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The origin of galactic magnetic fields and their impact on the interstellar medium

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Abstract

Galactic magnetic fields constitute one of the three basic constituents of the interstellar medium of galaxies, the other two constituents being the ordinary matter and the cosmic rays. In this short paper, I will address two important theoretical questions concerning galactic magnetic fields. First, by what physical processes were they generated and amplified? Second, how does their presence affect the other constituents of the interstellar medium?

1 Introduction

At the present time, no one would cast doubts on the existence and the importance of interstellar magnetic fields in galaxies. Although much has been learned about their physical properties, their spatial distribution, and their temporal evolution since they were discovered more than fifty years ago, there remain open theoretical questions related to their origin and their impact on the interstellar medium (ISM). These two important aspects of galactic magnetic fields will be the subject of the present paper.

In Section 2, I will discuss the origin of galactic magnetic fields. After explaining why they cannot simply be of primordial origin, I will 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 will write down the dynamo equation and review the main properties of its numerical solutions in the linear and nonlinear regimes. I will also tackle the problem of the seed field necessary to trigger dynamo action.

In Section 3, I will discuss the impact of galactic magnetic fields on the ISM. Through the Lorentz force, they affect the dynamics and the spatial distribution of both the ordinary matter and the cosmic rays at all scales. At large scales, they help to support the ordinary matter 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 inhibit diffusion processes, such as thermal conduction, they provide a heat source for the interstellar gas through magnetic reconnection, and they accelerate interstellar cosmic rays to higher energies.

2 The origin of galactic magnetic fields

2.1 Primordial field *versus* dynamo field

The first point to recognize is that the origin of galactic magnetic fields may not be explained by the primordial field theory. According to this 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. 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).

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".

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

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,

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

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

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

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 $\langle \mathbf{B} \rangle$ and the second term represents the effect of small-scale turbulent motions.

When there is a clear scale separation between average and turbulent quantities, $\mathcal{E}$ can be expressed as a linear function of $\langle \mathbf{B} \rangle$ and its first-order spatial derivatives:

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

[1] This conclusion could possibly become invalid if one allows for ambipolar diffusion, which enables magnetic field lines, tied to the charged particles, to slip through the neutral gas (Kulsrud 1986).

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 interstellar parameters and the sources of turbulence vary essentially along 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 $\langle \mathbf{B} \rangle$ is radial, azimuthal, and vertical, respectively, and the off-diagonal component, $v_{\rm esc}$, represents the effective vertical velocity at which $\langle \mathbf{B} \rangle$ 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, based on the assumption that the turbulent motions responsible for dynamo action are driven by supernova explosions.

2.3 Numerical Solutions

Several authors have set out to solve the galactic dynamo equation (1) numerically (e.g., Donner & Brandenburg 1990; Brandenburg et al. 1992; Panesar & Nelson 1992; Schultz, Elstner, & Rüdiger 1994; Elstner, Rüdiger, & Schultz 1996; Ferrière & Schmitt 2000). Here we summarize the main conclusions that can be drawn from their papers.

When the parameters describing the velocity field (the large-scale velocity, $\langle \mathbf{v} \rangle$, and the dynamo tensors, α_{ij} and β_{ijk}) are prescribed, the dynamo equation is linear in $\langle \mathbf{B} \rangle$, so that the computed $\langle \mathbf{B} \rangle$ either grows or decays exponentially with time. Solutions of the linear dynamo equation are customarily classified into modes with given azimuthal symmetry (denoted by the value of the azimuthal wavenumber, m, i.e., $m=0$ for axisymmetric modes, $m=1$ for bisymmetric modes ...) and vertical symmetry (indicated by the letter S or A according to whether the mode is symmetric or antisymmetric with respect to the midplane).

As far as the azimuthal symmetry is concerned, an important finding systematically emerges from all studies, namely, when the input parameters are axisymmetric, $m=0$ modes are always easier to excite than $m=1$ modes. The physical reason is easily understood: 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, while it undergoes a slower exponential decay in the rigidly-rotating innermost region. There exist, nevertheless, several factors that play in favor of $m=1$ modes, such as the absence of a large-scale shear, the thinness of the galactic disk, anisotropies in the alpha-tensor, and, of course, azimuthal variations in α_{ij} and β_{ijk} (arising, for instance, from the underlying spiral structure or from tidal interactions with a nearby galaxy).

The situation regarding the vertical symmetry is not quite as clear-cut. Let us first note that for axisymmetric magnetic fields, the azimuthal component dominates by more than one order of magnitude, as a direct consequence of the large-scale differential rotation being much more efficient at generating azimuthal field than the alpha-effect at generating meridional field. Under typical galactic conditions, the S0 mode grows faster than the A0 mode. This difference results from the characteristic disk geometry, which tends to favor quadrupolar fields when the azimuthal component dominates, in contrast to the spherical geometry prevailing in the Sun, which tends to favor dipolar fields. However, under certain circumstances, the A0 mode is found to be preferred, in particular, when the galactic disk is sufficiently thick, when the alpha-effect is active and strong enough in the halo, when dynamo action is dominated by the alpha-effect near the galactic center, when differential rotation is weak, or when the alpha-tensor possesses large anisotropies.

In their standard temporal behavior, too, galactic magnetic fields contrast with the Solar magnetic field. Indeed, whereas the latter is observed to oscillate in time with a 22-year period, the former are typically found to grow monotonously with time at a slow exponential rate ($\lesssim 2\ \mathrm{Gyr}^{-1}$ for our own Galaxy at the present epoch). Not surprisingly, certain circumstances can cause galactic magnetic fields to become oscillatory; these include all the circumstances favoring the A0 mode (see previous paragraph) as well as a strongly reduced escape velocity and a large-scale rotation rate decreasing away from the midplane. Furthermore, the A0 mode is generally the first to turn oscillatory, and it is only when the A0 and S0 modes have both turned oscillatory that the A0 mode is liable to grow faster.

The main limitation of the linear results discussed above resides in the faulty underlying assumption that α_{ij} and β_{ijk} are time independent. In reality, the dynamo parameters evolve in the course of time, insofar as they depend on basic interstellar parameters such as the large-scale rotation velocity, the supernova rate, the ambient interstellar pressure (including a magnetic component), the interstellar mass density, and the magnetic field itself, all of which vary with time in a complicated interrelated manner. In consequence, the evolution of $\langle \mathbf{B} \rangle$ is coupled to that of the other interstellar parameters.

Although the full problem has never been solved self-consistently, there have been attempts to go beyond the purely linear approach. These attempts generally consist of allowing the components of α_{ij} (and sometimes also β_{ijk}) to depend on $\langle \mathbf{B} \rangle$ via a multiplicative quenching function, $q(\langle \mathbf{B} \rangle)$, meant to represent the back-reaction of the Lorentz force on the turbulent motions responsible for the dynamo process. The quenching function is generally assigned a convenient form, which has the expected property of decreasing to zero as the magnetic field strength increases to infinity. A common choice is

$$q(\langle \mathbf{B} \rangle) = \frac{1}{1 + \left(\frac{|\langle \mathbf{B} \rangle|}{B_{\mathrm{eq}}} \right)^n} , \tag{6}$$

where B_{eq} is the equipartition field strength (such that $B_{\mathrm{eq}}^2/8\pi$ equals the interstellar gas pressure) and n is usually set to 2 (e.g., Jepps 1975; Brandenburg et al. 1992).

Evidently, nonlinear solutions differ from their linear counterparts in several respects. First, magnetic field growth is exponential only at early stages; it begins to saturate when $|\langle \mathbf{B} \rangle|$ approaches B_{eq}, and the fully saturated field strength generally does not exceed $\sim 2\, B_{\mathrm{eq}}$.

The time to saturation, which depends on the adopted seed field strength (see Section 2.4), is typically on the order of a few 10 Gyr. Second, since quenching and the ensuing reduction in field amplification are, by construction, more severe in stronger-field regions, the final magnetic configuration tends to be more smoothed out (i.e., less peaked) than in linear models. Third, nonlinear interactions between different magnetic modes make it possible to amplify certain modes that would otherwise decay away. These interactions can maintain mixed-parity configurations for extended periods of time, and in some cases, the magnetic field eventually evolves toward a state whose parity differs from the preferred linear parity.

2.4 Seed magnetic fields

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; Widrow 2002). In some of the proposed scenarios, the seed field has a pregalactic origin (as in the primordial field theory); in other scenarios, it dates back to a later period, following the formation of the first galaxies.

A first possibility would be that the Universe was directly born with a magnetic field. While such an initial cosmological magnetic field may not be ruled out a priori, there exist observational limits to its maximum amplitude (scaled down to the present epoch), e.g., from Faraday rotation measures toward high-redshift radio sources ($B \lesssim 10^{-9} - 6 \times 10^{-9}$ G), from anisotropy measurements in the cosmic microwave background ($B \lesssim 5 \times 10^{-9} - 10^{-8}$ G), and from observational tests of Big Bang nucleosynthesis predictions ($B \lesssim 10^{-6}$ G).

Another, equally speculative, possibility would be that some kind of exotic processes during a phase transition in the very early Universe (either during or after inflation) engendered the first magnetic fields. If real, such early-Universe magnetic fields would be subject to the first two observational upper limits that apply to an initial cosmological magnetic field.

Along a more standard line of thought, the first magnetic fields could have been produced by a battery effect before the recombination epoch. The idea is that rotational fluctuations caught in the cosmic expansion had their angular velocity decrease with time to conserve angular momentum. Electrons, which were strongly coupled to the background radiation photons through Thomson scattering, tended to spin down less rapidly than ions. The resulting charge separation led to electric currents, which in turn gave rise to very weak magnetic fields ($B \sim 10^{-18}$ G).

Alternatively, a battery effect could have come into play after the reionization epoch, during the collapse phase of rotating protogalaxies. In this case, electrons and ions would have both spun up, with the former, again coupled to the background photons, tending to do so less rapidly. Here, too, the difference would have entailed electric currents and hence very weak magnetic fields ($B \sim 10^{-20}$ G).

In a different kind of scenarios, it has been suggested that the seed magnetic field of a galaxy found its roots in the first generation of stars. Presumably, a battery effect inside the first rotating stars gave birth to stellar seed fields, which were subsequently amplified by a stellar dynamo. The stellar magnetic fields thus generated were then expelled into the ISM of the galaxy by the wind and/or supernova explosion of their parent star.

The last potential candidates are active galactic nuclei. The accretion disk surrounding their central black hole is propitious both to the creation of new magnetic fields through a battery effect and to their subsequent amplification by a local dynamo. These magnetic fields could then be transported outwards via the highly collimated jets emanating from the central black hole, in which case they would seed not only the ISM of the host galaxy, but also the surrounding intergalactic medium.

3 The impact of galactic magnetic fields on the interstellar medium

3.1 Dynamic role

The magnetic field of a galaxy acts on the interstellar matter through the Lorentz force, which sets the charged particles into gyration motion around field lines. Its effect is then transmitted to the neutrals via 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.

Interstellar cosmic rays, too, are effectively tied to magnetic field lines around which they are forced to gyrate. Moreover, their streaming motion along field lines excites resonant Alfvén waves, which in turn scatter them and limit their field-aligned velocity to roughly the local Alfvén speed (e.g., Kulsrud & Pearce 1969). Through these two mechanisms, the galactic magnetic field couples cosmic rays to the ordinary matter.

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.

On the other hand, the inflation of the gaseous disk by magnetic and cosmic-ray pressures as well as the presence of these pressures at high $|Z|$ bar most superbubbles from blowing out of the disk and venting their interior driving pressure into the halo, thereby allowing them to grow larger. This last effect counteracts the three effects listed above. Numerical simulations tend to indicate that when all the different factors are correctly taken into account, the net impact of the galactic magnetic field on the hot gas filling factor turns out to be weak (e.g., de Avillez & Breitschwerdt 2004).

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

The gyromotion of charged particles around magnetic field lines restricts their transverse displacements between successive Coulomb collisions to distances of order their gyroradius, which for typical galactic magnetic field strengths, is many orders of magnitude smaller than their Coulomb collision mean-free-path. As a result, thermal conductivity and other diffusion coefficients in the ISM are drastically reduced perpendicular to the magnetic field. The suppression of thermal conduction across the field has important implications for the thermal balance of the ISM, in particular, for the maintenance of steep temperature gradients at the interface between different interstellar phases, for the evaporation and shape of cold interstellar clouds, and for the lifetime of the hot cavities created by supernova explosions.

In most regions of interstellar space, the electrical conductivity, σ, is so high that magnetic field lines are effectively 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, $\mathbf{J} = \frac{c}{4\pi} \nabla \times \mathbf{B}$, 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 $\mathbf{J}$ 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.

Finally, the galactic magnetic field accelerates interstellar cosmic rays to higher energies, by having them repeatedly scatter off moving magnetic irregularities as they travel through interstellar space. This acceleration process may occur either stochastically in the turbulent ISM (second-order Fermi acceleration; Fermi 1949) or systematically at supernova shock waves, where the converging upstream and downstream flows scatter cosmic rays back and forth across the shock front (first-order Fermi acceleration; Blandford & Ostriker 1978).

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