Magnetic Fields in Galaxies: Their Origin and Their Impact on the Interstellar Medium

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Abstract In the first part of the paper, I discuss the origin of galactic magnetic fields. After showing that the primordial field theory is in disagreement with observations, I present the dynamo theory in which large-scale magnetic fields are amplified under the combined action of the large-scale galactic differential rotation and small-scale cyclonic turbulent motions. I write down the dynamo equation and interpret it physically. I then present numerical solutions of the dynamo equation for our own Galaxy, assuming that the required turbulence is driven by supernova explosions.

In the second part of the paper, I discuss the impact of galactic magnetic fields on the interstellar medium. Through the Lorentz force, they affect both the dynamics and the spatial distribution of the interstellar matter at all scales. At large scales, they help to support it against its own weight, while they confine cosmic rays to the galaxy. At smaller scales, they oppose the expanding gas motions driven by supernova explosions, they constrain the random motions of interstellar clouds, and they control the star formation process. In addition to their dynamical role, they provide a heat source for the interstellar gas through magnetic reconnection.

1 Introduction

Numerous observations, based on starlight polarisation, Zeeman splitting, Faraday rotation, and synchrotron emission, reveal the presence of magnetics fields in our Galaxy as well as in external spiral galaxies. These magnetic fields appear to have a pressure comparable to the galactic cosmic-ray pressure and somewhat higher than the interstellar gas pressure.

Two important issues will be addressed in this paper. The first issue (discussed in §2) concerns the origin of galactic magnetic fields: Are they of primordial origin or the result of a dynamo process? What is the nature of the turbulent motions necessary for dynamo action? And how are large-scale magnetic fields predicted to behave (both temporally and spatially) in the dynamo scenario? The second issue (discussed in §3) concerns the impact of galactic magnetic fields on the interstellar medium (ISM), in particular, on the dynamics and spatial distribution of interstellar matter at large and small scales, and on their energetics.

2 The Origin of Galactic Magnetic Fields

2.1 Primordial Field *versus* Dynamo Field

Two main theories have been put forward to explain the origin of magnetic fields in galaxies: the primordial field theory and the dynamo theory.

In the primordial field theory, present-day galactic magnetic fields would simply be the relics of a coherent magnetic field existing in the early Universe prior to galaxy formation. Presumably, the gas motions associated with the collapse of a protogalaxy would have compressed the lines of force of the ambient magnetic field (which tend to be frozen into the highly conductive gas), and from then on, the differential rotation of the galaxy would have wrapped them up about its center. In the absence of any other process, the galactic magnetic field would be wound up 50 to 100 times at the present time, i.e., much more than indicated by observations.

The traditional way of resolving the discrepancy is to invoke magnetic diffusion (supposedly of the turbulent kind). But if magnetic diffusion is sufficiently efficient parallel to the galactic plane to avoid a tight wind-up of magnetic field lines, it must also be sufficiently efficient perpendicular to the plane for field lines to diffuse out of the disk. Under these conditions, galactic magnetic fields would have completely decayed away by now, [1] without ever reaching the observed strengths of a few μG (Rosner & DeLuca 1989).

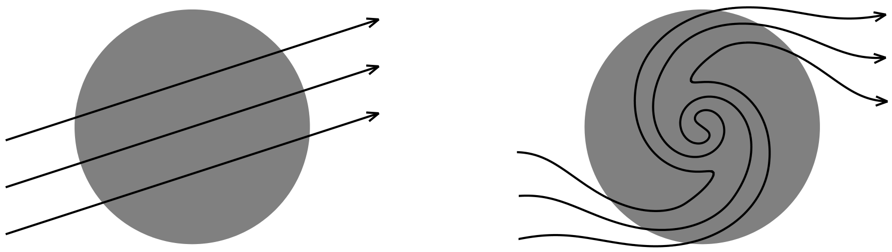

Fig. 1 Face-on view of the galactic disk showing the azimuthal stretching of magnetic field lines by the large-scale differential rotation

Fig. 2 Oblique view of the galactic disk illustrating the alpha-effect arising from small-scale cyclonic turbulent motions

This short reasoning suggests that an additional mechanism partakes in the generation of galactic magnetic fields. In the dynamo theory, this additional mechanism is due to small-scale turbulent motions which are cyclonic, i.e., which have acquired a preferred sense of rotation under the action of the Coriolis force. As these turbulent motions stretch and twist magnetic field lines, they impart to them a net rotation, whereby magnetic field is created in the direction perpendicular to the prevailing field. This process has been termed the "alpha-effect".

This conclusion could possibly become invalid in the case of ambipolar diffusion, which allows magnetic field lines, tied to the charged particles, to slip through the neutral gas.

Thus, in the dynamo theory, the large-scale differential rotation stretches magnetic field lines in the azimuthal direction about the galactic center (see Figure 1), while small-scale cyclonic turbulent motions regenerate, via the alpha-effect, the meridional component of the field from its azimuthal component (see Figure 2). It is the combination of these two complementary mechanisms that leads to magnetic field amplification in galaxies (Parker 1971; Vainshtein & Ruzmaikin 1971).

Obviously, the operation of a galactic dynamo requires a seed magnetic field to initiate the amplification process. Several possibilities have been advanced regarding the nature of this seed field (see Rees 1987). Briefly, the seed field could have a pregalactic origin (as in the primordial field theory), or it could arise in the protogalaxy as a result of charge separation due to electrons interacting with the microwave background photons (battery effect), or else it could originate in the first generation of stars and be expelled into the ISM by their winds and/or supernova explosions.

2.2 The Dynamo Equation

In the dynamo theory, the time evolution of the large-scale galactic magnetic field is governed by the dynamo equation,

$$\frac{\partial\langle \boldsymbol{B}\rangle}{\partial t} = \boldsymbol{\nabla} \times \Big(\langle \boldsymbol{v}\rangle \times \langle \boldsymbol{B}\rangle\Big) + \nabla \times \mathcal{E} \ , \tag{1}$$

where $\boldsymbol{B}$ is the magnetic field, $\boldsymbol{v}$ is the velocity field,

$$\mathcal{E} \equiv \langle \delta \boldsymbol{v} \times \delta \boldsymbol{B} \rangle \tag{2}$$

is the electromotive force due to turbulent motions, angle brackets denote large-scale (or ensemble-averaged) quantities, and the symbol δ denotes small-scale turbulent quantities (e.g., Steenbeck, Krause, & Rädler 1966). The first term on the right-hand side of equation (1) represents the effect of the large-scale velocity field – including chiefly galactic rotation – on $\langle \boldsymbol{B}\rangle$ and the second term represents the effect of small-scale turbulent motions.

In general, $\mathcal{E}$ can be expressed as a linear function of $\langle \boldsymbol{B}\rangle$ and its first-order spatial derivatives:

$$\mathcal{E}_i = \alpha_{ij} \, \langle B_j \rangle + \beta_{ijk} \, \frac{\partial \langle B_j\rangle}{\partial x_k} \ \cdot \tag{3}$$

The so-called alpha-tensor, α_{ij}, embodies not only the alpha-effect but also the effective advection of magnetic field by turbulent motions, whereas the tensor β_{ijk} describes turbulent magnetic diffusion (e.g., Moffatt 1978).

In the case of a galactic disk, where the parameters of the ISM and the sources of turbulence vary essentially in the vertical direction, the alpha-tensor takes on the form

$$\alpha_{ij} = \begin{pmatrix} \alpha_R & -v_{\rm esc} & 0 \\ v_{\rm esc} & \alpha_\Phi & 0 \\ 0 & 0 & \alpha_Z \end{pmatrix} \tag{4}$$

in a cylindrical reference frame $(\widehat{e}_R, \widehat{e}_\Phi, \widehat{e}_Z)$ with origin at the galactic center and $\widehat{e}_Z$ perpendicular to the galactic plane. The diagonal components, α_R, α_Φ, and α_Z, give the effective rotational velocity associated with the alpha-effect when $\langle \boldsymbol{B}\rangle$ is radial, azimuthal, and vertical, respectively, and the off-diagonal component, $v_{\rm esc}$, represents the effective vertical velocity at which $\langle \boldsymbol{B}\rangle$ is advected by turbulent motions (Ferrière 1993a). The diffusivity tensor, for its part, can be written as

$$\beta_{ijk} = \beta_h \left(\epsilon_{ijR}\, \delta_{kR} + \epsilon_{ij\Phi}\, \delta_{k\Phi}\right) + \beta_v\, \epsilon_{ijZ}\, \delta_{kZ} \ , \tag{5}$$

where β_h and β_v are the horizontal and vertical turbulent magnetic diffusivities, respectively, δ_{ij} is the unit tensor, and ϵ_{ijk} is the three-dimensional permutation tensor (Ferrière 1993b).

The rotation curves of spiral galaxies are reasonably well established observationally, mainly thanks to H I and CO velocity measurements. In contrast, the dynamo tensors, α_{ij} and β_{ijk}, are poorly constrained observationally, and their determination mostly relies on theoretical models of interstellar turbulence. For example, Ferrière (1998) calculated α_{ij} and β_{ijk} in our Galaxy on the assumption that the turbulent motions responsible for dynamo action are driven by supernova explosions.

2.3 Numerical Solutions for our Galaxy

Several authors have set out to solve the galactic dynamo equation numerically (e.g., Donner & Brandenburg 1990; Brandenburg et al. 1992; Panesar & Nelson 1992; Schultz, Elstner, & Rüdiger 1994; Elstner, Rüdiger, & Schultz 1996). Here we present the numerical solutions obtained for our own Galaxy by Ferrière & Schmitt (2000), who adopted the Galactic rotation curve of Fich, Blitz, & Stark (1989) together with the supernova-driven dynamo tensors of Ferrière (1998).

Ferrière & Schmitt (2000) first studied linear modes, which were allowed to be either axisymmetric (azimuthal wavenumber $m = 0$) or bisymmetric ($m = 1$) with respect to the rotation axis, and either symmetric (symbol S) or antisymmetric (symbol A) with respect to the equatorial plane. For each mode, they started by computing a reference solution corresponding to the case when all the input parameters take on their default values. Then, they systematically varied each of the input parameters, so as to determine its impact on the temporal evolution and on the spatial structure of the large-scale magnetic field.

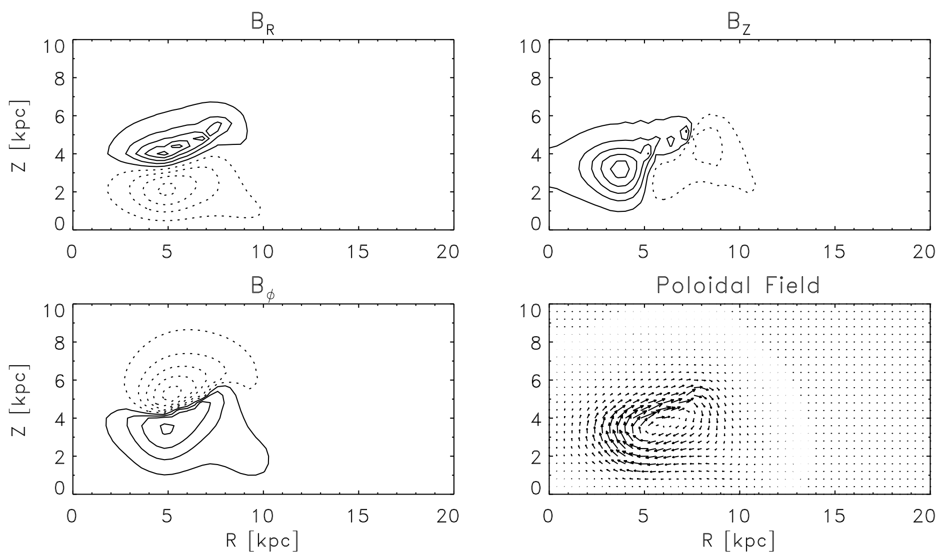

Fig. 3 Contour lines of the three cylindrical components of the large-scale magnetic field and lines of force of its poloidal component, in a given meridional plane of our Galaxy, for the S0 mode under the reference conditions.

They found that axisymmetric modes are always easier to excite than bisymmetric modes. Under the reference conditions, the S0 and A0 modes have very similar properties. Both grow monotonously with time at a slow exponential rate $\simeq 0.45\,\mathrm{Gyr}^{-1}$, which suggests that the Galactic magnetic field has presently reached a state close to saturation. The azimuthal field component dominates by more than one order of magnitude; as indicated by Figure 3, it exhibits, on each side of the midplane, two well-defined polarities peaking at $R \simeq 5\,\mathrm{kpc}$ and separated by a node at $|Z| \simeq 4\,\mathrm{kpc}$. The poloidal field peaks at a slightly smaller radius, and its lines of force rotate about a point located close to the maximum of α_Φ.

When the effective escape velocity, $v_{\rm esc}$, is set to zero, the exponential growth rate decreases and even turns slightly negative for the S0 mode. The magnetic field becomes oscillatory, and its overall pattern propagates toward the midplane. During most of a dynamo cycle, B_Φ, which is again the dominant field component, possesses four alternating polarities along the vertical (see Figure 4). Oscillatory behaviors are also obtained, albeit with an increased growth rate, when the diagonal components of α_{ij} are enhanced by a factor > 3 or when the magnetic diffusivities are reduced by a factor > 1.7 with respect to their reference values.

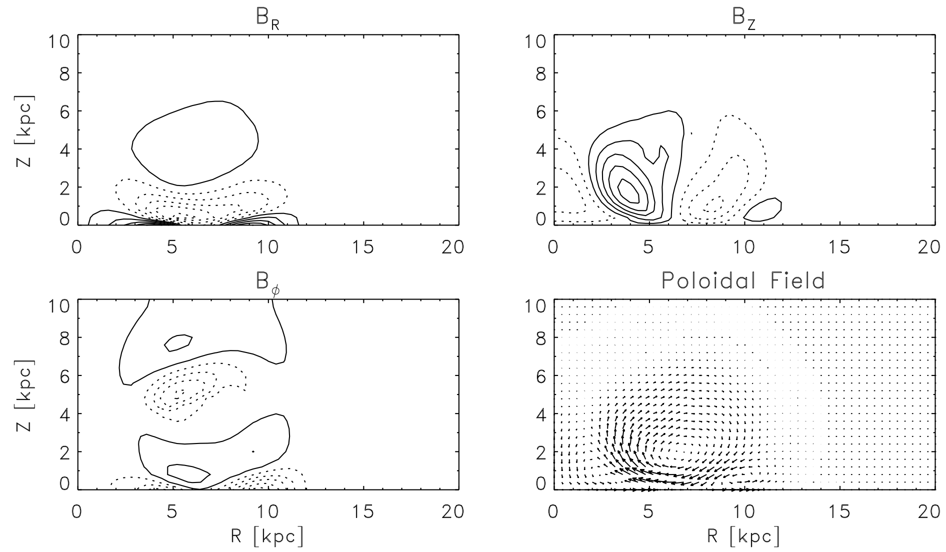

Fig. 4 Same as Figure 3, with $v_{\rm esc} = 0$

The large-scale rotation rate, Ω, too, has a considerable influence on the solutions. In particular, when in addition to being a decreasing function of R, Ω is assigned a vertical dependence in $\exp\left[-(Z/5\,\mathrm{kpc})^2\right]$, both the S0 and A0 modes decay oscillatorily with time. As before, the magnetic field is predominantly azimuthal, but now, the alternating polarities of B_Φ (displayed in Figure 5) migrate along an oblique axis, which can be verified as roughly parallel to lines of constant Ω.

For bisymmetric modes, the azimuthal stretching of magnetic field lines by the large-scale differential rotation has a destructive, rather than amplifying, effect. As a result, the magnetic field rapidly vanishes from the differentially-rotating parts of the Galaxy (outside $R \simeq 4$ kpc), while it undergoes a much slower exponential decay, accompanied by an azimuthal propagation, in the rigidly-rotating innermost region. Note that there exist significant differences between S1 and A1 modes, not only in the decay rate, but also in the

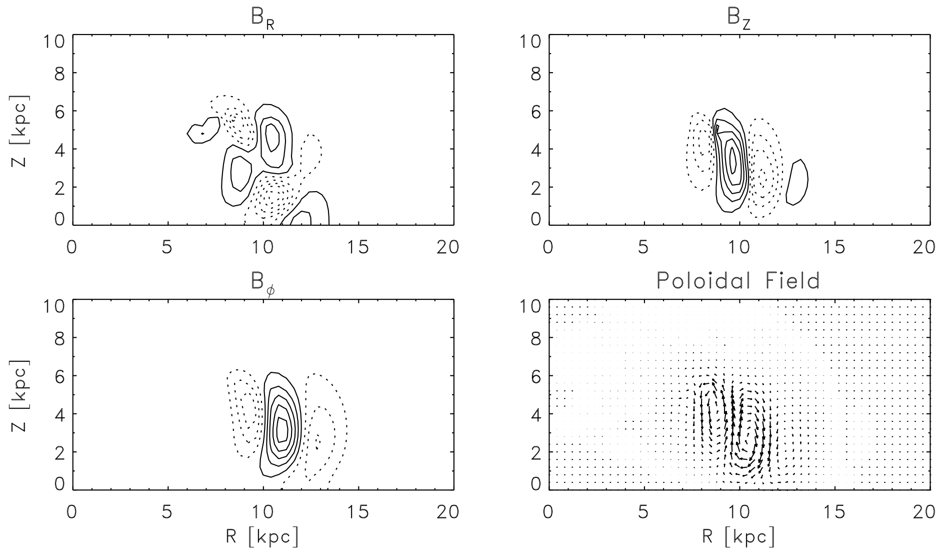

Fig. 5 Same as Figure 3, with $\Omega \propto \exp\left[-(Z/5\,\mathrm{kpc})^2\right]$

magnetic configuration.

The main limitation of the linear results described above resides in the fact that the adopted expressions for α_{ij} and β_{ijk} are proper to the present-day Galaxy, whereas the true dynamo parameters have undoubtedly evolved in the course of time, being presumably greater at the beginning, when the large-scale magnetic field was weaker. For this reason, Ferrière & Schmitt (2000) carried out a number of nonlinear calculations in which α_{ij} and β_{ijk} were multiplied by a decreasing function of $|\langle \boldsymbol{B} \rangle|$, meant to represent the back-reaction of the Lorentz force on the turbulent motions responsible for the alpha-effect and for magnetic diffusion. They found that, for the growing solutions, the magnetic field amplification saturates when its maximum intensity reaches $\sim 20\ \mu$G, corresponding to a magnetic pressure roughly equal to four times the local gas pressure. The time to saturation, which depends on the seed field strength adopted, is typically on the order of a few 10 Gyr.

3 The Impact of Galactic Magnetic Fields on the ISM

3.1 Dynamic Role

The magnetic field of a galaxy acts on the interstellar matter through the Lorentz force. Of course, the field acts directly on the charged particles only, but its effect is then transmitted to the neutrals by ion-neutral collisions. Apart from the densest parts of molecular clouds, whose ionization degree is exceedingly low, virtually all interstellar regions are sufficiently ionized for their neutral component to remain tightly coupled to the charged component and, hence, to the magnetic field.

At large scales, the galactic magnetic field helps to support the ordinary matter against its own weight in the galactic gravitational potential, and it confines cosmic rays to the galactic disk. In this manner, both magnetic fields and cosmic rays partake in the overall hydrostatic balance of the ISM and influence its stability. Boulares & Cox (1990) were the first authors to fully appreciate the importance of magnetic fields and cosmic rays in the hydrostatic balance. By the same token, they managed to solve the long-standing problem of apparent mismatch between the total interstellar pressure at a given point and the integrated weight of overlying interstellar material: by adopting higher magnetic and cosmic-ray pressures than previously estimated, they were able to bring the total pressure at low $|Z|$ into agreement with the integrated weight, and by including the magnetic tension force at high $|Z|$, they could explain why the weight integral falls off faster than the total pressure.

As magnetic and cosmic-ray pressures inflate the gaseous disk, they tend to make it unstable to a generalized Rayleigh-Taylor instability, now known in the astrophysical community as the Parker instability (Parker 1966). When this instability develops, magnetic field lines ripple, and the interstellar matter slides down along them toward the magnetic troughs, where it accumulates. This whole process, it has been suggested, could give birth to new molecular-cloud complexes and ultimately trigger star formation (Mouschovias, Shu, & Woodward 1974; Elmegreen 1982).

At smaller scales, the galactic magnetic field affects all kinds of turbulent motions in the ISM. Of special importance is its impact on supernova remnants and superbubbles (see Tomisaka 1990; Ferrière, Mac Low, & Zweibel 1991; Slavin & Cox 1992). First, the background magnetic pressure acting on their surrounding shells directly opposes their expansion. Second, the magnetic tension existing in the field lines swept into the shells gives rise to an inward restoring force, while the associated magnetic pressure prevents the shells from fully collapsing and, therefore, keeps them relatively thick. Third, the enhanced external "signal speed" causes the shells to merge earlier than they would in an unmagnetized medium. All three effects conspire to lower the filling factor of hot interstellar gas.

The galactic magnetic field also constrains the random motions of interstellar clouds. The latter are magnetically connected to their environment, namely, to the intercloud medium and possibly to neighboring clouds, through the magnetic field lines that thread them. When a given cloud moves relative to its environment, these field lines get deformed, and the resulting magnetic tension force modifies the cloud's motion, transferring part of its momentum to its environment (Elmegreen 1981). Likewise, angular momentum can be transferred from a rotating cloud to its environment by magnetic torques (Mouschovias & Paleologou 1979). This mechanism is particularly relevant to the star formation process, as it allows the contracting protostellar cores to get rid of angular momentum (e.g., Mouschovias & Morton 1985).

Finally, the galactic magnetic field plays a crucial role in the support of molecular clouds against their self-gravity and in the eventual gravitational collapse of protostellar cores. The magnetic support of molecular clouds is essentially provided by magnetic pressure gradients in the directions perpendicular to the mean field and, presumably, by nonlinear Alfvén waves in the parallel direction (Shu, Adams, & Lizano 1987). In the case of protostellar cores, magnetic support is insufficient to prevent their ultimate gravitational collapse. This is generally because their ionization degree is so low that neutrals are not perfectly tied to magnetic field lines, which enables them to drift inwards under the pull of their self-gravity and eventually form stars (Nakano 1979; Mestel 1985).

3.2 Energetic Role

In most regions of interstellar space, the electrical conductivity, σ, is extremely high, with the twofold consequence that magnetic field lines are frozen into the plasma and that ohmic dissipation is completely negligible. There exist, however, localized regions where magnetic field gradients are very steep, so that the electric current density, $\boldsymbol{J} = \frac{c}{4\pi}\,\boldsymbol{\nabla} \times \boldsymbol{B}$, is very strong, and where the effective electrical conductivity is greatly reduced with respect to its classical Coulomb value (for instance, an anomalous conductivity may result from microscopic wave fluctuations which increase the effective collision frequency through wave-particle interactions). The combination of strong $\boldsymbol{J}$ and reduced σ entails both a partial loss of the magnetic field frozen-in property and a resistive dissipation of magnetic energy.

In particular, when field lines of opposite polarities are forced to approach one another, a thin transition layer develops, in which the magnetic field gradient steepens and, accordingly, the current density rises, to the point where field lines decouple from the plasma, reconnect with field lines of the opposite polarity, and leave the transition layer sideways. The reconnection zone is subject to intense ohmic dissipation, with the dissipated magnetic energy being essentially converted into plasma thermal energy.

Thus, magnetic reconnection constitutes a source of heating – and, at the same time, ionization – for the ISM. This heating/ionization source could even be dominant in the galactic halo, which is not easily accessible to the powerful radiation from the luminous O and B stars. Based on this idea, Birk, Lesch, & Neukirch (1998) invoked magnetic reconnection within thin current filaments assumed present in the halo to solve the ionization/heating problem of the warm ionized medium at high Z. It was also suggested by Zimmer, Lesch, & Birk (1997) that interaction regions between high-velocity clouds traveling through the halo and the surrounding halo gas could be the sites of intense magnetic reconnection and, hence, plasma heating.

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