Magnetism of spiral galaxies

Alexander Ruzmaikin*, Dmitry Sokoloff† & Anvar Shukurov‡

* Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, Academy of Sciences, Troitsk 142092, Moscow Region, USSR
† Physics Department, Moscow State University, Lenin Hills, Moscow 119899, USSR
‡ Space Research Institute, Academy of Sciences, Profsoyuznaya ul. 84/32, Moscow 117810, USSR

The concept of the turbulent dynamo in interstellar gas combined with the discovery of global magnetic structures in spiral galaxies has led to a consistent picture of galactic magnetism. Large-scale magnetic fields are generated and maintained by helical turbulent motions of interstellar gas and by differential galactic rotation. Seed fields for the dynamo can be produced by outflows from supernovae and hot young stars.

GALAXIES are the largest magnets in the Universe, with scales naturally measured in kiloparsecs (1 kpc $= 3\times10^{21}$ cm). Because we are living within a spiral galaxy, the Milky Way, investigation of the magnetic fields of spiral galaxies has taken a special place in the study of cosmic magnetism, but magnetic fields are a universal property of all galactic-type objects, as is evident from the ubiquity of synchrotron emission from relativistic electrons gyrating in magnetic fields. The past ten years have been notable for rapid, qualitative progress in understanding the magnetism of spiral galaxies, a result of both theoretical and observational developments. A few decades ago, galaxies were considered as combinations of stars; forty years ago the role of interstellar gas and cosmic rays was realized, but only now are magnetic fields considered an equal component of the interstellar medium.

To a solid-state physicist, for example, the strength of galactic magnetic fields would seem miniscule. Although interstellar magnetic fields are as weak as few microgauss, in rarefied interstellar gas their energy density, $H^2/8\pi \approx 10^{-12}$ erg cm$^{-3}\approx$ 1 eV cm^{-3}, is comparable to the thermal energy of the interstellar medium $nkT\approx10^{-12}$ erg cm^{-3} ($n\approx1$ cm^{-3} and $T\approx10^4$ K), the energy density of interstellar turbulence $nm_pv^2/2\approx 10^{-12}$ erg cm^{-3} (the r.m.s. turbulent velocity $v\approx10$ km s^{-1}) and the cosmic ray energy density $\sim10^{-12}$ erg cm^{-3}.

Cosmic magnetism differs drastically in nature from the ferromagnetism of a permanent magnet or from magnetism produced by electromechanical induction devices. The magnetic fields of the majority of astrophysical objects are the self-excited offspring of hydrodynamic motions of an electrically neutral conductive medium, or plasma. The magnetic fields of the Earth, the Sun and spiral galaxies have a common source in the dynamo action of internal fluid motions. Galactic magnetic fields were discovered only recently, but our understanding of their properties is more advanced than that of geomagnetism or stellar magnetism. The reason for this is two-fold. First, we reside within a dynamo region in the Milky Way and are able to observe, at least in principle, all components of the magnetic field. (Note that electrodynamic vacuum boundary conditions forbid penetration of the probably dominant azimuthal axisymmetric components of magnetic fields outside the liquid core of the Earth, the convection zone of the Sun, or the ionized disk of a spiral galaxy.) Second, spiral galaxies are transparent to radiowaves and partly transparent to optical emission. This makes it possible to investigate both hydrodynamic and magnetic properties of external galaxies and of distant parts of the Milky Way.

The formation of regular magnetic structures in turbulent interstellar gas is a specific example of order emerging from chaos[1]. It is interesting to note that this order arises in a system that is linear in the magnetic field. The dynamo that creates the large-scale magnetic field acts by violation of the reflection symmetry of the turbulence in rotating galaxies; this violation is associated, in turn, with dominance of, for example, right-handed helical motions in the turbulent flow. The generation of magnetic fields is a threshold phenomenon; the analogue of the bifurcation parameter is the dynamo number, proportional to the intensity of the mean helicity of the flow.

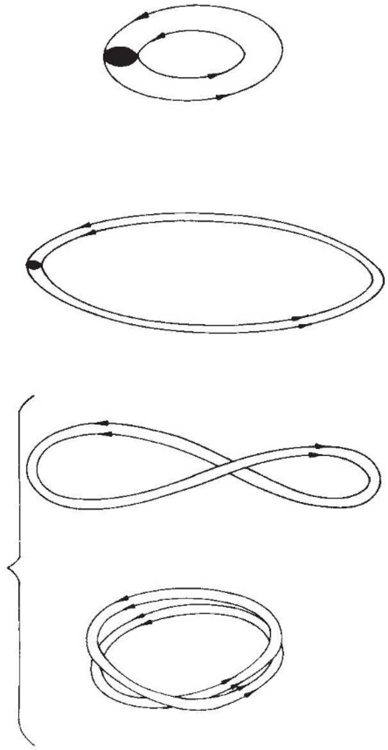

Fig. 1 This schematic of Zel'dovich's rope dynamo illustrates how a magnetic field can be generated by a helical turbulent hydromagnetic dynamo. A loop of magnetic flux is stretched to twice its radius, twisted and doubled upon itself. Solid shading shows the loop cross-section, which is halved after stretching. After every cycle shown here the magnetic flux of the loop is doubled. If the process can repeat, the flux density can grow exponentially.

The existence of an intrinsic galactic magnetic field was anticipated by Fermi[2] on the basis of studies of cosmic ray confinement[3,4]. Observational evidence of galactic magnetism was provided by the discovery of the polarization of starlight[5,6], the interpretation of non-thermal (synchrotron) galactic radioemission[7-10] and the discovery of its polarization[11-13]. Comprehensive discussions of observations of magnetic fields in our Galaxy are given in refs 14-16. The most reliable and detailed quantitative information on galactic magnetic fields currently comes from observations of the Faraday rotation of the polarization plane of radio emission passing through interstellar space.

Here we present a fundamental theoretical approach to magnetic fields of spiral galaxies, in which the hydromagnetic dynamo concept plays a key role. Our views on this subject

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have been profoundly influenced by discussions with Yakov Borisovich Zel'dovich. The dynamo generation process can be illustrated by Zel'dovich's rope dynamo model (Fig. 1).

Magnetic fields in spiral galaxies

Observation of cosmic magnetic fields is one of the most difficult problems in astronomy, and it is therefore understandable that observational data on magnetic fields in the Milky Way and other galaxies are often ambiguous, uncertain and even contradictory. Nevertheless, some conclusions can be drawn, more or less confidently, from existing observational data.

The Faraday effect is very useful in studies of galactic magnetism because it allows one to determine not only the strength but also the direction of a magnetic field. When an electromagnetic wave propagates through a magnetized interstellar thermal plasma the polarization plane rotates over an angle

$$\varphi - \varphi_0 = 0.81\lambda^2 \int_0^L n_e \mathbf{H}\, d\mathbf{l} \equiv \mathrm{RM}\lambda^2,$$

where φ is the positional angle of the polarization plane, φ_0 is its intrinsic value within a source (pulsar or radio galaxy) whose distance to the observer is L (pc), λ(m) is the wavelength, n_e (cm^{-3}) is the number density of thermal electrons, $\mathbf{H}$ (μG) is the magnetic field strength and integration is carried out along the path length. The integration factor is called the rotation measure, RM. Under galactic conditions RM acquires measurable values in the radio range $\lambda \approx 0.1$–1 m.

Statistical analysis of Faraday rotation measures of pulsars and extragalactic radio sources has yielded detailed information about magnetic fields within ~4 kpc of the Sun[17,18]. The large-scale field **B** (that is, the field whose scale exceeds the energy-range scale of interstellar turbulence, ~100 pc) is dominated by the azimuthal component B_φ. In the local spiral arm B_φ is parallel to the direction of Galactic rotation. There is ample evidence to suggest that the azimuthal component of the large-scale field has the same direction both above and below the Galactic plane: $B_\varphi(z) = B_\varphi(-z)$, where z is the vertical coordinate orthogonal to the Galactic plane. The strength of the large-scale magnetic field in the solar vicinity is $B \approx 2$–3 μG and the direction of this field, as determined from analysis of Faraday rotations of extragalactic sources, is toward Galactic longitude $106° \pm 8°$ (ref. 17, p. 250); recent pulsar data give instead longitude 96° (ref. 19). This means that the ratio B_r/B_φ is 0.1–0.3; the field is almost in alignment with the local spiral arm. Such alignment is typical of spiral galaxies[20,21]. Information on the vertical field B_z is obscured by statistical noise, except in central parts of galaxies, where B_z is anomalously strong and comparable to the other field components[22,23].

Analysis of interstellar Faraday rotation reveals strong disturbances imposed on the regular field by magnetic bubbles associated with supernova remnants and stellar winds[24,25]. Another factor that introduces irregularity to galactic magnetic fields is the fluctuating magnetic field associated with interstellar turbulence. The r.m.s. strength of magnetic field fluctuations in the Galaxy is 1–2 times greater than the regular field strength and their correlation scale is approximately the same as the energy-range scale of interstellar turbulence, $l \approx 50$–150 pc. Chaotic fields of comparable strength are also observed in other spiral galaxies[20,21].

In the past ten years, systematic observations using the 100-m radiotelescope in Effelsberg, Germany have constituted a major step forward in the study of galactic magnetism, making possible the investigation of global configurations of magnetic fields in nearby spiral galaxies[20,21,26]. Previous observations were restricted to the solar neighbourhood in the Milky Way, leaving much ambiguity about global structure of the magnetic field. Observations of nearby galaxies are restricted by angular resolution (somewhat relieved by recent interferometric observations with the VLA[26]) and they still leave unanswered many questions about the z-symmetry and chaotic components of the fields.

Yakov Borisovich Zel'dovich (8.3.1914–2.12.1987) was one of the guiding lights of modern physics. He made essential contributions to the theory of nuclear fission and, in later years, to astrophysics and cosmology, including work on the cosmological constant, black holes and neutron stars, galaxy formation and cosmic microwave background radiation.

Theoretical prediction[27] of a magnetic ring in the galaxy M31 (the Andromeda Nebula) was confirmed almost immediately by observations at Effelsberg[28,29]. Observations[30] of another nearby spiral galaxy, M51, were interpreted[31] as indicating a basically non-axisymmetric global magnetic configuration, with magnetic lines seemingly entering the galactic disk from one side and leaving it from another. Such a configuration is called bisymmetric[31]. Bisymmetric magnetic structures were a direct challenge to the theory of galactic magnetism[32,33].

Global magnetic structures have now been studied for a dozen nearby spiral galaxies. These structures are crudely divided into two basic configurations, axisymmetric and bisymmetric[20,21]. The majority of galaxies appear to possess bisymmetric fields, whereas only a few (M31, IC342 and, probably, the Milky Way) exhibit axisymmetric structures. But the dynamo theory predicts that combinations of such basic modes must be common, including those modes with still more complicated symmetries relative to the azimuthal angle. The estimated strengths of regular fields in different spiral galaxies range from 1 to 5 μG and the ratio of fluctuations to the regular field ranges from 0.4 to 2.5.

Contrary to earlier views, recent theories, confirmed by observations[26], stress that the field lines of large-scale magnetic fields in all structures are always spirals rather than closed circles[34,35].

There are many directions in which these observations can be further developed. Observations with higher angular resolution should provide new insights. There is much scope for improvement of data processing methods. Careful determinations of intrinsic Faraday rotation measure distributions are needed. Apparent dominance of bisymmetric fields among observed structures should be reconsidered for more representative samples and with better data processing. What is important, however, is the fact that the existence of non-axisymmetric regular fields seems to be firmly established. The discovery of various global magnetic structures in spiral galaxies has provoked interest in the origin of galactic magnetism.

The origin of galactic magnetic fields

Hoyle[36] attracted attention to the origin of the galactic magnetic field by pointing out that an enormous electromotive force (~10^{12} V) must act in the ionized galactic disk for the entire galactic lifetime to build up and maintain the observed large-scale field. This forced him to suggest that the field is a relic from pre-galactic stages of evolution of the Universe, requiring the presence of cosmological magnetic fields whose scales exceed the galactic one. Some ideas proposed to explain how these fields could be generated in the Universe are discussed in ref. 18. All proposed mechanisms give only very weak present-day intergalactic magnetic fields of $H_{\mathrm{IG}} = 10^{-9}$–$10^{-21}$ G at galactic scales. An upper limit on cosmological magnetic fields is provided by analysis of the observed Faraday rotation of polarized radio emission of remote radio sources (quasars and radio

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galaxies): $H_{IG} \lessapprox 5 \times 10^{-10}$ G for $n_e = 10^{-5}$ cm^{-3} in intergalactic space[37] (estimates of the latter parameter remain uncertain[38]). Primordial fields of below 10^{-8}–10^{-9} G are insufficient to explain the observed galactic magnetic fields[39]. But even if the cosmological magnetic field were of the 10^{-8} G strength required by the relic-origin hypothesis, it could not account for the observed large-scale magnetic fields in spiral galaxies because the conductive interstellar gas is in a state of intense turbulence that inevitably tangles away any large-scale magnetic field unless this is constantly replenished by some other mechanism[40]. The energy-range scale and velocity of the interstellar turbulence are $l \approx 100$ pc and $v \approx 10$ km s^{-1} respectively, which gives an estimate of $\beta \approx lv/3 \approx 10^{26}$ cm^2 s^{-1} for the turbulent magnetic diffusivity. Therefore, in galactic disks of half-thickness $h \approx 400$ pc the relic large-scale magnetic field would be destroyed in $h^2/\beta \approx 5 \times 10^8$ years, which spans only five per cent of the Galactic lifetime.

Thus, a relic origin of magnetic fields of spiral galaxies can be dismissed on both observational and theoretical grounds. Nevertheless, recent detection of non-axisymmetric global magnetic structures in nearby galaxies has resurrected suggestions of their relic origin on the grounds of their outward resemblance to the magnetic structures produced by differential rotation of galaxies from a uniform external magnetic field lying in the galactic plane. But the differential rotation winds up such magnetic fields very quickly (one rotation typically takes only 3×10^8 years) which enhances dissipation of the trapped field through decrease in its radial scale. Observations show that magnetic lines of the non-axisymmetric magnetic fields have moderate pitch angles to the circumferential direction[26], of order 10°–20°. This precludes the possibility that large-scale magnetic fields are passive remnants of an intergalactic field and consequently they must originate within galaxies.

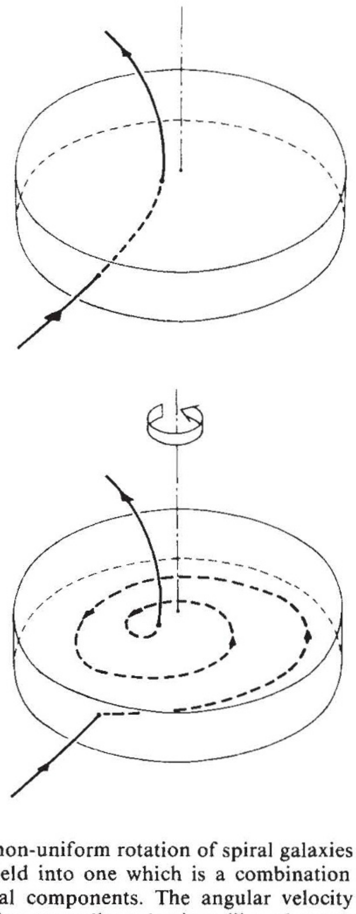

Fig. 2 The non-uniform rotation of spiral galaxies turns a purely meridional field into one which is a combination of meridional and azimuthal components. The angular velocity of the gas is generally higher at smaller galactic radii, and a trapped meridional field (top) is stretched into a trailing spiral (bottom).

It is now commonly accepted that galactic magnetic fields are generated by the action of a turbulent hydromagnetic dynamo, that is, by motions of the ionized interstellar gas. The idea that helical turbulent motions are able to generate large-scale magnetic fields was proposed by Parker[41] and became commonly accepted after the decisive work of Steenbeck, Krause and Rädler[42]. The dynamo theory was first applied to spiral galaxies by Parker[43] and Vainshtein and Ruzmaikin[44]. We consider now how the galactic dynamo works.

The galactic dynamo

In the evolution of magnetic fields embedded in interstellar gas, the most important characteristic of the medium is the magnetic Reynolds number $\mathrm{Re_m}$, which measures the role of the ionized gas motions relative to the role of magnetic diffusion:

$$\mathrm{Re_m} = \frac{VL}{\nu_m}$$

where V is the characteristic gas velocity, L is the velocity-field scale and ν_m is the magnetic diffusivity, $\nu_m = c^2/4\pi\sigma$, with σ the electric conductivity. Although conductivity of interstellar gas is low relative to that of metallic conductors, the galactic scales involved are so large that the magnetic Reynolds number is very high in the interstellar environment. For the values $V = 10$ km s^{-1}, $L = 100$ pc, which characterize the energy-range scale of interstellar turbulence, and $\nu_m \approx 2 \times 10^{21}$ cm^2 s^{-1} (this being the ambipolar diffusion in a partially ionized interstellar hydrogen plasma at $T = 10^4$ K, $n = 1$ cm^{-3}, for the total field strength $H \approx 5$ μG; note that $\nu_m \propto H^2$), we obtain $\mathrm{Re_m} \approx 5 \times 10^4$. This very high value indicates that interstellar magnetic fields can be conveniently considered as frozen into the interstellar gas unless the scales involved are below 10^{-1}–10^{-2} pc (refs 45, 46).

In the dynamo theory, the term 'generation' is always understood as an exponential time-growth of magnetic flux. At the initial stage of exponential growth the velocity field may be considered as fixed and the dynamo is called kinematic. Any magnetic field can be decomposed into azimuthal (B_φ) and meridional (B_r and B_z) components. It is clear that the field can grow exponentially only when both components are mutually coupled, that is, when there is a way of transforming the meridional component into the azimuthal one and vice versa. This situation is typical of any instability. Because the induction equation is linear in **B**, then if one component were fixed the other could grow at best linearly with time.

The first stage of the galactic dynamo process, the effect of differential rotation, is illustrated in Fig. 2. The feedback loop of the galactic dynamo is associated with a more subtle feature of the motions of the interstellar gas, the mean helicity of the turbulence (Fig. 3). Deviations of the averaged characteristics from reflection symmetry are exceptional in laboratory turbulent flows but they are a quite general feature of cosmic environments where turbulent volumes rotate and are density-stratified. The average deviation from reflection symmetry in the presence of an azimuthal field results in emergence of a mean meridional magnetic field (Fig. 4).

We have illustrated the galactic dynamo mechanism for magnetic fields frozen into the interstellar medium, but finite magnetic diffusivity is necessary for galactic mean-field dynamos[18]. We note that the possibility of a dynamo arising in ideally conducting medium is still under debate: it is traditionally believed that a dynamo cannot exist in finite bodies without resistivity, but there exists an explicit example of a dynamo for $\nu_m = 0$, this being the case of renovating flow in infinite space[47].

Generation of the meridional field implies a growing azimuthal electric current. In other words, the action of helical turbulence is equivalent to the generation of an azimuthal electromotive force αB_φ where α is a function of position and is proportional to the mean helicity of the turbulence. Therefore, the induction equation, when averaged over turbulent pulsa-

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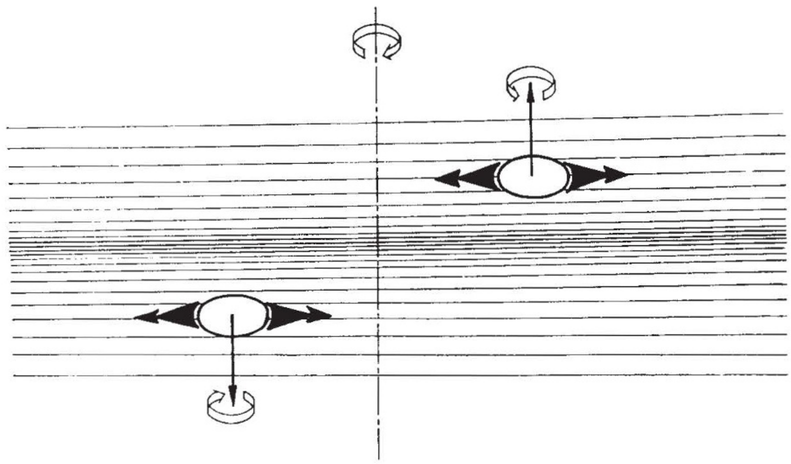

Fig. 3 A schematic vertical section through a galactic disk illustrating breaking of the reflection invariance of the turbulent flow, characterized mathematically by the scalar product $\mathbf{v} \cdot \nabla \times \mathbf{v}$, called the helicity. A turbulent cell rising up through the disk expands because the density scale height of the interstellar gas only slightly exceeds the correlation scale of the turbulence. The Coriolis force from galactic rotation delivers an additional rotation to the expanding cells. Descending cells contract and acquire an oppositely directed Coriolis rotation, but all cells above (or below) the galactic plane have helicity of the same sign. The mean helicity $\langle \mathbf{v} \cdot \nabla \times \mathbf{v} \rangle$, where $\langle \cdots \rangle$ denotes an ensemble average, is thus an odd function of the vertical coordinate z, and breaks the mirror symmetry of the galactic plane.

tions, acquires an additional term associated with this e.m.f.:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\alpha \mathbf{B}) + \nabla \times (\mathbf{V} \times \mathbf{B}) + \beta \Delta \mathbf{B} \qquad (1)$$

where $\mathbf{B} = \langle \mathbf{H} \rangle$, $\mathbf{V}$ is the regular velocity and $\alpha = -\tau \langle \mathbf{v} \cdot \nabla \times \mathbf{v} \rangle / 3$ with τ the correlation time and $\mathbf{v}$ the turbulent velocity. Mathematically rigorous averaging procedures for the induction equation are described for various conditions in refs 18 and 47–49.

Equation (1) describes the generation of magnetic fields not only in galaxies but also in stars and planets. Differences in geometries of these objects result in drastic differences in properties of the generated fields: in disk galaxies they are quadrupolar and non-oscillating in a rotating frame, in a thin convective shell of the Sun they are dipolar and oscillatory whereas a thick spherical shell of the Earth's outer core generates a dipolar quasi-stationary field[17,48].

Self-induced fields in galactic disks

In a spiral galaxy the intestellar gas is concentrated predominantly within a very thin disk. For example, in the solar vicinity of the Milky Way the ratio of the half-thickness of the disk of ionized gas to the disk radius is

$$\lambda = \frac{h}{r} \approx \frac{400\ \text{pc}}{10\ \text{kpc}} = 0.04 \qquad (2)$$

The disk thickness grows somewhat towards the edge. Of course, in central parts ($r \approx h$) the disk cannot be considered thin and the solution of the dynamo problem is then a separate problem[50].

As explained above, the large-scale magnetic field in the disk of a spiral galaxy is produced by competition between regenerative action of the mean helicity and differential rotation, and attenuation by turbulent diffusion. The diffusion time across a thin disk is obviously much shorter than that along the radius or azimuth. This allows us first to solve the local generation problem and to deduce the field distribution across the disk, and then to use this solution as a basis for evaluation of the radial and azimuthal distributions of the field.

The strengths of the two generation sources—the mean helicity and differential rotation—that compete with turbulent diffusion are measured by the respective dimensionless numbers,

$$R_\alpha = \frac{\alpha_0 h_0}{\beta} \quad \text{and} \quad R_\omega = \frac{|r\, \mathrm{d}\Omega/\mathrm{d}r|_0 h_0^2}{\beta}$$

where subscript zero denotes characteristic values of the corresponding quantities and Ω is the angular velocity of rotation.

In the kinematic formulation of the dynamo problem, the generation sources are considered as fixed and therefore uninfluenced by back-action of the generated field. This formulation is adequate for determination of the field origin and is applicable over most of the galactic lifetime. When generation sources have fixed strengths the dynamo equation (1) has solutions that evolve exponentially with time and for small R_α and R_ω the solutions decay. For positive growth rate of the field (that is, self-excitation) the following necessary condition must be fulfilled:

$$R_\alpha R_\omega \geq D_c$$

where D_c, the critical dynamo number, is of order 10 (see below).

The solution of the dynamo equation (1) in an axisymmetric disk with $\mathbf{V} = \mathbf{\Omega} \times \mathbf{r}$ has the form

$$\mathbf{B} = \mathcal{B}(r, z) \exp(\Gamma t + im\varphi)$$

where r is the distance to the rotation axis and m is the azimuthal wave number. It is convenient to introduce dimensionless variables by measuring the vertical coordinate in units $h_0 = 400$ pc, the radius in units $r_0 = 10$ kpc, and the time in units of the diffusion time $h_0^2/\beta \approx 5 \times 10^8$ years. The mean helicity and the angular velocity are conveniently normalized by $\alpha_0 = 1$ km s^{-1} and $\Omega_0 = 25$ km s^{-1} kpc^{-1}. The growth rate Γ is measured in units of β/h_0^2.

Equation (1) is essentially a system of three linear second-order differential equations. For uniform coefficients (the sources α and $r\, \mathrm{d}\Omega/\mathrm{d}r$) this system can be solved analytically. But in galaxies these coefficients depend on position, and numerical solutions are then appropriate. We can make a crude estimate of the computer memory required for a straightforward solution, which indicates that vectors with 10^9 components and matrices with 10^{18} elements must be stored. This impractical result is associated with the presence of the small parameter λ, which makes the intrinsic geometry very inconvenient for straightforward solution; for cubic geometry, some 3×10^3 mesh points would suffice to reach the same accuracy. Some progress can be made with numerical methods through the presence of certain symmetries, judicious choice of the mesh, restriction to simplified models of galaxies, and other factors[51,52].

The smallness of λ can, however, be used to advantage. When $\lambda \ll 1$, one can employ a simple asymptotic method (in combination with some numerical calculations) to find the growth rate eigenvalue Γ and the eigenfunctions $\mathcal{B}(r, z)$ for suitably chosen boundary conditions and for distributions of the generation sources inferred from observations. The boundary conditions routinely used in galactic dynamo models assert that the galactic disk is surrounded by vacuum[17,18,40,48]. Formulation of more adequate boundary conditions would be desirable because galactic disks are in fact surrounded by conducting coronae. Nevertheless, the vacuum boundary conditions are partially justified by the observation that, because of higher turbulent scales and velocities in galactic coronae relative to the disk, the turbulent magnetic diffusivity is expected to be some 30 times higher in the corona.

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In this asymptotic solution the radial scale of the field is assumed to be large, of order $\lambda^{-1/2}$, so that the radial derivatives of the dimensionless field components are of order $\lambda^{1/2}$ whereas the vertical derivatives are of order λ (refs 34 and 53). With such ordering, and retaining only the terms up to order λ^2, equation (1) reduces to

$$\left\{\Gamma + imR_\omega\Omega(r) - \frac{\partial^2}{\partial z^2} - \lambda^2\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}(r\times.)\right]\right\}\begin{bmatrix}\mathcal{B}_r\\ \mathcal{B}_\varphi\end{bmatrix} = \begin{bmatrix} 0 & -R_\alpha\dfrac{\partial}{\partial z}(\alpha\times.) \\ R_\omega r\dfrac{d\Omega}{dr} & 0\end{bmatrix}\begin{bmatrix}\mathcal{B}_r\\ \mathcal{B}_\varphi\end{bmatrix} \qquad (3)$$

At this order, the equation for the vertical field component, B_z, factorizes out and may be solved separately. In equation (3) we have neglected a term in R_α in the evaluation of $\mathcal{B}_\phi$, as it is generally somewhat smaller than the R_ω term (typically, $R_\omega \approx 10$ and $R_\alpha \approx 1$ in galactic disks) and is not qualitatively significant in a thin disk[54]. But in some galaxies (for example, M33 and NGC6946) the large-scale field is generated at rather small distances from the centres, where the disk cannot be considered thin; in these cases inclusion of the R_α term is essential[50].

To lowest order in λ, equation (3) has a solution of the form $\mathcal{B}(r, z) = Q(r)\mathbf{b}(z)$, where $Q(r)$ is a radial function and $\mathbf{b}(z)$ is the matrix of local radial (b_r) and azimuthal (b_ϕ) components of the field. These local components satisfy one-dimensional 'local dynamo equations' with eigenvalues $\gamma(r)$ that represent local growth rates of the field. Vertical and radial distributions of the field will be discussed separately.

Vertical distribution of the field. For conditions typical of spiral galaxies the local eigenvalue $\gamma(r)$ is real. The local dynamo equation has growing solutions $\gamma(r) > 0$ only for sufficiently strong generation sources. Specifically, the product $D_{\text{eff}}(r) \equiv R_\alpha R_\omega h^3|\alpha r\, d\Omega/dr|$, the local dynamo number, must exceed a certain threshold value that depends on the distribution of the mean helicity (or α) across the disk. For instance, for $\alpha = \sin(\pi z)$ this threshold is $D_{\text{cr}} \approx 8$ while for $\alpha = z$, $D_{\text{cr}} \approx 11$.

In the principal magnetic mode b_φ and b_r are even functions of z. In addition, the azimuthal field turns out to be considerably larger than the other components, $b_r/b_\varphi = O(R_\alpha/R_\omega)^{1/2}$ (refs 17, 18) (here, local values of R_α and R_ω should be used). The field runs almost parallel to the galactic plane and has a small pitch angle with respect to the circumferential direction. All these results agree favourably with observations of magnetic fields in the solar vicinity.

Because the dynamo equations have only decaying solutions when either of the field components identically vanishes, growing solutions can never have magnetic lines that form closed circles in the galactic plane. Magnetic lines of the dynamo-generated fields are always spirals. The radial and azimuthal field components have different signs, which means that the spirals are trailing.

The azimuthal wave number m does not enter the local generation problem. This implies that modes with different m are distributed over z nearly identically. Furthermore, pitch angles of magnetic lines are approximately the same for all m; this is also confirmed by observations[26].

Radial distribution of the field. It is easily shown that the growing magnetic fields are concentrated within those radial ranges where $\gamma(r) > 0$. Moreover, the global growth rate Re (Γ) can be positive only when the potential well is sufficiently wide and deep, that is, when $D_{\text{eff}}(r) > D_{\text{cr}}$ over a sufficiently wide radial range. The value of Re (Γ) can be considerably lower than the maximal value of γ; for instance, $\max(\gamma) \approx (5\times10^8\ \text{yr})^{-1}$ (ref. 17) whereas Re $(\Gamma) \approx (1.5\times10^9\ \text{yr})^{-1}$ (ref. 54) in the Milky Way. Within an order of magnitude, $\mathcal{B}_z \approx \lambda^{1/2}\mathcal{B}_r \approx (\lambda R_\alpha/R_\omega)^{1/2}\mathcal{B}_\varphi$.

Analysis of the local generation problem shows that under

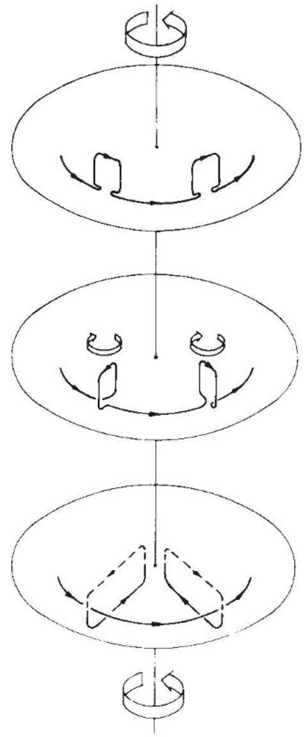

Fig. 4 Helical turbulence in a conducting fluid creates a meridional magnetic field from an azimuthal one. Turbulent cells locally distort the azimuthal magnetic line (top); because the turbulence is helical, local magnetic loops rotate about the vertical axis (middle). Oppositely directed fields at the base of each loop are quickly removed by electric resistivity, and small loops detach from the parent azimuthal magnetic line to merge, again due to electric resistivity which is important at small scales. In helical turbulence the total numbers of oppositely twisted loops are not identical and after their merging the small-scale fields are not cancelled completely but produce a large-scale meridional magnetic line (bottom). The upper part of the resulting line (dashed) leaves the disk. The meridional field thus growing within the disk has the direction required for further amplification of the azimuthal component by differential rotation (compare Fig. 2). Helicity can also produce an azimuthal field from a meridional one but in spiral galaxies this process is generally weak compared with a similar action of the differential rotation.

galactic conditions field generation is possible only when $d\Omega/dr < 0$; when the angular velocity grows with r the critical dynamo number is very high, of the order of a few hundreds. This fact explains why the magnetic field in the galaxy M31 is concentrated within a ring around $r = 10$ kpc and in the central region: these domains are separated by a gap in the region $2 \leqslant r \leqslant 2.6$ kpc, for which $d\Omega/dr > 0$ and where consequently a field cannot be maintained. Magnetic field generation proceeds independently in the outer and inner regions. This gap in the magnetic field distribution of M31 was predicted theoretically[27] and observed with the Effelsberg radiotelescope[29].

Although in the Milky Way $d\Omega/dr < 0$ for all r, in the region $3 \leqslant r \leqslant 6$ kpc rotation is relatively close to rigid-body rotation (see, for example, ref. 55). Therefore, $\gamma(r)$ may become a double-well potential and the generated field will be then concentrated in an outer ring, coincidentally near $r = 10$ kpc, and in the central part of the disk. But the value of D_{eff} depends not only on $d\Omega/dr$ but also on the ionized disk half-thickness h, the value of which is uncertain. For sufficiently large disk thickness, $D_{\text{eff}} > D_{\text{cr}}$ for all r, in which case there are no gaps in the magnetized region[34]. Thus, from the field distribution one can infer an estimate of the galactic disk thickness.

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Dynamo modes with different azimuthal wave numbers behave very differently, because differential rotation creates distinct generation conditions for different m-modes. Generation conditions are most favourable for the axisymmetric mode because its radial and azimuthal scales are the largest. Radial and azimuthal diffusion is more important for non-axisymmetric fields, which have smaller growth rates[32]. In the absence of a dynamo, non-axisymmetric magnetic fields would be expelled from regions with strong differential rotation; similarly, dynamo modes with $m \neq 0$ concentrate at larger radii, where the local value of R_ω is smaller, than axisymmetric ones. An important prediction of the galactic dynamo model is the presence of combinations of axisymmetric and non-axisymmetric fields in spiral galaxies[34], indications of which have been detected in the Andromeda Nebula[29].

The current theory of galactic dynamos is in general agreement with observations; theoretical models exist for nearly all galaxies whose large-scale magnetic fields have been observed in any detail[34,50,53,54]. For example, Fig. 5 shows magnetic lines of the growing dynamo modes $m=0$ in M31 and $m=1$ in M51 as determined[54] from the theory outlined earlier. Observations, however, seem to indicate a much wider abundance of non-axisymmetric magnetic structures among spiral galaxies than is expected from theory: only two out of a dozen galaxies investigated definitely host axisymmetric fields. This observation constitutes one of the intriguing current problems in galactic magnetism. The theory described above considers generation of a field in an axially symmetric disk, and it is therefore no surprise that axisymmetric magnetic modes always have the greatest growth rates in this model. Why, then, do non-axisymmetric modes dominate amongst observed magnetic structures? Deviations of galactic disks from exact axial symmetry, associated with the presence of spiral arms, would facilitate generation of bisymmetric fields. But these perturbations correspond to $m=2$ (two-armed spiral patterns dominate) and therefore they cannot affect generation conditions for the $m=0$ and $m=1$ modes, at least at the level of the weak-perturbation analysis. The observed dominance of the $m=1$ modes in spiral galaxies may be the result of corresponding $m=1$ non-axisymmetric perturbations[54] associated with tidal interactions with companion galaxies and with warpings of galactic disks. The connection between galactic satellites and bisymmetric fields is discussed on observational grounds in ref. 56. Another possible explanation is provided by anisotropy of interstellar turbulence[54].

Amongst other problems associated with the galactic dynamo theory we mention an urgent need for more precise observational determination of the thickness, as a function of radius, of the ionized gas layers in spiral galaxies and for the measurement of the mean helicity of interstellar turbulence and its distribution across the disk. Helical turbulent flows are also crucial for generation of magnetic fields in planets and stars, so their detection in galaxies plays a fundamental role. Interstellar gas, being a unique dynamo region transparent to optical and radio waves, offers an exceptional opportunity to verify fundamental tenets of the dynamo theory.

Seed fields

Like other dynamo mechanisms, the mean-field turbulent dynamo requires some initial large-scale magnetic field. If we reject the hypothesis of a relic intergalactic magnetic field we are forced to propose a galactic-scale seed field and must then address the problem of its origin. Battery effects are effective only at small scales and can produce only exceedingly weak seed fields at the relevant larger scales[18].

An unexpected solution to the problem may be found in the magnetic fields ejected from stars by supernova explosions and by stellar winds. Such ejections yield a chaotic field whose value is zero when averaged over an infinitely large and homogeneous volume. But galactic disks have finite volumes that can contain, within the region of field generation, perhaps 300 or so of the 100-pc magnetic loops that characterize such ejections. The ejected field averaged over such volumes may be significantly different from zero. Thus the long-range order originates from a fluctuation and is stabilized by the dynamo. The importance of fields ejected by stars in the global galactic context was noted in refs 57 and 58, but an adequate formulation of the problem was developed only recently[32] (see also the discussion by Rees[59]).

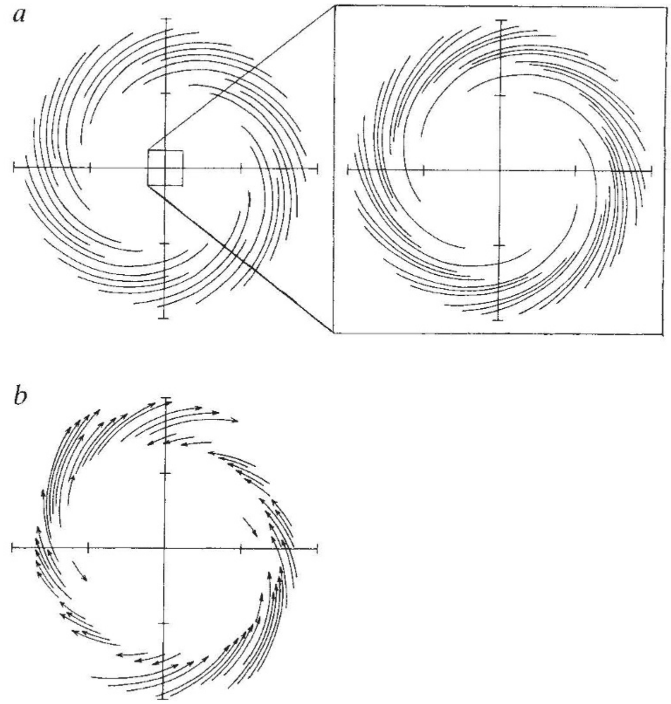

Fig. 5 Magnetic flux lines in *a*, the Andromeda galaxy, M31, and *b*, M51 are shown here projected onto their respective galactic planes. The magnetic field in M31 is generated both in the outer ring and near the centre. The field structures are dominated by the $m=0$ mode in M31 and possibly the $m=1$ mode in M51. Because the kinematic dynamo equations are invariant under $\mathbf{B} \to -\mathbf{B}$, the directions of the field lines in *a* are arbitrary, provided only that the direction at all azimuthal angles is uniform. Likewise, the arrows in *b* may all be reversed.

To examine the evolution of a large-scale magnetic field that originates in this way, one can expand the ejected seed field $\mathbf{B}_0(\mathbf{r})$ over eigenfunctions $\mathbf{B}(\mathbf{r})$ of the kinematic dynamo problem. Magnetic lines of the field $\mathbf{B}_0$ are small loops closed in correlation cells. Thus the field $\mathbf{B}_0$ oscillates rapidly with a characteristic scale $l \approx 100$ pc, much smaller than the scales of the dynamo modes. Because the loops are placed randomly, the oscillations cannot be described by a periodic function but are instead characterized as an ensemble of derivatives of δ-functions scattered randomly in space (Fig. 6). This model preserves the closed-loop solenoidality of the small-scale magnetic field. By approximating the lowest axisymmetric eigenfunction as a radially uniform field directed along the azimuth and with radial width Δr, one can integrate the scalar product of $\mathbf{B}(\mathbf{r})$ with $\mathbf{B}_0(\mathbf{r})$ over the volume of the galactic disk to give an estimate of the initial (seed) amplitude of the large scale field as:

$$B_\varphi \Big|_{t=t_0} \approx \frac{bl}{N^{1/2}\Delta r}$$

where b is the r.m.s. strength of the random field ejected by stars and N is the number of correlation cells within the localization region of the dynamo mode. If we use the typical values $b \approx 1\ \mu$G, $N \approx 300$ and $\Delta r \approx 3$ kpc, we obtain a seed amplitude of $2\times10^{-3}\ \mu$G. A growth rate of $(1.5\times10^{9}\ \text{yr})^{-1}$ is required to

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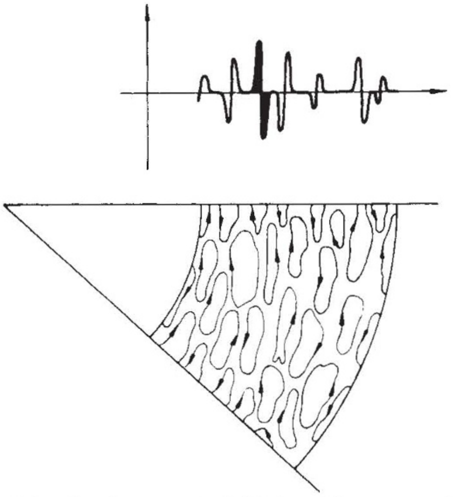

Fig. 6 The chaotic magnetic field ejected by stars can be approximated, along any radial slice, by a collection of derivatives of δ-functions. This model preserves solenoidality of the chaotic magnetic field and allows an estimation of the seed field for the galactic dynamo.

amplify this field up to the observed strength of 2 μG, which is in excellent agreement with estimates of the dynamo theory. Magnetic fields of first-generation stars formed in non-magnetized interstellar gas can be produced by battery mechanisms[60].

Nonlinearity

The exponential growth of the magnetic field described by the kinematic dynamo saturates when the nonlinear influence of magnetic fields on the generating motions becomes important. Because differential rotation (R_ω) is a stronger generator (by orders of magnitude) than the mean helicity of turbulence (R_α), it is clear that generation is suppressed because of modification of the mean helicity. The helicity is produced by the Coriolis force, so it is expected that the field approaches a steady state when magnetic stresses balance the Coriolis force:

$$\frac{B_r B_\varphi}{4\pi h} \approx \rho v \Omega,$$

where h is the minimal field scale and ρ is the gas density. Because $B_r/B_\varphi \approx O(R_\alpha/R_\omega)^{1/2}$ (refs 17, 18), one obtains

$$B_\varphi \simeq \left[\frac{R_\alpha}{R_\omega}\right]^{-1/4} (4\pi\rho v h \Omega)^{1/2}$$

For $h \approx 400$ pc, $\rho \approx 10^{-24}$ g cm^{-3}, $v \approx 10$ km s^{-1}, $\Omega \approx 10^{-15}$ s^{-1}, $R_\alpha \approx 1$ and $R_\omega \approx 10$, this estimate yields $B_\varphi \simeq 7$ μG, which is of the same order as the observed strength of the large-scale field. Accompanying estimates are $B_r \approx 0.3 B_\varphi$ and $B_z \approx \lambda^{1/2} B_r \approx 0.05 B_\varphi$. We emphasize that these estimates are valid only as an average over the disk. In some regions the local ratios of the field components can be very different. For instance, in the centre of a galaxy, where λ effectively approaches unity, the vertical field becomes comparable to other field components. Magnetic fields at distances of several parsecs from galactic centres can be generated by a turbulent dynamo independently of the global field[18,23].

In the galactic dynamo, nonlinearity serves mainly as a saturation factor. Such complex, essentially nonlinear, global magnetic phenomena as irregular inversions of the Earth's magnetic field or global activity minima in the Sun (for example, the Maunder minimum) simply never have time to develop in spiral galaxies, because the typical growth time of the large-scale magnetic field (1.5×10^9 years for the Milky Way) is only slightly shorter than the galactic lifetime (10^{10} years). Large-scale galactic magnetic fields have sufficient time to grow from an initial 10^{-3} μG ejected by stars only up to the present-day strength. In this respect, spiral galaxies are rather young. Nonlinear effects certainly play a role in galactic dynamos. This can be seen, for example, in the fact that the radial widths of magnetic field distributions observed in spiral galaxies are significantly larger than those of the kinematic dynamo eigenfunctions, which is explicable in terms of nonlinear dynamo theory[32]. More varied nonlinear effects can be expected at smaller, turbulent scales.

Galaxies may differ considerably in their magnetic ages. Comparable large-scale field strengths in different galaxies indicate that galactic dynamos are at or near saturation. In addition, the characteristic time is much shorter, and nonlinear effects are therefore much stronger, in the centre of the Milky Way and, presumably, other galaxies. But in the solar vicinity of the Milky Way, where the dynamo is comparatively weak, we witness a unique epoch, of duration $\sim 1.5 \times 10^9$ years, when its large-scale dynamo is just entering the nonlinear stage.

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