Cosmic Magnetic Fields: Their Origins and Properties

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This document is one of a series of “White Papers” prepared over Summer 2007 to demonstrate the potential of the Arecibo 305-m telescope for providing exciting, transformational science within the time frame of the next 5–15 years. Here, potential Arecibo “cutting-edge” contributions towards our knowledge of cosmic magnetic fields are considered. Magnetic fields are a constituent of the Universe that undoubtably plays a great role in its overall evolution, but they are poorly understood in almost every possible way. In this short survey of how Arecibo could be the “instrument of choice” to interested scientists, I move from our local corner of the Milky Way, represented by research on cool red stars and brown dwarves, to the possibility of studying magnetic fields in cosmologically large scale structures such as “supercluster galaxy filaments”.

1 The Magnetic Fields of Very Late-type Dwarf Stars

The detection of unexpectedly strong radio emission from some late-M, L and T dwarf stars has provided direct evidence for magnetic activity in substellar objects. However, the strength of the emission and the different activity patterns compared to X-rays and H-α (i.e. radio activity increases with later spectral type, while X-ray and H-α luminosity decreases) suggest that in these objects the magnetic field generation differs from that in early-type stars. It is presently unclear whether a different dynamo mechanism is active in these stars compared to the solar-type $\alpha\Omega$ mode found for radiative-convective objects. A valuable clue is the recent detection of periodic radio bursts in these objects with $P \sim 2-3$ hr (Berger et al., 2005, ApJ, 627, 960; Hallinan et al., 2006, ApJ, 653, 690), suggesting that close, planetary-mass companions could possibly excite the magnetic dynamo. VLBI observations present the *only* viable way to test this possibility, and perhaps find for the first time planets around late-M, L and T dwarfs. The persistent emission from these dwarf stars is at the sub-mJy level, while the periodic, circularly-polarized bursts can exceed 1 mJy, though only for a few minutes per period. Thus, the most sensitive VLBI observations possible are needed to study even the strongest examples. Of interest are, a) physical sizes to give evidence on whether the fields are confined to the corona, or more extended, providing constraints on the particle acceleration process, b) to compare the sizes and locations of the persistent and flaring emission components, and c) to look for stellar motion caused by a close companion. Clearly, Arecibo’s huge sensitivity contribution to any VLBI array will be vital.

2 The Magnetic Field of the Milky Way

Optical and radio polarization studies have established that the Milky Way and many nearby spiral galaxies have well-organized, large-scale magnetic fields (see Beck et al., 1996, ARA&A, 34, 155). The presence of coherent magnetic fields on large scales points to a powerful, ubiquitous process which organizes random motions into highly ordered structures. Galaxies and clusters of galaxies are likely formed from collisions of smaller constituents, and then are continually energized by galaxy mergers, stellar winds and supernovae. Thus, it is remarkable that the magnetic fields produced by the resulting complicated gas flows and electrical currents are some of the largest organized structures in the Universe. The dynamo mechanism, in which small-scale turbulent magnetic fields are amplified and ordered by cyclonic motions and differential rotation, is the preferred explanation to account for such structures (Beck et al. 1996), although dynamos are not fully understood and still face theoretical problems. The main rival is the "primordial field theory" which assumes that the observed magnetic field patterns arise directly from a pre-galactic magnetic field, distorted by galactic differential rotation. While this theory has major problems in explaining the fields in spiral galaxies, such a field may have provided the "seed" field for a dynamo.

The topologies of magnetic fields in galactic disks are broadly classified into axisymmetric (ASS), bisymmetric (BSS) and mixed (MSS) structure. The distinguishing symmetry axis between ASS and BSS galaxies is with respect to a 180° rotation of the disk. The field direction is unchanged following such a rotation for ASS galaxies, while the field direction reverses for BSS galaxies. Different mechanisms of field generation and maintenance lead to different symmetries. For example, the lowest-order dynamo mode yields an ASS structure, with the first excited-mode producing a BSS structure. Characterizing these symmetries is of fundamental importance for understanding how galactic fields are generated and maintained.

2.1 Faraday Rotation Studies and the Large-Scale Field

For external galaxies, polarized synchrotron emission provides valuable information on the geometry of the magnetic field, but no information about field direction. Since dynamo models are characterized by field coherence, the measurement of Faraday rotation is needed to provide the extra information required to understand dynamos and the fields that they generate. The Milky Way is an excellent "test-bed" to address these issues, as it covers a huge ensemble of background extragalactic sources, whose rotation measures (RMs) can be used to probe the three-dimensional magnetic field structure. Indeed, RMs for pulsars and extragalactic sources have led to the identification of field reversals in the spiral magnetic pattern of our Galaxy (for a recent discussion, see Brown et al., 2007, ApJ, 663, 258), and measurement of the polarity of the vertical structure of the field (e.g. Han et al., 1997, A&A, 322, 98); these are properties which are key to understanding the dynamo process, and establishing which dynamo modes operate in the Milky Way. The recent work from the IGPS (Brown et al., 2007) also suggests a strong correlation between the disc field and spiral arms.

In terms of radically improving the global picture, the sampling of RMs in the first Galactic quadrant is especially poor. The soon-to-begin GALFA Continuum Transit Survey (GALFACTS) and its Arecibo follow-ups will alter this. GALFACTS will cover the full Arecibo sky for the frequency range 1225 - 1525 MHz and measure the percentage polarizations, position angles and RMs of an estimated 30-40,000 extragalactic sources, where currently less than 2,000 such RMs are known over the whole sky. These RMs can be brought to superb precision via subsequent measurements over the other frequency bands available at Arecibo. Naturally, this would be most satisfactorily achieved using the widest possible frequency coverage at a single epoch, say 1 – 10 GHz via a broad-band feed on the 305-m telescope. Such wide-frequency coverage for a huge number of sources would allow both the detailed modeling of the large-scale structure of the Galactic field, and in-depth exploration of its small scale structure. It is significant that Arecibo is also the instrument of choice to augment the number of measured pulsar RMs over the same area of sky.

This vast catalog of RMs distributed widely over the sky will be the definitive tool for determining the detailed field structure of our Galaxy. Huge number of accurate RMs at high latitudes would offer the possibility of exploring magnetic fields in the halo, where to date only limited studies have been made (Han & Qiao, 1994, A&A, 288, 759), and of the disk-halo interface (Beck, 2001, Sp. Sci. Rev., 99, 243). The numerous "plumb-lines" through the halo provided by Arecibo RM measurements would reveal the geometry and symmetry of the halo field, providing a discriminant as to which dynamo mode(s) are operating, and perhaps whether a different dynamo operates in the halo compared to the disk. In the disk-halo interface region of exchange of mass and energy, magnetic fields are likely to play a very important role.

2.2 Smaller-scale Coherent Features

The discovery in interferometric images of highly structured arcmin-scale polarized features, both at high (e.g. Wieringa, 1993, A&A, 268, 215; Haverkorn et al. 2003, A&A, 404, 233) and low Galactic latitudes (Gaensler et al. 2001, ApJ, 549, 959; Taylor et al. 2003, AJ, 125, 3145), provide a challenging puzzle. These structures are superposed on the polarized emission of the diffuse Galactic synchrotron radiation, but themselves have no Stokes-I counterparts. It is thought that while the polarized "background" is intrinsically smoothly distributed, differential Faraday rotation by structures in the intervening magneto-ionic medium (the Faraday screen) imposes the fine structure on this. This phenomenon can be optimally investigated from Arecibo, which has both the appropriate frequency coverage and angular resolution for this, plus full spatial frequency coverage.

2.3 Turbulence in the Magneto-ionic Medium

Our view of the ISM as an equilibriated, quasi-static cloudy medium has been modified in recent years. Now, it is pictured more as a continually evolving, turbulent gas, with a broad range of temperatures, densities and ionization states (e.g. Ferrière 2001). Interstellar turbulence plays a critical role in a wide range of processes such as star formation, cosmic-ray propagation and the energy balance of the gas (e.g. Elmegreen & Scalo 2004, ARA&A, 42, 211). However, fundamental questions regarding the physical characteristics of the ISM turbulence and its driving sources remain unanswered.

Fluctuations in the RMs of extragalactic sources can be analyzed via their structure function. While this is usually well approximated by a power law whose slope reveals the nature of the ISM turbulence, its saturation gives the typical scale size for energy injection. The RM distribution can also reveal anisotropies. Further, Faraday tomography for the polarized Galactic background emission would allow the characterization of magneto-ionic fluctuations in the ISM as a function of position and environment throughout the Galaxy. Distinguishing between turbulence in the arm and inter-arm regions, and between the disk and the halo, are important aspects of such a study. With its 300-MHz bandwidth at 1.4 GHz, GALFACTS will be an important first step for such work. However, to achieve high resolution along the RM axis from Faraday tomography, even greater frequency coverage is essential, and background polarization studies at both higher and lower frequencies than L-band are needed. At higher frequencies, an Arecibo focal-plane feed array operating (say) between 4 and 8 GHz would be ideal for such work. For lower frequencies, Arecibo full-Stokes mapping, (possibly combined with higher spatial-frequency measurements from synthesis arrays; e.g. Kronberg et al. 2007, ApJ, 659, 267) could provide comparable resolution to the GALFACTS images.

2.4 Magnetic Fields and Star Formation

A largely unexplored question is the role of magnetic fields in the cold neutral ISM. However, such fields are thought to play an important role in the formation of molecular clouds and in generating the conditions for star formation (Heiles et al., 1993, in *Protostars* & *PlanetsIII*, 279). Sadly, observational data to impact theory are sparse. Recent CGPS results show polarization position angles variations of the synchrotron background that seem to be due to dust clouds. These are imposed by differential Faraday rotation as the synchrotron radiation propagates through the cloud. Wide frequency polarization mapping of nearby molecular clouds will provide a unique way to study the structure of magnetic fields in the molecular ISM. Further, wide frequency studies of the depolarization of background polarization by HII regions will allow determination of the physical conditions in the interiors of these objects.

2.5 Synergy with GLAST

The main processes producing γ-rays in our Galaxy are believed to be, a) brehmsstrahlung from the interaction of cosmic-ray electrons and the interstellar gas, and b) the decay of neutral pions produced in interactions between the gas and cosmic-ray protons and heavier nuclei. The former is thought to dominate at < 1 MeV, and the latter at energies higher than this. Similar distributions of γ-rays are found at low latitudes in both energy ranges, suggesting that the cosmic-ray heavy particle-to-electron ratio is constant over the Galaxy. If so, the γ-ray emissivity, η_γ, is proportional to the product of the cosmic-ray intensity and the *total* gas density (ρ), i.e.;

$$\eta_\gamma \propto N_0 \rho \tag{1}$$

where the cosmic-ray energy distribution is,

$$N(E)dE = N_0 E^{-\Gamma} dE \tag{2}$$

Now, for the synchrotron component of the Galactic radio emission, the emissivity is,

$$\eta_R \propto N_0 B_\perp^{(\Gamma+1)/2} \tag{3}$$

where $B_\perp$ is the magnetic field strength perpendicular to the line of sight.

The Galactic distributions of the three quantities, N_0, ρ and B, are of considerable interest. Arecibo can contribute significantly to a knowledge of ρ over the accessible sky as GALFA (via projects TOGS2 and I-GALFA) will provide, a) the 2-dimensional distribution of HI, while the thermal-nonthermal separation of the continuum emission mapped by the GALFACTS continuum survey will provide the 2-D distributions of b) the thermal emission from HII and c) the non-thermal synchrotron emission. The 2-D distribution of the molecular gas is already available from CO surveys of similar resolution. Hence, combining imminent Arecibo ALFA work with other radio data and the high-fidelity GLAST γ-ray background images, will provide the necessary information to "unfold" the 2-D distributions and derive the Galactic distributions of N_0, ρ and B. This would represent a major contribution to our understanding of the detailed distribution of the magnetic field in the disk of our Galaxy. Data from the same surveys will also be available for a study of the distribution of the magnetic field away from the central plane of the Galactic disk.

3 Magnetic Fields in Normal Galaxies

The understanding of magnetic fields in galaxies is of fundamental importance for understanding their formation and evolution. Previous linear polarization mapping of nearby spiral galaxies have suggested that magnetic fields and star formation activity in spiral arms are closely correlated (Beck et al. 1996; Sofue et al. ARA&A, 24, 459). However, there are indications of deviations from the large-scale structures both in spiral arms and in the centers of galaxies, and in several instances regular fields are concentrated between the optical spiral arms. The GALFACTS team will map the polarized emission in the largest nearby galaxies in the Arecibo sky, of which 17 are larger than 10 arcmin, with > 50 being larger than 7 arcmin. The positional variation of RM over a galaxy will be used to study the global magnetic field configuration, distinguishing between the two predominant configurations (see Section 2) of a global magnetic field in a spiral galaxy. We note that the number of well resolved galaxies increases quickly for frequencies higher than the 1.4 GHz used by GALFACTS, and a 4–8 GHz feed array would greatly increase Arecibo's potential in this field. In addition, Arecibo is the only single-dish telescope that can fill in fully the low spatial frequencies to VLA observations of such galaxies right up to that array's B-configuration.

With the Arecibo telescope, Heiles and collaborators have recently detected a large number of line-of-sight magnetic fields in the range 1–10 mG from the Zeeman splitting of OH megamaser emission components in a small sample of Ultra-Luminous Infra-Red Galaxies (ULIRGs). While the number of single-dish magnetic-field detections for this class of galaxy will doubtless multiply considerably over the coming few years, it also becomes crucial to discriminate whether these fields are typical of just the compact masing sites (often only a fraction of the total megamaser emission), or are representative of the ISM as a whole. VLBI Zeeman measurements can unambiguously measure magnetic fields, including line-of-sight direction, in individual compact maser spots and should answer the above question, while aiding our understanding of the structure and origin of the large-scale fields in ULIRGs. The fields in ULIRGs could either be due to dynamo action, or result from "flux freezing" of the combined fields of the merging galaxies that formed the ULIRG. The role of magnetic fields in the creation and fueling of any central AGN should also be elucidated. However, such VLBI observations will need the highest possible sensitivity, and the presence of Arecibo in arrays such as the HSA ("High Sensitivity Array") will be vital.

4 Magnetic Fields in AGN

Radio galaxies and quasars have been shown to possess huge RMs in the vicinity of their nuclei (Junor et al. 1999, MNRAS, 308, 955; Mantovani et al. 2002, A&A, 389, 58). The wide bandwidth potentially available with a 1 − 10 GHz receiver could measure the broadband depolarization properties of a huge number of radio galaxies and quasars. This would allow a tomographic investigation of the emission properties within the sources themselves in terms of field orientation and emission strength as a function of Faraday depth.

Polarization VLBI (pVLBI) offers unique insights into the radio-source phenomenon, although the low-to-moderate polarization levels of the majority of components within AGNs dictates the participation of the world's largest telescopes, up to two orders of magnitude greater sensitivity being required than for total-intensity VLBI of the same targets. High demand for Arecibo is anticipated for this endeavor, and its presence will often be the essential element for pVLBI success.

As an example of potential targets, many compact steep-spectrum radio sources (CSSs) have been shown to possess very large RMs, presumably due to dense cocoons of thermal gas that seem to offer a convincing explanation for the small CSS sizes. pVLBI certainly provide the details to investigate the situation. Further, since the plane of linear polarization is unaffected by gravitational lensing (in the weak field limit), pVLBI can play an important role in the discovery and study of gravitationally lensed objects.

Multi-wavelength pVLBI adds information about the opacity and Faraday depth of emitting regions, and pVLBI can probe the effects of shocks on the magnetic-field structure in jets. Arecibo's rapid frequency agility, together with that of the VLBA and the GBT, is vital for HSA studies of Faraday rotation. With frequency-agile pVLBI, it is straight-forward to map the distribution of rotation measure (RM) across the compact structure of AGNs, allowing us to study the over-lying emission line gas. Wardle & Roberts (1994, "Compact Extragalactic Radio Sources", 217) suggest using multi-wavelength pVLBI and the proper motions of VLBI components to probe the foreground Faraday screen of a nucleus with unprecedented resolution using both Faraday rotation and depolarization effects.

5 Magnetic Fields on Cosmic Scales

The existence of magnetic fields in and near the periphery of clusters of galaxies, and their implied μG-level strengths, poses the question as to whether significant fields exist on yet larger scales in the intergalactic medium (IGM), say on the scale of galaxy filaments found in cosmological large scale structure (LSS). If so, this offers a unique chance to investigate the intergalactic magnetic field strength and structure, as well as to measure the intergalactic Cosmic Ray spectrum and to define the propagation environment of ultra high energy cosmic rays. The achievement of these goals is important for solving unsolved puzzles in high energy astrophysics, astro-particle physics, the origin of cosmic magnetic fields, and the evolution of LSS. Faint, diffuse, synchrotron radiation has been detected beyond galaxy cluster boundaries (Kim et al. 1989, Nature 341, 720; Enßlin et al., 1999, "Diffuse Thermal and Relativistic Plasma in Galaxy Clusters", 21), and a first attempt to probe local LSS via Faraday rotation has been made by Xu et al. (2006, ApJ 637, 19).

Both the feedback of outflows driven by galactic black holes (BH) (e.g. Furlanetto & Loeb 2001, ApJ, 556, 619; Kronberg et al. 2001, ApJ, 560, 178) and the gravitationally-driven evolution of large scale cosmic filament structure (e.g. Ryu, Kang & Biermann, 1998, A&A, 335, 19; Dolag et al, 2004, J. Korean Ast. Soc., 37, 427) affect the physics of the IGM, and to understand both galaxy and LSS evolution over the redshift range of $0 < z \lesssim 15$, it is important to determine the strength and structure of intergalactic magnetic fields on size scales $10 - 100$ times that of galaxy clusters.

At present, faint synchrotron radiation is the most promising indicator of widespread magnetic fields. The detection of weak radio emission from cosmic ray electrons gyrating in intergalactic magnetic fields requires high sensitivity to both large and small scale structures at frequencies low enough that the synchrotron radiation is relatively intense. While most interferometers provide sensitive images of small scale structure, they inherently filter out structures broader than the angular size corresponding to their shortest spacings. In contrast, the largest single-dish antennas, with low noise receivers and vast collecting areas, provide enhanced surface brightness sensitivity for the detection of faint large scale emission, but have insufficient resolution to resolve blends of discrete radio sources. The answer is to combine the sensitivity of a large single dish with a well calibrated, wide-field interferometer that gives high precision images of smaller scale features and discrete sources.

Recently, Kronberg et al. (2007, ApJ, 659, 267) produced a deep, ~410-MHz image of an 8° diameter region in the "Great Wall" of galaxies near the North Galactic Pole using a combination of data from the Arecibo 305-m telescope and the wide-angle DRAO interferometer at Penticton. The complementary nature of the two instruments enabled production of a distortion-free image that is sensitive to radiation on scales from 8° down to that of an individual galaxy halo at the 100 Mpc distance of the Great Wall. The image reveals a remarkable distributed radio "glow" well above the detection limit, some of which appears associated with galaxies groupings near the Coma cluster. IGM magnetic fields of $\sim 10^{-7}\mu$G are implied on scales of up to ~ 5 Mpc. This deep, wide-angle search for continuum tracers of LSS demonstrates that intergalactic radio continuum glow is a different tracer of LSS baryonic matter than that represented by optical galaxy surveys. The next step will be to follow this up by imaging a much wider area to a similar sensitivity or deeper, possibly using a frequency near 330 MHz via a combination of Arecibo (via its soon-to-be-delivered, cryogenically-cooled, P-band receiver) and mosaiced VLA observations.