with single-dish radio telescopes. The enormous increase of sensitivity and the angular resolution of SKA will allow us to obtain a significant improvement in this field. [31] has also recently described the science goals that can be achieved from Zeeman observations with SKA.

2 The Zeeman effect and SKA

For the typical magnetic field strengths measured in the ISM, the Zeeman splitting produced in spectral lines is extremely small, much smaller than their line width. Therefore, the effect of the Zeeman splitting can only be measured through circular polarization observations (with the exception of a few cases of maser observations at high angular resolution: e.g., [21]) and requires high spectral resolution ($\simeq$ 0.1–0.5 km s^{-1}). Figure 2 shows a typical example of a Zeeman detection in circularly polarized emission.

Within the SKA1 frequency coverage (specially at $\nu \geq 1$ GHz) there are a number of atomic and molecular transitions with strong Zeeman splitting factors (see presentation by Robishaw et al. at AASKA14). However, in many of them, the Zeeman effect has not yet been detected. The SKA1 sensitivity may allow us to expand the feasibility of the Zeeman effect detection to a larger sample of spectral lines. These will allow us to widen the sample of physical environments where the magnetic field can be measured. As previously stated, a problem of the radio astronomical polarimetric observations is that the instrumental polarization is of the same order of the polarized signal (in the case of Zeeman observations, polarized signal could be significantly smaller than the instrumental polarization). The present aperture synthesis radio telescopes correct the instrumental polarization on-axis. The large field of view of SKA implies that a special care would be necessary to characterize and correct the off-axis instrumental polarization (e.g., [33]).

3 Diffuse H I Medium

In the diffuse atomic ISM, the H I mass is distributed approximately half in the so-called Cold Neutral Medium component (CNM) and half in the so-called Warm Neutral Medium component (WNM). The Zeeman observations of the 21 cm H I line typically target regions with strong radio continuum sources. In these cases, the H I lines appear in absorption. This implies that Zeeman observations trace the magnetic fields in the CNM (the H I line opacity is inversely proportional to the gas temperature, so the H I absorption features are more sensitive to the colder H I diffuse component; [24]). The Zeeman observations of the H I line in emission, although technically more difficult (because of the instrumental polarization issues, [25]), can provide interesting results since it allows the mapping of large areas [25]. However, no positive detection of the Zeeman effect in the H I line in emission has been made with an aperture synthesis radio telescope [31]. SKA is going to provide a major step in

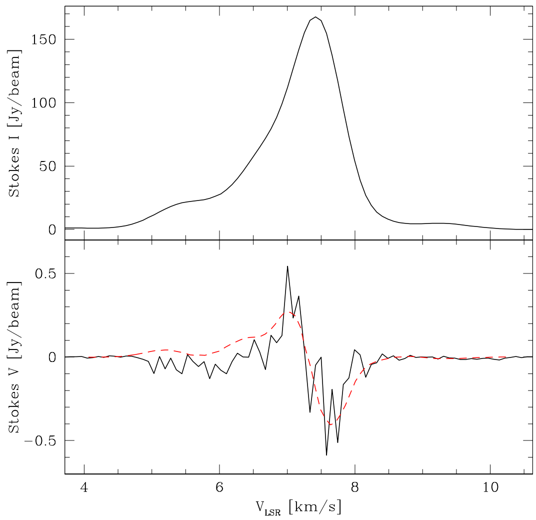

Figure 2: Typical spectra in Zeeman observations: Stokes I (total intensity, upper panel) and Stokes V (circular polarization, lower panel) spectra of the water maser emission at 22.23 GHz. The red dashed line is the scaled derivative of the total power Stokes I in order to guide the eye (Figure from [3]). Note that the water maser frequency will not be available for SKA1, but it will possibly be within the observing frequency for SKA2.

this field: SKA1 is expected to detect in a few hours of observation the Zeeman splitting of H I lines corresponding to (line-of-sight) magnetic fields strength of $\sim$ 1 μG, which in addition to the great imaging coverage (field of view and angular resolution) will improve the understanding of the magnetic field properties in the CNM (Robishaw et al. at presentation at AASKA14).

4 Molecular clouds and Star formation

The last decade has seen a significant progress in the characterization of the magnetic field distribution (more specifically the projected component on the plane of the sky) in molecular clouds and toward star forming regions (e.g., [16, 8, 40, 26]). However, there is a lack of direct measurement of the actual magnetic field strength [15, 32]. The most effective way to measure the magnetic field strength in molecular clouds at centimeter wavelengths is observing the 18 cm OH lines in absorption with respect to a strong continuum source, typically H II regions generated by massive young stars (e.g., [9], [6]). Observations of the Zeeman effect of the 18 cm OH lines in emission is also feasible, but because, in general the emission is weak, long observing times are required to obtain meaningful upper limits of the field strength, specially toward dark molecular clouds (see [32]). SKA will allow us to measure the magnetic field strength through OH observations of the 18 cm lines (regardless of the presence of H II regions) toward star forming molecular dense cores. However for the proper interpretation of the results, the chemistry of the OH should be well characterized in the observed regions, as its abundance may change significantly (specially toward the densest part of molecular clouds: e.g., [34]).

The OH masers (in the 18 cm lines) associated with high mass star forming regions are also used as a tracers of the Galactic magnetic field [21]. The Galactic ASKAP Survey (GASKAP, [12]) will already provide an unbiased, flux-limited survey of OH masers associated with high-mass star forming regions. This survey will serve as base to carry OH Zeeman observations with SKA1 towards a large amount of sources.
In addition, the 18 cm OH masers are also an excellent probe to study the ISM in nearby galaxies, but also in high redshift galaxies [28, 31].

Other type of masers that need a higher volume density to be excited (e.g., CH_3OH line at 6.7 GHz, OH line at 6.0 GHz: e.g., [14], [2]) can be used to more specifically study the role of the magnetic fields at the scales of few thousand AU in very dense and hot molecular environments around massive prostars.

A more complete information on the study of molecular clouds and star formation in the context of SKA to the can be found in the chapters of this book by Anglada et al., Osorio et al. and Martin-Pintado et al.

5 Circumstellar envelopes

An interesting phenomenological issue in the last phases of the stellar evolution is the morphological change from expanding spherical envelopes in the AGB phase to the mostly aspherical and very varied shapes of the PNs [5, 38, 4]. Among the interesting observational features is the presence of fast collimated outflows, with properties resembling those of the star forming regions and that cannot be produced by the stellar radiation pressure [7]. The origin of the asphericity is attributed to the influence of a binary companion, a disk, a magnetic field, or a combination of these [30, 37]. Most of the information on magnetic fields in circumstellar envelopes and proto-PN comes from polarization observations of maser emission, mainly from SiO, H_2O, OH (e.g., [1, 29, 20, 35]). Recently, polarization has also been detected in non-masing molecular lines [36, 19].

SKA1 is going to provide a significant step in understanding of the magnetic field in the last phases of stellar evolution through the observations of the maser emission of the 18 cm OH lines. Note, that a few thousand of OH masers have already been detected in different phases of evolved stars (e.g., AGB stars, young Planetary Nebulae: [13]). A high fraction of the OH masers exhibit polarized emission [39] . As in the case of high-mass star forming regions, GASKAP [12]) will obtain an unbiased, flux-limited survey of OH masers associated with evolved stars. The catalogue obtained could be used to carry out extensive studies to characterize the role of magnetic fields in the mass-loss processes of evolved stars, and how these depend on mass and evolutionary stage. Finally, we note that more information about the scientific contribution from SKA to the study of circumbinary envelopes can be found in the chapters of this book by Alcolea et al. and by Gomez et al.

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References

[1] Alcolea, J., Bujarrabal, V., & Gallego, J. D. 1989, A&A, 211, 187

[2] Al-Marzouk, A. A., Araya, E. D., Hofner, P., et al. 2012, ApJ, 750, 170

[3] Alves, F. O., Vlemmings, W. H. T., Girart, J. M., & Torrelles, J. M. 2012, A&A, 542, AA14

[4] Balick, B. 2012, IAU Symposium, 283, 53

[5] Balick, B.; Frank, A. 2002, ARA&A, 40, 439

[6] Bourke, T. L., Myers, P. C., Robinson, G., & Hyland, A. R. 2001, ApJ, 554, 916

[7] Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Sánchez Contreras, C. 2001, A&A, 377, 868

[8] Chapman, N. L., Davidson, J. A., Goldsmith, P. F., et al. 2013, ApJ, 770, 151

[9] Crutcher, R. M. 1999, ApJ, 520, 706

[10] Crutcher, R. M. 2012, AR&AA, 50, 29

[11] Crutcher, R. M., Wandelt, B., Heiles, C., Falgarone, E., & Troland, T. H. 2010, ApJ, 725, 466

[12] Dickey, J. M., McClure-Griffiths, N., Gibson, S. J., et al. 2013, PASA, 30, e003

[13] Engels, D., & Bunzel, F. 2013, Database of Circumstellar Masers v2.3

[14] Fish, V. L., & Sjouwerman, L. O. 2010, ApJ, 716, 106

[15] Falgarone, E., Troland, T. H., Crutcher, R. M., & Paubert, G. 2008, A&A, 487, 247

[16] Franco, G. A. P., Alves, F. O., & Girart, J. M. 2010, ApJ, 723, 146

[17] Girart, J. M., Rao, R., & Marrone, D. P. 2006, Science, 313, 812

[18] Girart, J. M., Beltrán, M. T., Zhang, Q., Rao, R., & Estalella, R. 2009, Science, 324, 1408

[19] Girart, J. M., Patel, N., Vlemmings, W. H. T. & Rao, R. 2012, ApJ, 751, L20

[20] Gómez, Y., Tafoya, D., Anglada, G., et al. 2009, ApJ, 695, 930

[21] Green, J. A., McClure-Griffiths, N. M., Caswell, J. L., Robishaw, T., & Harvey-Smith, L. 2012, MNRAS, 425, 2530

[22] Goldreich, P., & Kylafis, N. D. 1981, ApJ, 243, L75

[23] Heiles, C. 2009, Astro2010: The Astronomy and Astrophysics Decadal Survey, 2010, 121

[24] Heiles, C., & Crutcher, R. 2005, Cosmic Magnetic Fields, 664, 137

[25] Heiles, C., & Robishaw, T. 2009, IAU Symposium, 259, 579

[26] Hull, C. L. H., Plambeck, R. L., Kwon, W., et al. 2014, ApJS, 213, 13

[27] Klein, U., & Fletcher, A. 2015, Galactic and Intergalactic Magnetic Fields, Springer Praxis Books, 63

[28] Lo, K. Y. 2005, ARA&A, 43, 625

[29] Miranda, L. F., Gómez, Y., Anglada, G., & Torrelles, J. M. 2001, Nature, 414, 284

[30] Nordhaus, J., Blackman, E. G., & Frank, A. 2007, MNRAS, 376, 599

[31] Robishaw, T., Green, J. A., Surcis, G., et al. 2015, Proceedings of Science, in press, arXiv1503.01779

[32] Troland, T. H., & Crutcher, R. M. 2008, ApJ, 680, 457

[33] Uson, J. M., & Cotton, W. D. 2008, A&A, 486, 647

[34] Viti, S., Hartquist, T. W., & Myers, P. C. 2006, Ap&SS, 302, 109

[35] Vlemmings, W. H. T., Diamond, P. J., & Imai, H. 2006, Nature, 440, 58

[36] Vlemmings, W. H. T., Ramstedt, S., Rao, R., & Maercker, M. 2012, A&A, 540, L3

[37] Vlemmings, W. H. T. 2014, IAU Symposium, 302, 389

[38] van Winckel, H. 2003, ARA&A, 41, 391,

[39] Wolak, P., Szymczak, M., & Gerard, E. 2012, A&A, 535, A5

[40] Zhang, Q., Qiu, K., Girart, J. M., et al. 2014, ApJ, 792, 116