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A COMPREHENSIVE VIEW OF LARGE-SCALE MAGNETIC FIELDS, WITH EMPHASIS ON THE GALACTIC MAGNETIC FIELD NEAR THE SUN

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ABSTRACT

We examine the observations of large-scale magnetic fields in the Universe. We begin at the largest scale with clusters of galaxies and work our way down through galaxies and finally to the Milky Way, on which we concentrate in detail. We examine the observations of the Galactic magnetic field, and their interpretation, under the philosophy that the Galactic magnetic field is like that in other spiral galaxies. We use pulsar data, diffuse Galactic synchrotron emission, and starlight polarization data to discuss the Galaxy's global magnetic configuration and the uniform (B_u), random (B_r), and total (B_t) components of the field strength. We find disagreement among conclusions derived from the various data sets and argue that the pulsar data are not the best indicator for large-scale Galactic field. Near the Solar circle, we find that the azimuthal average of B_t is 4.2 μG and we adopt $B_u \sim 2.2$ and $B_r \sim 3.6$ μG. B_t is higher in spiral arms, reaching ~ 5.9 μG. B_t is higher for smaller R_{Gal}, reaching ~ 8.0 μG for $R_{Gal} = 4.0$ kpc. The pattern of field lines is not concentric circles but spirals. The inclination of the magnetic spiral may be smaller than that of the Galaxy's spiral arms if our sample, which refers primarily to the interarm region near the Sun, is representative. However, it is not inconceivable that the local field lines follow the Galaxy's spiral pattern, as is observed in external galaxies.

Key Words : magnetic fields

I. MAGNETIC FIELDS ON THE LARGEST SCALES

Detections of synchrotron radiation and Faraday rotation from clusters of galaxies provide secure evidence for intercluster magnetic fields. Mean Faraday Rotation Measures (*RM*s) of extragalactic radio sources located behind clusters of galaxies exceed those of a control sample (Kim, Tribble, and Kronberg 1991). Although there is a tight correlation of *RM* with mass flux in clusters with cooling flows (Taylor, Barton, and Gee 1994), the excess *RM*s are not restricted to clusters that have cooling flows(Goldschmidt and Rephaeli (1993). The excess *RM*, typically $\sim$ 30 rad m^{-2}, combined with typical electron densities derived from the thermal X-ray emission, requires $B_u \sim 0.02$ μG. Near the centers of the clusters the scale lengths for field variability become very much smaller and the field strengths larger; for example, for the Coma cluster the scale length becomes ≤ 1 kpc and the field strength $B_u \sim 8$ μG (Feretti *et al.* 1995).

Faraday rotation provides only the uniform component of the field and says nothing about the total field strength B_t. Furthermore, Faraday rotation relies on the presence of intergalactic electrons and may not sample the intracluster volume in an unbiased way. These difficulties could be avoided, deriving a more representative volume-average field strength, by comparing the observed radio synchrotron emission with radiation at other wavelengths. Unfortunately, the absence of observable radiation at other wavelengths means that these comparisons provide only lower limits for B_t. As it happens, there is only one cluster for which the derived lower limits are interesting: the Coma cluster. Comparing the observed radio synchrotron intensity with the upper limits on still-undetected inverse-Compton (IC) X-ray intensity provides $B_t \geq 0.1$ μG (Rephaeli, Ulmer, and Gruber 1994). A more recent larger lower limit, $B_t \gtrsim 0.4$ μG, is derived from the absence of γ-ray emission produced by the relativistic electrons interacting with the hot intracluster gas (Sreekumar *et al.* 1996). A second, but less direct and therefore less reliable estimator of B_t, uses the angular variability of the surface brightness of the synchrotron-emitting intracluster volume to estimate the scale length for variability of the field r_0; the smoother the emission the smaller r_0 and the larger B_t. This method yields $r_0 \approx 15$ kpc and $B_t \gtrsim 1$ μG for the Coma cluster (Tribble 1991). If B_t is, indeed, as strong as 1 μG, then the field is dynamically significant for the gasdynamics.

II. GALACTIC MAGNETIC FIELDS AT MODERATE COSMOLOGICAL REDSHIFTS

The first studies of Faraday rotation of quasars lying behind high-redshift galaxies concluded that the absorption line systems did indeed produce statistically significant *RM* detections (Welter, Perry, & Kronberg 1984) and also found that damped systems produced significantly higher *RM*s than undamped systems (Wolfe, Lanzetta, & Oren 1992); the former are thought to be galactic disks, while the latter may be extended halos. However, reconsideration of the systematic errors calls the statistical significance into question (Perry, Watson, & Kronberg 1993; Oren & Wolfe 1995).

Nevertheless, we feel that future studies will improve the statistics and regain the original conclusions. In particular, we suspect that larger *RM*s will be found in damped than undamped systems. There are two damped systems that exhibit high *RM*s, which makes the fraction very high (albeit statistically uncertain) compared to undamped systems. Also, a VLBI study of the remarkable damped system in front of PKS1229–021 measures *RM*s that change sign on a length scale that is similar to those seen for magnetic reversals in some nearby spiral galaxies (Kronberg, Perry, & Zukowski 1990) and the inferred magnetic field strength is a few μG.

III. MAGNETIC FIELD STRENGTHS AND CONFIGURATIONS IN NEARBY GALAXIES

Nearby external galaxies afford a "bird's-eye view" of the global field structure that is unattainable in the Milky Way (MW). In external galaxies, the intensity and polarization of the diffuse synchrotron radiation and its Faraday rotation are the primary observables. The synchrotron polarization shows that the field lines appear to follow the spiral arms very closely. In some cases, the magnetic spirals are better defined than the material spiral arms: two outstanding examples are the spiral galaxy NGC6946, in which the magnetic arms are particularly well defined in the interarm regions (Beck & Hoernes 1996), and the flocculent galaxy NGC5055, which has ill-defined material arms but a definite spiral field (Beck 1996). Theoretically, one expects the inclination angle of the field lines to be larger inside spiral arms than in interarm regions because of compression by the spiral density wave, but this is not observed. A minority of galaxies, which includes the MW, have extensive radio halos, indicating large scale heights for the magnetic field.

The parity of the azimuthal field is usually considered to be either axisymmetric spiral (ASS; even parity with respect to rotation by π about the rotation axis of the galaxy), or bisymmetric spiral (BSS; odd parity) and, from the theoretical standpoint, depends on the mechanism by which the field is produced. In a sample of 20 galaxies, only 3 are unambiguously classified: one (M81) as BSS and two (M31, IC 342) as ASS (Beck *et al.* 1996). These results may not be representative because detecting reversals in the magnetic field with radius requires high angular resolution, which is difficult to attain.

Magnetic field strengths in external galaxies cannot be unambiguously derived from Faraday Rotation measurements because electron densities are not measured independently. One can obtain an estimate of field strength from the synchrotron volume emissivity by assuming energy equipartition between relativistic particles and the magnetic field. The equipartition field strengths range from 4 μG for the "ring" in M33 to 12 μG for NGC6946 and 19 μG in NGC2276 (Buczilowski & Beck 1991; Hummel & Beck 1995). These are averages over the galaxies; the field strengths always increase towards the centers and often increase within spiral arms.

The assumption of equipartition is sometimes but not always reasonable. It is good for the MW (Heiles 1995, 1996a). However, field strengths in the starburst galaxy M82 and in the Magellanic Clouds greatly exceed the equipartition field (Chi & Wolfendale 1993). Unfortunately, there is unfortunately no way to determine whether equipartition holds in most galaxies.

For both observational and theoretical reasons, it is important to separate out the uniform component of the field $B_u \equiv \langle B \rangle$. At high frequencies, where Faraday effects are small, the best observational indication is the fractional polarization of the synchrotron radiation. In external galaxies, polarization universally decreases from typically $\gtrsim$ 30% in the outer parts (somewhat larger than the local MW) to a few percent in the main star forming regions (these polarizations correspond to $B^2_{\perp,u}/B^2_{\perp,t} \sim 0.4$ and 0.04, respectively).

Polarizations are smaller in spiral arms than in interarm regions. This is attributed to the dynamical effects of massive stars, which deliver momentum and energy to the interstellar gas through powerful winds during their lifetimes and through supernova explosions when they die. Both phenomena lead to bubble-like spherical distortion of the field and to the generation of hydromagnetic turbulence as the remnants cool and break up (McCray & Kafatos 1987) and interact with interstellar clouds (Spitzer 1982; Miesch & Zweibel 1994).

IV. MAGNETIC FIELD STRENGTH AND CONFIGURATION IN THE MILKY WAY

In the MW we see the details—the "trees" instead of the "forest". On scales of a few kpc, polarimetry of thousands of stars shows that B_u is parallel to the galactic plane (Mathewson & Ford 1970), while field strength and direction are derivable from the RMs of galactic pulsars (Rand & Lyne 1994) and of extragalactic radio sources (Clegg *et al.* 1992). Once local features are properly removed, the mean field directions found by these two methods are similar. The starlight data, which we believe are superior on both statistical and systematic grounds, reveal a spiral field inclined to the azimuth by 7.2°± 4.1° (Heiles 1996b), which probably differs significantly from the local spiral arm inclination of 12.5°. The RM data show two reversals in field direction interior to the solar circle (Rand & Lyne 1994), both between spiral arms, as is also seen in the BSS galaxy M81 (Krause, Beck, & Hummel 1989). There may also be two reversals in the outer galaxy (Clegg *et al.* 1992). These reversals might be evidence for BSS structure of the MW, but ASS symmetry can exhibit reversals, too (Valleé 1996). These reversals need to be probed further by measuring RMs from many pulsars in the southern hemisphere.

The magnitude of B_u derived from pulsar RM data is $1.4 \pm 0.2 \mu$G. As this method samples primarily the warm ionized gas (WIM), this value may not be representative. Below, we argue that B_u is actually larger.

There are three ways to estimate B_u^2/B_t^2 in the MW (Heiles 1996a). First, the Galactic diffuse synchrotron background near longitude $\ell \sim 180°$ is about 22% polarized, implying $(B_u^2/B_t^2) \approx 0.3$ (Spoelstra 1984). Second, the analysis of pulsar data implies a random field strength $\sim 5\ \mu$G (Rand & Kulkarni 1989; Ohno & Shibata 1993), and so implies the much smaller value $B_u^2/B_t^2 \approx 0.07$. Third, the dispersion of infrared and optical polarization of starlight implies $B_u^2/B_t^2 \sim 0.45$ (Jones, Klebe & Dickey 1992).

The latter two data sets also provide estimates of the scale length for variability r_0, but the scale lengths differ, being ~ 100 pc for the pulsars and 500 to 1000 pc for the starlight polarization. This discrepancy is so large that it is probably real. Much smaller scale lengths are obtained from measurements of the angular structure function of *RM*s of extragalactic sources (Minter & Spangler 1996). This analysis leads to $r_0 \sim 7$ pc and $B_r \sim B_u$.

The differences in large-scale field structure, scale length, and the degree of field randomness derived from different observational probes are not well understood (Zweibel 1996). Heiles (1996a) discusses some of these differences and settles on values for both the Solar vicinity and the main star-forming region of the MW, which is about half way to the Galactic Center. Near the Sun he adopts $B_u = 2.2\ \mu$G and $B_u^2/B_t^2 \sim 0.27$.

In addition to evidence for random fields in the aggregate, we see individual examples of fluctuations. On scales of ~ 100 pc we see magnetic perturbations in the form of large interstellar shells produced by individual and clustered supernovae. This is evident for nearby objects in the optical polarization of starlight, and spectacularly so in the case of the North Polar Spur (Radio Loop I; Egger 1995), which is the huge ($\sim 120°$ diameter) circular structure centered near $(\ell, b) \sim (-30°, 20°)$ that is so obvious in maps of stellar polarization. Measurements of Zeeman splitting of the 21-cm line (Heiles 1989; Myers *et al.* 1995) and Faraday rotation measures (Valleé 1993) show that the magnetic field is enhanced in shells, and the shells are fairly thick, as expected from theory (Ferrière, MacLow, & Zweibel 1991).

At the ~ 10 pc scale, starlight polarization maps show magnetic distortions near molecular clouds. The dense gas near the Orion nebula is associated with a highly perturbed field, which can be interpreted fairly successfully as being deformed by the multiple supernovae explosions that produced the Eridanus Loop (Heiles 1997). In contrast, the polarization map of the Taurus complex exhibits a large-scale wavy pattern whose physical significance remains obscure (Goodman *et al.* 1990). Although there were suggestions that the shapes of the molecular clouds were related to the direction of the local magnetic field in these patterns, it is now known that there is no systematic relation (Goodman *et al.* 1990). Thus, in contrast to shells, which are reasonably well understood, the nature of these smaller scale features in molecular gas remains mysterious.

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