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IN SITU ORIGIN OF LARGE-SCALE GALACTIC MAGNETIC FIELDS WITHOUT KINETIC HELICITY?

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ABSTRACT

The origin and sustenance of large-scale galactic magnetic fields has been a long-standing and controversial astrophysical problem. Here an alternative to the "standard" α-Ω mean field dynamo and primordial theories is pursued. The steady supply of supernovae-induced turbulence exponentiates the total field energy, providing a significant seed mean field that can be stretched linearly by shear. The observed microgauss fields would be produced primarily within one vertical diffusion time since it is only during this time that linear stretching can compete with diffusion. This approach does not invoke exponential mean field dynamo growth from the helicity α-effect but does employ turbulent diffusion, which limits the number of large-scale reversals. The approach could be of interest if the helicity effect is suppressed independently of the turbulent diffusion. This is an important but presently unresolved issue.

Subject headings: galaxies: magnetic fields — Galaxy: general — ISM: magnetic fields

1. INTRODUCTION

Magnetic fields are important to dynamics or emission in almost all astrophysical systems. The formation of observed microgauss, large-scale magnetic fields in the interstellar medium (ISM) of spiral galaxies has been considered a fundamental unsolved astrophysical problem (Beck et al. 1996; Zweibel & Heiles 1997). There is an important distinction between the large- and small-scale magnetic fields observed in the ISM. Observations suggest that the small-scale field is typically ordered on subkiloparsec scales and that a large-scale, primarily azimuthal mean field is superimposed on that. While it is more or less agreed that the small-scale component of this field is injected and sustained by supernovae turbulence (e.g., Beck et al. 1996), the generation of the large-scale field is where the main controversy lies.

Whether the large-scale fields are of primordial origin or whether they are produced in situ is difficult to determine observationally, and both "standard" competing explanations suffer from difficulties. For example, even if primordial fields could be produced, in situ processing of the field during the galactic lifetime needs to be addressed and would likely dominate the present character of the observed field. The standard in situ mean field "α-Ω dynamo" (Parker 1979; Moffatt 1978; Ruzmaikin, Shukurov, & Sokoloff 1988) has been threatened by some nonlinear simulations (e.g., Tao, Cattaneo, & Vainshtein 1993; Cattaneo & Hughes 1996). While stretching of field lines by differential rotation (which provides the "Ω-effect") is not controversial, the helical property of the turbulence (which provides the "α-effect") and the turbulent diffusion (the "β-effect") may be suppressed. Here I suppose that the α-effect is suppressed but that the β-effect is not. Whether these two effects can be disentangled is unclear (Field & Blackman 1997), but the possibility can still be explored.

Turbulent amplification of the small-scale field can provide a steadily supplied seed mean field (MF) whose subsequent stretching by differential rotation may produce and sustain large-scale galactic magnetic fields without a dynamo α-effect or a primordial seed. I first give the basic magnetic MF equations and summarize the complications of standard MF dynamo theory. The MF equation is then solved without the α-effect, but keeping in turbulent diffusion. It is shown that in one vertical diffusion time, differential shearing can increase the MF by an order of magnitude. It is also shown that the MF is maximized on a radial scale of 1 kpc or so: turbulent diffusion tends to favor large-scale field stretching, but this competes with the seed field's inverse dependence on scale. Simple statistical arguments are then used to predict the most likely number of reversals. That the small-scale field is not necessarily dominant on only one scale is also emphasized. The assumptions employed here are no more controversial than those in standard MF theory. Generally speaking, MF theory as applied to the Galaxy is most certainly an oversimplification, but it does provide a useful framework from which some understanding can be gained.

2. ASPECTS OF STANDARD THEORY

Writing the magnetic field (and velocity) as a sum of mean and fluctuating components, i.e., $\boldsymbol{B} = \overline{\boldsymbol{B}} + \boldsymbol{B}'$, the MF equation can be obtained by spatially averaging the magnetic induction equation over scales that are large compared with the fluctuations but small compared with the overall scale of the system (e.g., galaxy):

$$\partial_t \overline{\boldsymbol{B}} = \boldsymbol{\nabla} \times (\overline{\boldsymbol{v}} \times \overline{\boldsymbol{B}}) + \boldsymbol{\nabla} \times \langle \boldsymbol{v}' \times \boldsymbol{B}' \rangle + \nu_M \nabla^2 \overline{\boldsymbol{B}}, \qquad (1)$$

where $\boldsymbol{v}$ is the velocity, ν_M is the magnetic diffusivity, and the primed and barred (or bracketed) quantities indicate fluctuating and mean values, respectively. The turbulent electromotive force in equation (1) can be written $\langle \boldsymbol{v}' \times \boldsymbol{B}' \rangle = \alpha_{ij}(\boldsymbol{B}, \boldsymbol{v}) B_j - \beta_{ijk}(\boldsymbol{B}, \boldsymbol{v}) \nabla_j B_k + \ldots$, where the ellipsis indicates higher order gradients. In linear kinematic dynamo theory for isotropic incompressible plasmas, $\alpha \propto \langle \boldsymbol{v}' \int \boldsymbol{\nabla} \times \boldsymbol{v}'(t') dt' \rangle$ and $\beta \propto \langle \boldsymbol{v}' \int \boldsymbol{v}'(t') dt' \rangle$. In dynamic, nonlinear theory, these can be functions of $\boldsymbol{B}$ and are not necessarily isotropic.

In the standard α-Ω dynamo ($\alpha\Omega D$) applied to the Galaxy (e.g., Ruzmaikin et al. 1988), supernovae-induced turbulent eddies on ~100 pc scales stretch field lines into loops or cells. The Coriolis force, in principle, conspires to twist statistically all of these loops in the same direction, providing a much larger scale mean loop. This, resulting from the large-scale reflection asymmetry, provides the nonvanishing pseudoscalar α-effect (Parker 1979; Moffatt 1978). The outer portions of these loops must incur turbulent diffusion in order to leave a net mean flux in each hemisphere of the Galactic disk (Parker 1979). The large-scale field formed in this way is further sheared by differential rotation (the Ω-effect), providing a new toroidal field and starting the process again. In principle, this feedback leads to exponential MF growth of a primarily azimuthal field with a growth time of $\sim 4 \times 10^8$ yr (Ruzmaikin et al. 1988).

Standard kinematic $\alpha\Omega D$ treatments ignore the back-reaction of the growing magnetic field on the turbulence. Because high magnetic Reynolds numbers make the last term in equation (1) negligible on the energy-dominating scales, the field exponentially grows to equipartition with the turbulent energy by a fast dynamo (FD) on a timescale much shorter than any MF evolution time (e.g., Parker 1979) and does not require helicity. In combination with even a weak MF that is $\gtrsim \rho^{1/2} v'/R_m^{1/2}$ (where R_m is the magnetic Reynolds number and ρ is the density), this may make Lorentz forces (Kulsrud & Anderson 1992; Cattaneo 1994) lock a significant fraction of motions into oscillations. The magnetic fields act like springs that the required turbulent motions must fight against. Although simulations in two dimensions show β-suppression (Cattaneo 1994), there are not yet simulations that show β-suppression in three dimensions. There have been some simulations showing α-effect suppression in three dimensions (Tao et al. 1993; Cattaneo & Hughes 1996), and others that do not (Brandenburg & Donner 1997; Pouquet, Frisch, & Léorat 1976). Intermittency (Blackman 1996; Subramanian 1997) and the nature of the forcing function may play a role in overcoming both α- and β-suppression in three dimensions. Basically, there is no clear consensus on what happens in fully nonlinear mean field dynamo theory with respect to the back-reaction, even as to whether suppression of α and β are intertwined (e.g., Field & Blackman 1997) or independent.

3. LINEAR MEAN FIELD GROWTH FROM A RANDOM SEED FIELD

Supernovae (SNe) inject turbulent energy into the ISM and also inject the magnetic field (Ruzmaikin et al. 1988; Rees 1994). Because of the observed dispersal of heavy elements (Rana 199l), the supernova ejecta at least mix with the remnant material. Theoretical estimates for the mean seed field injected from SNe range from 10^{-13} G from simple flux freezing to 10^{-8} G for including winding in pulsar winds (Rees 1994).

Both theory and simulation (Parker 1979; Piddington 1981; Beck et al. 1996) show that the FD builds up small-scale magnetic field energy on a growth time on the order of the energy-dominating eddy turnover time $\sim l/v' \sim 10^7$ yr, where $l \sim 100$ pc is usually taken as the energy-dominating eddy scale and $v' \gtrsim 10$ km s^{-1} is a typical observed speed of these eddies. Thus, once the Galactic volume is full of a weak seed magnetic field from the first set of SNe, the next generation of eddies stirs the field to equipartition. The SN remnants fill the Galactic disk (the height is $\sim$500 pc by radius 12 kpc) every 10^7 yr given their observed rate of $\sim$0.02 yr^{-1} (Ruzmaikin et al. 1988), and this maintains a steady random field energy. How the field actually mixes from the SNe to the ambient ISM is complicated. The amount of magnetic annihilation, the amount of enhancement, the geometry/topology of the injected field (e.g., Ruzmaikin et al. 1988), and the role of boundary instabilities are all subtle issues. Despite these complications, the basic picture of SN seed field injection and subsequent stirring, as described above, leading to equipartition fields at a time $\lesssim 2.5 \times 10^8$ yr (where this upper limit comes from using the 10^{-13} G seed value given above) and all subsequent times, is consistent with observations: the magnitude of the random field is observed to be $B \sim (5\text{–}10) \times 10^{-6}$ G (e.g., Rand & Kulkarni 1989; Ohno & Shibata 1992; Heiles 1995). Rand & Kulkarni (1989) impose a single cell model whose best-fit small scale over which the field is ordered is 50–100 pc. Although this has become the standard quoted range for the small scale, it will be emphasized later why multiple and larger cell sizes (Ferrière 1996) are important.

The above small-scale field would give a corresponding MF of magnitude $B_0 \sim B/N^{1/2}$, where N is the number of small-scale coherence volumes in the region of averaging. Such a residual large-scale field has been argued to be a viable source of seed field for the Galactic $\alpha\Omega D$ (Ruzmaikin et al. 1988; Rees 1994), but below I suggest that even if α is suppressed, an appropriate large-scale field can still be produced. Let us assume α is suppressed well below the critical value required (Parker 1979) for the standard α-Ω dynamo growth, i.e., $\alpha \ll \alpha_{\rm crit} \sim \beta^2/(\Omega h^3)$ (where h is the disk height), so we can then ignore it in what follows. The MF induction equations in cylindrical coordinates become

$$\partial_t \overline{B}_r = \beta \nabla^2 \overline{B}_r, \tag{2}$$

$$\partial_t \overline{B}_\phi = r\partial_r \Omega \overline{B}_r + \beta \nabla^2 \overline{B}_\phi, \tag{3}$$

$$\partial_t \overline{B}_z = \beta \nabla^2 \overline{B}_z. \tag{4}$$

Equations (2) and (4) are decoupled from equation (3), implying pure diffusion of B_r and B_z. As in standard treatments (e.g., Ruzmaikin et al. 1988), the Ω-effect (differential rotation) increases the azimuthal field in equation (3) linearly on a time of order the rotation time. For the Galaxy, this is $\Omega^{-1} \sim 3.3 \times 10^7$ yr. Because the rotational energy far exceeds that which can be transferred into the magnetic field during the age of the universe, the Ω-effect is not controversial; there is no back-reaction on the large-scale rotational motion. As shown below, this Ω-effect can generate a factor of $\sim$10 increase in the large-scale field. This is sufficient without an α-effect since the seed field is continually supplied.

To solve the equations and determine the dominant scale of the MF, I assume that $\boldsymbol{B} = \boldsymbol{B}_t e^{(ik-x)}$, where k is the wavevector of the MF and the subscript t labels the time dependence. The MF equations (e.g., Ruzmaikin et al. 1988) without an α-effect and with homogeneous β for the azimuthal and radial fields are then

$$\partial_t \overline{B}_{\phi t} = \overline{B}_{rt} f\Omega - \beta k^2 B_{\phi t}, \tag{5}$$

and

$$\partial_t \overline{B}_{rt} = -\beta k^2 \overline{B}_{rt}, \tag{6}$$

where $f\Omega = r\partial\Omega/\partial r$. Solving equation (6) gives $\overline{B}_{rt} = B_{r0} \exp(-k^2\beta t)$, so equation (5) gives

$$\partial_t \overline{B}_{\phi t} = f\Omega B_{r0} \exp(-k^2\beta t) - k^2\beta \overline{B}_{rt}. \tag{7}$$

Multiplying both sides of equation (7) by $\exp(k^2\beta t)$, using the chain rule and solving, gives

$$\bar{B}_{\phi t} = B\,(f\Omega t + 1)\,(3N)^{-1/2} \exp\left[-\,(k_\phi^2 + k_z^2 + k_r^2)\,\beta t\right]$$
$$\simeq B\,(f\Omega t + 1)\,[(3hDR)\,(4\pi l^3/3)]^{-1/2}$$
$$\times\ \exp\left[-\,(D^{-2} + h^{-2} + R^{-2})\,\beta t\right], \tag{8}$$

where I have taken $\bar{B}_{r0} \sim \bar{B}_{\phi 0} \sim \bar{B}_0/3^{1/2} = B/(3N)^{1/2}$, $N \sim hDR/(4\pi l^3/3)$, and h is the Galactic scale height, while D and R are the azimuthal and radial mean field gradient lengths corresponding to their wavevectors and defined only for scales $\gtrsim h$.

The dominant contribution to the MF at any one time is that produced within a vertical diffusion time, τ_{d_v}, from the observation time. Thus, $\beta t \sim 1/h^2$, and from equation (8),

$$\bar{B}_{\phi\tau_{d_v}} = B\,(f\Omega h^2/\beta + 1)\,[3hDR/(4\pi l^3/3)]^{-1/2}$$
$$\times\ \exp\left[-\,(1 + h^2/D^2 + h^2/R^2)\right]. \tag{9}$$

The scale height of the disk is fixed at $h \sim 500$ pc, but $\bar{B}_{\phi\tau_{dr}}$ can be extremized as a function of R and D, giving a maximum at $R = D = 2(\beta l)^{-1/2}$. Using $\beta \sim 10^{26}$ cm^2 s^{-1} (e.g., Ruzmaikin et al. 1988), a Galactic disk scale height of $h \sim 500$ pc, $\Omega \sim 10^{15}$ s^{-1}, and $f \sim 1$, this gives $D = R = 1$ kpc. Thus, $\bar{B}_{\phi\tau_{d_v}} = 1.42 \times 10^{-6}\,(B/5 \times 10^{-6}\ \mathrm{G})$ G. If instead we take $D = 3$ kpc to match the radial scale measured by the Faraday rotation (e.g., Rand & Lyne 1994), this becomes $1.02 \times 10^{-6}\,(B/5 \times 10^{-6}\ \mathrm{G})$ G. The approximate magnitude of the local MF (e.g., Heiles 1995) may therefore be reproduced without the α-effect.

Note that $\bar{B}_{\phi\tau_{d_v}}$ depends on the value of the characteristic averaging azimuthal distance as $D^{-1/2}\exp(-h^2/D^2)$, on the characteristic small-scale structure size l to the $-3/2$ power, and linearly on B. The actual small-scale field of the Galaxy has been shown from observations to be inconsistent with a single scale size (Rand & Kulkarni 1989): the statistical dispersion between the observed field and their model large-scale field shows little evidence of falloff with the distance to pulsars as it should if the single cell size model were appropriate. This highlights the importance of superbubbles and other larger scale fluctuations known to be important to the field structure (Ferrière 1996). If the region of the measured MF were composed of primarily $\gtrsim$200 pc instead of 100 pc structures, then the estimate given above would be magnified by an additional factor $\gtrsim 2^{3/2} = 2.8$. Also, Heiles (1995) finds that the total magnetic energy does not scale simply with the mean azimuthal field as measured by Faraday rotation in different parts of the Galaxy. This can be explained in the present model, since the mean field is proportional to the rms field divided by $N^{1/2}$, where N is the number of small-scale cells of uniform field in the region determining the Faraday rotation measure. Regions of different cell sizes would therefore produce different observed mean fields, even if the total magnetic energy density were the same. All of this highlights the possible importance of multiple small-scale sizes.

4. DISCUSSION OF MEAN FIELD REVERSALS

The calculation in § 3 shows that a scale height of $h = 500$ pc maximizes the azimuthal MF for a radial averaging scale of $D = R = 1$ kpc. This results from two competing effects: (1) The time for shear to increase the field strength by an order of magnitude is relatively independent of scale. Thus, large scales are preferentially sheared in a fixed time because the competing turbulent diffusion depends on the scale squared. (2) However, the initial seed field depends inversely on the averaging scale. The scale of 1 kpc optimizes (1) and (2). This defines the minimum radial scale over which the maximum average azimuthal field could reverse sign. This does not mean that there would necessarily be reversals every 1 kpc. It means that between 1 kpc anuuli, the mean field may or may not reverse. Within a 10 kpc Galactic radius, there are approximately nine interfaces between l kpc annuli. The probability $P(n)$ of observing n reversals by Faraday rotation would be 9 "choose" n, i.e., $9!/(9-n)!\,n!$, which is maximized for $n = 4$ or 5.

Galactic Faraday rotation observations can determine the sign of the large-scale field in the line of sight (cf. Beck et al. 1996; Zwiebel & Heiles 1997). (Unlike Galactic measurements, where pulsar dispersion measures can be used, extragalactic measurements require independent determinations of the density to obtain any information from Faraday rotation. The data for external galaxies are therefore less reliable [Heiles 1995; Zwiebel & Heiles 1997].) Generally, a large-scale theoretical Galactic field model is statistically compared with observations (e.g., Rand & Kulkarni 1989). Field reversals seem to occur in each of the two interarm regions immediately inside of the solar circle (Beck et al. 1996; Heiles 1995), with perhaps two more outside. The reversals are not necessarily periodic between spiral arms (Vallée 1996). Also, because of fluctuations in rotation measure data for some quadrants (Rand & Lyne 1994; Beck et al. 1996), averaging over smaller scales then shows smaller intermediate-scale reversals. This again highlights that intermediate scales (Rand & Kulkarni 1989; Ohno & Shibata 1992) from 50 to 500 pc complicate theoretical and observational interpretations. The precise structure of the large-scale field in spiral galaxies is difficult to determine conclusively (Beck et al. 1996).

Note that turbulent diffusion is distinct from dissipation. The former describes a transfer of magnetic energy between scales, whereas dissipation is a removal of magnetic energy. Turbulent motions on subkiloparsec scales both randomize the mean field and amplify the small-scale field, thereby reseeding the mean field. Although a turbulent cascade drains energy to the dissipation scale, the magnetic energy is steadily replenished by the FD, and the total magnetic energy density remains steady.

Previous work has recognized the importance of diffusion for reversal reduction (Poezd, Shukarvov, & Sokoloff 1993). In fact, the weaker the α-effect in dynamo models, the less vigorously the $\alpha\Omega D$ can compete with turbulent diffusion and the fewer reversals that survive. Primordial models are sometimes employed with the assumption that turbulent diffusion is not operating (Zweibel & Heiles 1997). Although this seems unlikely, other proposed mechanisms would then be needed to eliminate reversals (cf. Zweibel & Heiles 1997). Another possibility is that the winding of a proto–galactic field in the subsequently formed galaxy (Howard & Kulsrud 1997) generates the correct number of reversals.

For some external galaxies (e.g., NGC 6946), observations indicate that the large-scale field is actually stronger in the interarm regions (Beck & Hoernes 1996). In the present approach, the deficit of the large-scale field in the spiral arms would be the result of a reduced shear there (Elmgreen 1994) and thus an $f < 1$ in equation (5). This is generally consistent with rotation curves of NGC 6946 and other galaxies that show reduced differential rotation in spiral arms (Sofue 1996; Rubin et al. 1980). In contrast, an enhanced MF strength might result in the arms if their increased electron density dominates the effect of reduced shear. The total magnetic energy can be larger in spiral arms if the turbulent energy is higher there. Varying density complicates the interpretation of rotation measures of external galaxies if the density variation cannot be independently measured.

5. DISCUSSION

It is important to understand whether α and β can actually be disentangled. If so, the main point herein is to suggest that it may not be absolutely certain that the observed large-scale Galactic magnetic field requires a dynamo α-effect, even if the mean field is produced in situ. The well-known exponential growth of the small-scale field by the FD and its steady replenishing of seed MF, combined with the subsequent linear growth of the large-scale azimuthal field by the Ω-effect, might supply a large-scale Galactic field without requiring the dynamo α-effect. The linear growth may be sufficient because it proceeds faster than the time for the field to diffuse below microgauss values. The observed field of any spiral galaxy would be that produced within τ_{d_v} of the time of observation, and since the field is steadily replenished, this statement is true at any time in a galaxy's lifetime $\geq 10^8$ yr from the time of the galaxy's birth. The most likely number of reversals in the large-scale field within 10 kpc radius would be on the order of 4–5 in the presence of turbulent diffusion for the simplest approach. (Unlike the cellular model of Michel & Yahil 1973, here turbulence is important.) If flux tubes were present with a small volume filling fraction, and/or if the energy-dominating small scale of the field were much reduced from the semiempirically determined 100 pc scale, too many mean field reversals might be produced by the present approach. A small filling fraction may also aid the standard dynamo (Blackman 1996; Subramanian 1997), making the approach herein less useful. However, unlike the Sun, the tube filling fraction in galaxies may be large if the average particle pressure does not overwhelm the magnetic pressure (Blackman 1996).

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