PHYS:7730 Example for Literature Review

Galactic Dynamics with Magnetic Fields

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1 Magnetic Fields in the Universe

The identification of a non-thermal radio emission from the interstellar medium of the Milky Way as synchrotron radiation (Alfven and Herlofson, 1950; Keipenheuer, 1950; Shklovskii, 1953)—radiation emitted by relativistic electrons in a magnetic field (Schwinger, 1949)—marked the first chapter in the study of astrophysical magnetic fields. Subsequent Faraday rotation measure studies of the Milky Way (Davies, 1968) demonstrated that a magnetic field coherent on kiloparsec scales permeates the disk of our Galaxy. The mechanism by which such a large-scale field can be generated and maintained has provoked heated debate among galactic astronomers. Current observations demonstrate magnetic fields ordered on kiloparsec scales of microgauss strength both within galaxies and in clusters of galaxies; a swarm of theories have been proposed to explain various observations. But a complete picture of the origin and evolution of magnetic fields in the universe requires a synthesis of observations and concepts over all time and space scales, from the Big Bang to the present day, from the immense voids of intergalactic space to the subparsec scales of magnetized outflows from accretion disks.

Proposed theories for the origin and evolution of magnetic fields fall into four general categories:

1. Cosmological Generation: Cosmological magnetogeneration before recombination
2. Protogalactic Dynamo: Dynamo amplification during structure formation
3. Galactic Dynamo: Galactic dynamo production of magnetic fields and ejection of fields into intergalactic regions
4. Compact Objects: Magnetization of large volumes of intergalactic space by highly magnetized jet outflows from compact objects

Numerous variants on these theories exist, as well as the possibility that a combination of these mechanisms may be operating.

For much of the universe the magnetohydrodynamic (MHD) equations provide an accurate description of the dynamics of magnetic fields (Shu, 1992). In the MHD approximation, the magnetic field is evolved according to the induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{\eta}{4\pi}\nabla^2 \mathbf{B}, \tag{1}$$

where η is the magnetic diffusivity, or molecular resistivity. The first term on the right hand side is the inductive term, the second is the diffusive term. The ionized interstellar medium is highly conductive so the diffusive term tends to be important only for magnetic fields at small scales. A useful approximate formula for the magnetic diffusivity (in the range of conditions considered here) is given by

$$\eta = \frac{10^7 \text{ cm}^2/\text{s}}{T^{3/2}} \tag{2}$$

where the temperature T is given in eV. The plasma temperature in the interstellar medium varies enormously but the hot component is typically $T > 3$ eV. We can estimate the length scale below which resistivity will destroy the magnetic field over the lifetime of the universe, $\tau \sim 10^{10}$ years. This scale can be approximated by

$$L \sim \sqrt{\eta\tau/4\pi} \sim 10^{11} \text{ cm} \sim 10^{-8} \text{ pc} \tag{3}$$

At scales much larger than this, the resistive term may be neglected and the magnetic flux evolves as a frozen-in component to the interstellar medium (Shu, 1992). For a frozen-in magnetic flux, one can derive a scaling relation between the magnetic field strength and the density of the interstellar medium given an isotropic expansion or collapse when the field is too weak to influence the dynamics,

$$B \propto \rho^{2/3}. \tag{4}$$

Likewise, the length scale of the magnetic field under the same conditions scales with density as

$$l_B \propto \rho^{1/3}. \tag{5}$$

In order for the magnetic field to change in time by (1), the field must initially be nonzero. If a magnetic field does not exist in the initial conditions of the universe, the inclusion of non-MHD effects to generate a seed magnetic field is required. Hence, theories typically require two separate processes to generate the microgauss fields we observe today: the generation of an extremely weak seed field followed by a more efficient dynamo process to amplify that seed field on cosmologically short time scales to the presently observed magnitude. In most cases, the dynamo must be responsible for a field strength amplification of 10–15 orders of magnitude.

The majority of mechanisms for the generation of seed magnetic fields are based on a battery mechanism driven by non-parallel pressure and density gradients. Biermann (Biermann, 1950) suggested keeping a pressure term in Ohm's Law, a term that is dropped in the MHD approximation, resulting in an extra term in the magnetic induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{\eta}{4\pi}\nabla^2\mathbf{B} + \frac{c\nabla p_e \times \nabla n_e}{n_e^2 e} \tag{6}$$

where p_e is the electron pressure and n_e is the electron number density. This extra "battery" term in the induction equation generates magnetic field from zero-field initial conditions. This battery effect is a natural consequence of the fact that electrons and ions have the same charge but different mass. Any phenomenon that drives a non-barotropic flow, $p_e \neq p_e(n_e)$, leads to magnetic field generation through this battery effect. Although Biermann introduced the idea to explain the generation of magnetic fields in stars, a number of other plausible astrophysical causes for the battery production of magnetic fields have been proposed; most of the seed field generation mechanisms discussed below differ in detail but are based in general on this Biermann battery effect. Note also that the presence of two gradients in the battery term means that the battery term becomes non-negligible only at small scale. The seed fields thus generated are on the same scale as the smallest structures in the environment; depending on the epoch of generation, however, these "small" scales may correspond to large scales, perhaps megaparsec scales, in the present day universe. A final point concerns the relative importance of the two terms in (6) as the magnetic field evolves. Initially, for zero or small magnetic field, the battery term dominates, typically effecting linear growth of the magnetic field at small scales. But as this seed field grows, the magnitude of the inductive term approaches that of the battery term. An estimate of the magnetic field strength at which these two terms are equal is informative. For a variation length scale L, the terms are approximately equal when

$$\frac{vB}{L} \sim \frac{cp_e n_e}{n_e^2 e L^2}. \tag{7}$$

Substituting $p_e = n_e k T_e$ and solving for B results in the expression

$$B \sim \frac{ckT_e}{veL}. \tag{8}$$

A typical temperature of the ionized component of the protogalactic medium is $T \sim 3$ eV. Assuming thermal equilibrium between the ions and electrons in the protogalactic plasma $T_e \sim T_i$, estimating the velocity as the ion thermal velocity $v_{T_i} = (kT_i/m_i)^{1/2}$, and taking the range of fluctuation lengths to be $L \sim 1$ pc to 1 kpc, the range of magnetic field strengths at which the two terms are equal is $B \sim 10^{-19}$G to 10^{-16}G. For field strengths much greater than this, the inductive term dominates, yielding exponential growth of the magnetic field if there exists any shear in the velocity field. This clarifies why a combination of two separate mechanisms are needed to explain the presently observed magnetic fields.

In a highly conducting medium, two types of turbulent dynamo are currently known: the *isotropic dynamo* and the *mean-field dynamo*. The isotropic dynamo—also known as the small-scale or fluctuation dynamo—operates in any homogeneous, isotropic turbulent flow by amplifying the magnetic energy by the random stretching of field lines (Batchelor, 1950; Kazantsev, 1968; Kulsrud and Anderson, 1992). Although the isotropic dynamo is indeed a dynamo by virtue of amplifying the magnetic energy at the expense of turbulent kinetic energy, it does *not* amplify the mean magnetic field. Thus, the isotropic dynamo produces a strong but highly tangled magnetic field; the bulk of the magnetic energy is concentrated at small scales (Kulsrud and Anderson, 1992; Maron et al., 2004). The growth rate of the magnetic field by the isotropic dynamo is determined by the turnover time of the smallest scale eddies in the turbulent cascade; these small eddies have short turnover times so this dynamo amplifies fast. In contrast, the mean field dynamo depends on anisotropy in the turbulence to achieve mean-field amplification via the α–Ω dynamo (Moffatt, 1978; Parker, 1979; Ruzmaikin et al., 1988). The requisite anisotropy—typically provided by rotation, stratification, shear, or strong magnetic fields (Beck et al., 1996)—leads to a non-zero helicity in the turbulent velocity field. This helicity is what leads to an amplification of the mean field. The mean-field dynamo has a growth rate typical of the turnover rate of the larger scale eddies; the turnover time for these large eddies is long, yielding a slow dynamo. Most studies of dynamo growth have concentrated on *kinematic growth* where the field is too weak to affect the flow. Both the isotropic and the mean-field dynamos will figure prominently in the following discussion of magnetic field generation and maintenance.

I define now some terminology to clarify the discussion:

Interstellar Medium (ISM) the medium filling the galaxy

2 Galactic Magnetic Fields—Observations

Observations of magnetic fields in spiral galaxies show a uniform field component of strength 3–4 μG ordered on kiloparsec scales (Beck et al., 1996; Zweibel and Heiles, 1997). The ratio of uniform, or large-scale, magnetic field strength to random, or small-scale, magnetic field strength is typically around 0.5, but can drop to about 5% in regions of vigorous star formation (Zweibel and Heiles, 1997). Since polarized synchrotron emission and Faraday RM measurements depend differently on the magnetic field volume filling factor, the near equivalence of coincident measurements by each method suggests that the filling factor is not very small (Beck et al., 1996). Magnetic field intensities typically increase towards the galactic center and within spiral arms with a larger proportion of magnetic energy at smaller scales in these regions. The field appears to be more well-ordered in interarm regions and in the outer parts of the galactic disk (Kronberg, 1994). Strength of the ISM magnetic fields appear to decline more slowly than disk matter density with galactocentric radius (Nelson, 1993; Battaner et al., 1991). Magnetic field strengths appear to correlate with the neutral hydrogen column densities in galactic disks and in molecular clouds (Han and Qiao, 1994).

Coherence scale measurements within the Milky Way are not consistent in the estimation of the size and magnitude of the small-scale magnetic field. For a total magnetic field given by $B_t^2 = B_u^2 + B_r^2$, where B_u is the largest scale component and B_r is the magnitude on smaller scales, polarization measurements of synchrotron radiation suggest $B_u^2 \sim 0.5 B_r^2$ (Spoelstra, 1984) while pulsar RM data yield $B_u^2 \sim 0.1 B_r^2$ (Rand and Kulkarni, 1989; Ohno and Shibata, 1993). A variety of measurement techniques have found evidence for fluctuation over distance scales from less than a parsec (Minter and Spangler, 1996) to 50–100 pc (Rand and Kulkarni, 1989; Ohno and Shibata, 1993) to 1 kpc (Jones et al., 1992). Each of these methods samples only a limited range of fluctuation sizes, and each measurement finds a fluctuation at least as large as the uniform field; in some cases it is possible the measurement samples a localized fluctuation atypical of the Galactic disk as a whole. Howard and Kulsurd (Howard and Kulsrud, 1997) argue that the belief that the magnetic field in the galaxy does not reverse on small scales is based on the analyses (Rand and Kulkarni, 1989) of rotation measures of pulsars (Hamilton and Lyne, 1987) that employed only models with fields that changed on scales of the order of 1 kpc.

The dominant energy density is the kinetic energy of the galactic rotation in balance with the gravitational potential energy of the galaxy. Below these, the energy density of the magnetic field is typically in equipartition with the thermal energy density, the cosmic ray energy density and the kinetic energy density of the small-scale turbulent motions (Kronberg, 1994; Grasso and Rubinstein, 2001). In the Magellenic Clouds and M82, however, the magnetic fields seem to be stronger than equipartition with the turbulent kinetic energy (Zweibel and Heiles, 1997).

The geometry of the galactic magnetic field is typically a global field organized on a grand scale, often similar to spiral structure of the ISM density. The azimuthal structure is typically characterized as an Axisymmetric Spiral Structure (ASS) or a Bisymmetric Spiral Structure (BSS); the vertical structure is characterized as odd (dipolar) or even (quadrupolar). Observations show examples of galaxies with field of each type and some galaxies show a mixed structure (Beck et al., 1996). A Fourier decomposition of annular rings of the magnetic field are usually well fit by a combination of only the $m = 0$ and $m = 1$ components, indicating a genuine global structure (Beck et al., 1996). The pitch angle of the magnetic field is typically about $p = -(10°\text{–}35°)$ inclined to the azimuth (Beck et al., 1996). RM data give an indication of two reversals of azimuthal field direction within the solar orbit in the Milky Way (Rand and Lyne, 1994); there is also evidence for two more reversals outside of the solar circle (Clegg et al., 1992). Magnetic field reversals have also been observed in M81 (Krause et al., 1989). At Galactic Center of the Milky Way, a strong vertical magnetic field of approximately 1 mG is inferred from observations of nonthermal radio filaments (Morris and Serabyn, 1996); this strong central field is estimated to contain a significant fraction of the total vertical magnetic flux in the Galaxy (Chandran et al., 2000).

Some galaxies show an extensive radio halo indicating large scale heights for the magnetic field (Zweibel and Heiles, 1997). The magnetoionic scale height of the Milky Way is 1.4 kpc (Simard-Normandin and Kronberg, 1980) and the scale height of the hot gas is approximately 1 kpc (Kulkarni and Heiles, 1987; Reynolds, 1990). External edge-on galaxies show full synchrotron widths of 2–4 kpc (Klein et al., 1984; Hummel, 1990). Larger halos are typically observed in galaxies with increased star formation activity. Halo magnetic fields are typically associated with outflowing winds driven by supernovae and related stellar activity (Heiles, 1987).

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