Mesoscale Magnetic Structures in Spiral Galaxies

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1 Introduction

Virtually all spiral galaxies host magnetic fields ordered at scales comparable to the galactic size (Beck et al., 1996; Beck, 2000, 2001). Observations of polarized radio emission at improved resolution and sensitivity have revealed details of the global magnetic structures that can shed new light on the problem of their origin. Reversals of the regular magnetic field along radius and/or azimuth and magnetic arms are such features, whose scale exceeds significantly the correlation scale of interstellar turbulence but remains smaller than the overall galactic dimension. Despite a few decades of debate, there remains doubt as to what features of the observed field could have been inherited from the pre-galactic past, and which have been formed and maintained more recently in a relatively mature galaxy. In what follows, we briefly review the current understanding of the origin of the mesoscale magnetic structures and their implications for the origin of galactic magnetic fields.

The Milky Way appears to possess a global magnetic field of unusual structure. The regular magnetic field in our Galaxy has one or more large-scale reversals, where the magnetic field coherent over a scale of order a few kiloparsecs changes its direction by about 180° along a line presumably extended along the azimuth. The number of reversals has not been firmly established, their origin has not been fully understood, and the shape of the lines along which the reversals occur is not known.

There are just a few galaxies where similar large-scale reversals cannot be excluded. The nearby galaxy M 81 might host a bisymmetric magnetic structure (Krause et al., 1989), i.e., a global structure where the regular spiral magnetic field reverses along azimuth and, perhaps, radius. However, the magnetic structure of M 81 needs to be reconsidered with observations at higher resolution and sensitivity and with more reliable interpretation techniques. A magnetic reversal between the inner and outer regions in the galaxy NGC 2997 has been suggested in Han et al. (1999). A magnetic reversal in the disc of M 51 (Berkhuijsen et al., 1997) is discussed in detail below.

The unusual structure of the Galactic magnetic field has attracted significant attention. Numerous papers have been published attempting to establish the number of reversals and their positions from observations. However, there is only a handful of papers where the origin of the magnetic reversals is addressed. In this review, we discuss some limitations of the observational evidence for the reversals and put the observational effort into a broader physical perspective of the theory of galactic magnetic fields.

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Another peculiar feature of galactic magnetic fields, as yet discovered in only a few galaxies but believed to be of general significance, are magnetic arms where the large-scale magnetic field is observed to be enhanced between the gaseous spiral arms. In other words, the large-scale magnetic field in these galaxies is observed to be stronger where the gas density is smaller. This immediately implies that the strength of the regular magnetic field is not uniquely determined by gas density, and therefore that the regular magnetic field cannot be frozen into the gas at scales exceeding a few kiloparsecs (Beck, 2001). It is quite remarkable that the turbulent magnetic fields are still stronger in the gaseous arms, indicating that the turbulent and regular magnetic fields are subject to distinct physical processes. This invites explanations in terms of the mean-field dynamo theory. The origin and implications of magnetic arms are reviewed in the second half of this paper.

2 Observational Evidence for Magnetic Reversals

The first indication of a reversal of the regular magnetic field in the inner Galaxy was obtained by Simard-Normandin and Kronberg (1980) from their analysis of Faraday rotation measures of extragalactic radio sources. This reversal occurs in the inner Galaxy between the local Orion arm and the Sagittarius arm at a distance of about 0.5 kpc from the Sun. The existence of this feature has been later confirmed by most of the studies of the Faraday rotation measures of extragalactic radio sources and pulsars (Heiles, 1996, Chap. 5), and its extension to the fourth Galactic quadrant has recently been detected (Frick et al., 2001).

The only observational tracer of a large-scale magnetic field that is sensitive to its direction is the Faraday rotation measure RM (the Zeeman effect is strong enough only in relatively dense clouds that have a locally enhanced magnetic field). Thus, all the discussions of magnetic field reversals rely on the signatures of the Galactic magnetic field in the rotation measures of extragalactic radio sources and pulsars. Extragalactic polarized radio sources – radio galaxies and quasars – possess their own regular magnetic fields, so their RM contain a significant, and unknown intrinsic contribution. Polarized emission from the radio sources propagates through the turbulent magneto-ionic interstellar medium, so their Faraday rotation measures are contaminated by the strong random contribution of interstellar turbulence. The *maximum* contribution of a regular Galactic magnetic field B to the observed RM is given by

$$|\mathrm{RM}|_{\max} = 0.81 n_\mathrm{e} B L_B \approx 220\,\mathrm{rad\,m^{-2}} \left(\frac{n_\mathrm{e}}{0.03\,\mathrm{cm^{-3}}}\right)\left(\frac{B}{3\,\mu\mathrm{G}}\right)\left(\frac{L_B}{3\,\mathrm{kpc}}\right), \qquad (1)$$

when the line of sight is aligned with the field, where n_e is the mean number density of thermal electrons, and the path length L_B is limited to 3–6 kpc by the curvature and finite width of the spiral arms. Meanwhile, the r.m.s. contribution of the interstellar turbulence to RM along the path length L through the Milky Way is given by (Burn, 1996; Sokoloff et al., 1998)

$$\sigma_{\rm RM} = 0.81\sigma_n\sigma_B(2Ll)^{1/2}$$
$$\simeq 170\,{\rm rad\,m^{-2}}\left(\frac{\sigma_n}{0.03\,{\rm cm^{-3}}}\right)\left(\frac{\sigma_B}{5\,\mu{\rm G}}\right)\left(\frac{l}{0.1\,{\rm kpc}}\right)^{1/2}\left(\frac{L}{10\,{\rm kpc}}\right)^{1/2}, \quad (2)$$

where σ_n and σ_B are the standard deviations of fluctuations in thermal electron density and magnetic field, respectively, and l is the size of turbulent cells. Equations (1) and (2) are only valid if fluctuations in thermal electron density and magnetic field are statistically independent. This assumption is an oversimplification and it can affect very significantly magnetic field estimates obtained from Faraday rotation measures Beck et al. (2003).

Thus, $|{\rm RM}|_{\rm max} \simeq \sigma_{\rm RM}$, and we have data with a signal-to-noise ratio of order unity. With such a signal, we need to reveal quite delicate features of the magnetic field $\boldsymbol{B}$. In the case of pulsars, a change in the sign of the line-of-sight magnetic field, associated with a reversal, would produce a change in the slope of RM as a function of distance from the source to the Sun. For extragalactic radio sources, reversals would produce localized, relatively weak extrema of RM against a broad RM distribution produced by the local magnetic field. The situation is further complicated by nearby fluctuations in the magnetic field (e.g., associated with supernova remnants) that can occupy large regions in the sky and be stronger than the features produced by the large-scale magnetic field. H II regions can contribute significantly to the observed Faraday rotation measures, and this can affect our conclusions about the large-scale magnetic field, especially when the number of radio sources in the sample is only modest (Mitra et al., 2003). It is obvious that meaningful results can only be obtained from careful analysis based on mathematically and statistically rigorous procedures. Any 'eye-ball fitting' is dangerous and can be misleading. Equations (1) and (2) indicate that random deviations of individual RM values from a regular pattern (for both pulsars and extragalactic sources) are comparable to or exceed the magnitude of the features that might result from reversals; hence, conclusions derived using a statistically insignificant number of sources are rarely convincing. This applies to the often employed arguments relying on the dependence of pulsar RM on their dispersion measures along individual lines of sight, where just a handful of sources (often less than 10) is used.

In an attempt to reduce the noise, most authors average extragalactic RM, often with a Gaussian weight function. However, such a smoothing contaminates the data because the mean value of a Gaussian filter function differs from zero, and a few strongly deviating values of RM can distort the result. Therefore, sources with $|{\rm RM}| \gtrsim 100$–$300\,{\rm rad\,m^{-2}}$ are often excluded from analysis. It is, however, more appropriate to *filter out* small-scale fluctuations in RM rather than to smooth them. An noise filtering method used by Frick et al. (2001) involves wavelets, weight functions that have zero mean. Filtering by Fourier analysis along Galactic longitude was used by Johnston-Hollitt et al. (2004); expansion in spherical harmonics was earlier applied to a smaller data set (Seymour, 1984).

A more traditional approach involves model fitting based on well defined statistical criteria for the fit quality. Such an approach was applied to RM of both extragalactic sources and pulsars (Ruzmaikin and Sokoloff, 1977a,b; Rand and Kulkarni, 1989). It is then important to remember that the best fit is not necessarily the one that provides the minimum value of χ^2 (if this statistic is used to access the quality of the fit); instead, χ^2 must be close to an *optimal* value for the model to be acceptable (e.g., Wall and Jenkins, 2003). However, most results regarding the structure of the Galactic magnetic field are based on minimizing a certain statistic without subsequent comparison with its optimal value. As a result, models to be distinguished between are often either equally unacceptable or equally acceptable, with the data being insufficient to distinguish between them.

Since several models can provide equally good or equally bad fit to the data, it is important to explore all reasonable models before making any conclusions. For example, the dependence of RM on Galactic longitude is often used to establish the number and position of magnetic reversals from extragalactic RM, especially in the outer Galaxy. However, plausible modifications of the field configuration and strength in remote arms can produce indistinguishable longitudinal profiles of RM in models with very different magnetic configurations, including those with and without reversals (Stepanov et al., 2005).

The feature of the global magnetic field of the Milky Way confirmed with all models (including those that employ reliable statistical procedures) is the reversal in the inner Galaxy at a distance of about 0.5 kpc from the Sun. The even symmetry of the horizontal magnetic field with respect to the Galactic equator also seems to be firmly established (Frick et al., 2001). Despite rather optimistic assessments. of the reliability of the results (e.g., Han, 2004), further reversals in the inner and the outer Galaxy remain controversial, in particular because remote regions occupy small areas in the sky and are probed by a small number of sources. Recent massive determinations of Faraday rotation measures in the Canadian Galactic Plane Survey (Brown et al., 2003) have provided significant improvement in this respect. However, these data are restricted to a narrow strip extended along the Galactic equator, which complicates their analysis.

Altogether, our confident knowledge of the global magnetic structure of the Milky Way can be conservatively summarized as follows. The distance from the Sun to the reversal in the inner Galaxy is about 0.5 kpc. The reversal has been detected in the first and fourth Galactic quadrants (Frick et al., 2001). This, however, does not imply that the reversal extends over the whole Galaxy (i.e., to all azimuthal angles about the Galactic centre): this may be a relatively local phenomenon, with the reversed field extended by not more than several kiloparsecs in the azimuthal direction. Evidence for further reversals, especially in the inner Galaxy, is compelling but still not fully convincing. Forthcoming extensive RM data will hopefully help to clarify the mesoscale structure of the Galactic magnetic field.

In what follows, we discuss the theoretical understanding of the origin of magnetic field reversals in the Milky Way. There have been few attempts to explain global magnetic field reversals in the Milky Way. The dichotomy between primordial and dynamo theories of galactic magnetic fields has strongly influenced both the data interpretation and modelling. The primordial theory interprets the reversals as a global phenomenon, so that they are *assumed* to extend, in both azimuth and radius, over the whole Galaxy (Sect. 3.1). In the framework of the dynamo theory, the reversals can represent an axially symmetric magnetic configuration with alternating spiral field – then they are viewed again as a global feature (Sect. 3.2). Otherwise, a nonlinear state of the bisymmetric magnetic structure can represent a reversed magnetic field confined to a localized region near the corotation radius (Sect. 4).

3 Global Reversals

In this section we briefly review two concepts of galactic magnetic fields, the primordial and dynamo theories, with emphasis on magnetic field reversals. It is useful to draw a distinction between reversals that occur along azimuth and those occurring along radius. The azimuthal reversals, a signature of a strongly nonaxisymmetric global magnetic structure (e.g., a bisymmetric one) arise from different physical effects than reversals along radius in an (almost) axially symmetric magnetic structure. The nonaxisymmetric structures are subject to rapid wound-up by the galactic differential rotation, and so must be maintained at the global scale. Reversals in an axially symmetric magnetic field are not affected by differential rotation, and so can be supported at a smaller scale: these are genuine mesoscale structures.

3.1 Primordial Magnetic Fields

It is often (wrongly) assumed that a bisymmetric global magnetic structure is a direct indication of the primordial origin of the magnetic field. An external (extragalactic) magnetic field oriented along the plane of the galactic disc is twisted by differential rotation into a bisymmetric configuration, so magnetic field reversals arise naturally, along both radius and azimuth. This conceptual simplicity is, however, deceptive: there are no detailed models that would demonstrate that any primordial magnetic field can be twisted by differential rotation into a configuration compatible with what is known about the global magnetic field of any spiral galaxy, if only a realistic galactic model is adopted (Shukurov, 2000).

In particular, the observed pitch angle of magnetic field p (i.e., the angle between the magnetic field and the circumference) is a sensitive diagnostic of the origin of magnetic field (Shukurov, 2000). The large-scale magnetic fields observed in spiral galaxies have $p = -(10^\circ\text{–}30^\circ)$ (Ruzmaikin et al., 1988; Beck et al., 1996; Beck, 2000, 2001) (here and below, a negative value of p indicates a trailing spiral).

Consider a uniform external magnetic field of a strength B_e parallel to the disc plane and frozen into the interstellar gas (Moffatt, 1978). The differential rotation of the disc twists the field into a bisymmetric spiral. The magnetic pitch angle p of the twisted magnetic field reduces with time t as $\tan p \simeq -(|G|t)^{-1}$, where $G = r\,d\Omega/dr$ is the shear rate due to differential rotation at angular velocity Ω and r is the galactocentric radius. The winding-up proceeds until a time $t_0 \simeq 5\times10^9\,\mathrm{yr}$ such that $|G|t_0 \simeq |C_\omega|^{1/2}$, where $C_\omega = GR^2/\beta = 10^3\text{–}10^4$ is a dimensionless number quantifying rotational shear, with $R \simeq 10\,\mathrm{kpc}$ the representative galactic radius, and β is the turbulent magnetic diffusivity whose standard estimate is $\beta \simeq 10^{26}\,\mathrm{cm^2\,s^{-1}}$. At later times, the magnetic field decays because of diffusion and reconnection since the field direction flips over a radial scale that decreases with time as $\Delta r \simeq R/(|G|t)$ down to $\Delta r \simeq R|C_\omega|^{-1/2} \simeq 0.1\,\mathrm{kpc}$ at $t = t_0$. The wound-up magnetic field attains its maximum value $B_\mathrm{max} \simeq B_\mathrm{e}|C_\omega|^{1/2}$ at $t = t_0$ before decaying rapidly. Even neglecting this inevitable decay, an external magnetic field of order $B_\mathrm{e} = 10^{-8}\,\mathrm{G}$ is required to explain the observed field strength, $B_\mathrm{max} \simeq 2\,\mu\mathrm{G}$. Such an external field appears to be rather strong, but perhaps not unrealistic since an extragalactic magnetic field can be amplified by the fluctuation dynamo in the protogalaxy and by compression during its collapse (Beck et al., 1996; Kulsrud, 1999). What represents a real problem is that the corresponding value of the pitch angle is $|p| \simeq$

$|C_\omega|^{-1/2} \simeq 1^\circ$, a value much smaller than the observed values of order 10°. In order to obtain $|p| \simeq 10^\circ$ as observed (Beck et al., 1996; Beck, 2000, 2001), one would need $|C_\omega| \simeq 30$ – a value of C_ω two orders of magnitude too small – but even then the maximum field strength would be just $|C_\omega|^{1/2} \simeq 5$ times larger than the extragalactic value, which is obviously unacceptable.

A primordial magnetic field could avoid the catastrophic reduction in the radial scale due to radial twisting if it is oriented parallel to the rotation axis and is amplified by the vertical shear, $\partial\Omega/\partial z$ (e.g., Moffatt, 1978; Sofue et al., 1986). From symmetry, $\partial\Omega/\partial z \approx 0$ at the disc midplane, $z = 0$, and so this effect, if important at all, can only be significant in the galactic halo rather than in the disc. The steady state magnetic field can be strong in this case, $B_{\max} \simeq C_\omega B_\mathrm{e}$, but this state can be reached only at a very late time, $t \gg R^2/\beta_\mathrm{h} \simeq 10^{10}\,\mathrm{yr}$, where $\beta_\mathrm{h} \simeq 5\times10^{27}\,\mathrm{cm^2\,s^{-1}}$ is a tentative estimate of the turbulent magnetic diffusivity in the galactic halo (Poezd et al., 1993), and the halo radius is assumed to be $R = 10\,\mathrm{kpc}$. At earlier times, the azimuthal field grows linearly in time as $B = rB_\mathrm{e}(\partial\Omega/\partial z)t \simeq B_\mathrm{e}\Omega t \simeq B_\mathrm{e}(t/5\times10^7\,\mathrm{yr})$. In $10^{10}\,\mathrm{yr}$, an external field of a strength $B_\mathrm{e} = 10^{-8}\,\mathrm{G}$ could be amplified to about $B \simeq 2\,\mu\mathrm{G}$, but only in the halo rather than in the disc. The field will have odd symmetry with respect to the galactic equator with its azimuthal component vanishing at the equator, contrary to what is observed in the Milky Way.

The primordial theory has never been able to resolve this difficulty (among several other problems – see Ruzmaikin et al., 1988; Shukurov, 2000), which apparently explains the lack of any quantitative comparisons of this theory with magnetic fields observed in specific galaxies, including the Milky Way.

3.2 Axisymmetric Dynamo Fields

Mean-field dynamo action is capable of maintaining both axially symmetric and bisymmetric global magnetic structures (Ruzmaikin et al., 1988; Beck et al., 1996). Axially symmetric magnetic structures are the easiest for the dynamo to produce. Bisymmetric magnetic structures can also be generated, but their *dominance* in most galaxies would be difficult to explain (Beck et al., 1996). For example, the galaxy M 81, the only candidate for the dominant bisymmetric structure, is able to support the bisymmetric dynamo mode, but there are no models that would explain convincingly its dominance throughout the galactic lifetime in the whole galaxy (cf. Moss, 1995). However, the dynamo can produce a strongly nonaxisymmetric magnetic structure with a field reversal in the neighbourhood of the corotation radius; such a structure can be described as a nonlinear state of the linear bisymmetric solution. This possibility is discussed in Sect. 4.

The dynamo action is just one of many effects that affect regular magnetic fields in galaxies, so it is natural that the perfect magnetic symmetry supported by the underlying dynamo action is distorted into the complicated observed picture by the spiral arms, Parker instability, gas outflows to the galactic halo, etc. It is therefore not surprising that recent radio polarization observations of external galaxies at enhanced sensitivity and resolution have produced radio maps where the global symmetry of the magnetic field is obscured by the wealth of details. Again, quantitative analysis of the observations is required to reveal the underlying global symmetries.

We note that strong disc-halo connections in spiral galaxies can play an important role in supporting dynamo action via advection of magnetic helicity from the disc (Shukurov, 2005). Intense exchange of gas and magnetic fields between the discs and halos of spiral galaxies has been firmly confirmed by both observations and theory (Bloemen, 1991). This makes questionable the arguments of Rafikov and Kulsrud (2000) and Kulsrud (Chap. 4) that it is unlikely that any significant quantity of magnetic flux can be expelled from the discs of the Milky Way and other galaxies.

The magnetic pitch angle of a dynamo-generated magnetic field (either bisymmetric or axisymmetric) is given by $p \simeq -\arctan(l/h) \simeq -10^\circ$ for a flat rotation curve (Shukurov, 2000), where $l \simeq 0.1\,\mathrm{kpc}$ is the turbulent scale and $h \simeq 0.5\,\mathrm{kpc}$ is the scale height of the warm interstellar gas. The magnitude of the pitch angle and the tendency of $|p|$ to decrease with galactocentric radius (because h increases with r in a flared disc) are in fair agreement with observations.

The alignment between the regular magnetic field and spiral arms is often quite tight, albeit not perfect. (We stress that the alignment of the magnetic field with the gaseous arms does not imply that magnetic field is aligned with the gas velocity which is directed along azimuth within a few degrees.) The mean-field dynamo does produce magnetic spirals with a pitch angle close to those observed. The alignment can be further improved by the refraction of magnetic lines in the gaseous arms: since the component of magnetic field normal to the arm is not affected by the gas density increase within the arm, whereas the tangential component increases in proportion to the gas density (under one-dimensional compression), the result is that the regular magnetic field becomes better aligned with the arm. If the arm-interarm density contrast is $\xi = \rho_\mathrm{a}/\rho_\mathrm{i}$ and the magnetic field between the arms makes an angle p_i to the arm, the angle between the arm axis and field within the arm follows as $\tan p_\mathrm{a} = \xi^{-1} \tan p_\mathrm{i}$, which yields $p_\mathrm{a} \approx 2.5^\circ$ for $p_\mathrm{i} = 10^\circ$ and $\xi = 4$. Velocity shear due to streaming in the galactic spiral arms can improve the alignment even further.

In the present context, it is important to appreciate that the dynamo can maintain an axisymmetric magnetic field with spiral magnetic lines and with direction alternating along radius, compatible with reversals observed in the Milky Way (Ruzmaikin et al., 1985). The dynamo mode that grows most rapidly has no reversals, the next one has one reversal, etc. Since the mode without reversals grows most rapidly, no reversals would occur at $t \to \infty$ unless nonlinear effects had halted the growth before this mode could become dominant. Since the growth rates of the different modes do not differ much in a thin disc, with the difference between the growth rates being of order $\beta/Rh \simeq (1.5 \times 10^{10}\,\mathrm{yr})^{-1}$, reversals can persist over periods of order Rh/β comparable to the galactic lifetime. We emphasize, however, that the situation is different in galaxies such as M51 where the time scales involved are an order of magnitude shorter (mainly because of stronger differential rotation), and so reversals are less plausible to survive for a long time.

This idea was further confirmed by nonlinear dynamo models (Belyanin et al., 1994; Poezd et al., 1993). Under a reasonable approximation, the signed amplitude of the axially symmetric large-scale magnetic field Q in a thin disc is governed by the equation (Poezd et al., 1993)

$$\frac{\partial Q}{\partial t} = \gamma_0 Q \left(1 - \frac{Q^2}{B_0^2}\right) + \lambda^2 \frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r} r Q\right), \tag{3}$$

where $\gamma_0(r)$ is the local growth rate of magnetic field (the same for all the modes mentioned in the previous paragraph), $B_0(r)$ is the steady-state strength of the large-scale magnetic field, and $\lambda = h_0/R = 0.5\,\mathrm{kpc}/10\,\mathrm{kpc} \ll 1$ is the aspect ratio of the galactic disc, with h_0 the typical scale height of the ionized gas layer. This equation is written in terms of dimensionless variables, where time is measured in the units of the magnetic diffusion time $h_0^2/\beta \simeq 7.5 \times 10^8\,\mathrm{yr}$, z in the units of h_0, and radius in the units of R. Different signs of $Q(r)$ correspond to magnetic fields of opposite directions. An important feature of (3) is that it admits solutions of both positive and negative sign: if $Q(r)$ is a solution, then $-Q(r)$ is also a solution; this situation is of course typical of equations with quadratic nonlinearity.

Asymptotic analysis of (3) with $\lambda \ll 1$ has shown (Belyanin et al., 1994) that, even in a nonlinear stage of the dynamo action, the reversals remain unsteady and migrate along radius at a speed of the order of the diffusion velocity $\beta/h \simeq 1\,\mathrm{km\,s^{-1}}$. However, the migration speed can be as small as $\beta h/R^2 \simeq 10^{-3}\,\mathrm{km\,s^{-1}}$ if the reversal occurs at a radius $r = R_{\mathrm{rev}}$ such that

$$U(R_{\mathrm{rev}}) = 0 ,$$

where

$$U(r) = r^2\gamma_0\left(\frac{1}{r} + 2\frac{B_0'}{B_0}\right) + \tfrac{1}{2}r^2\gamma_0' = 0 , \tag{4}$$

and prime denotes derivative with respect to galactocentric radius. For qualitative estimates, one can use an approximate solution of the mean-field dynamo equations applicable to a quadrupole mode with $\alpha \propto \sin \pi z/h$ (Ruzmaikin et al., 1988; Shukurov, 2005):

$$\gamma_0 \simeq -\tfrac{1}{4}\pi^2 + \left(-\tfrac{1}{4}\pi D\right)^{1/2} , \quad D \simeq 10\frac{h^2 \Omega G}{v^2} , \quad G = r\frac{d\Omega}{dr} , \tag{5}$$

where D is the local dynamo number (i.e., the dynamo number defined at a given galactocentric radius r (Ruzmaikin et al., 1988), Ω is the angular velocity of rotation, and h is the scale height of the ionized layer. For B_0, a value corresponding to energy equipartition with turbulent kinetic energy can be adopted,

$$B_0(r) \simeq (4\pi\rho v^2)^{1/2} , \tag{6}$$

where $\rho(r)$ is the gas density and $v \simeq 10\,\mathrm{km\,s^{-1}}$ is the turbulent velocity. For $v = \mathrm{const}$, as observed over broad radial ranges in spiral galaxies, $B_0'/B_0 = \rho'/2\rho$. Thus, all the variables in (4) can be expressed in terms of observable quantities.

Equation (6) represents a crude heuristic estimate of the regular field strength attainable by the mean-field dynamo. Putting aside the recent controversy about the nonlinear states of the mean-field dynamo (see Brandenburg and Subramanian, 2005 and Chap. 9 for a review), this estimate can be slightly refined by invoking the balance of the Lorentz and Coriolis forces that presumably occurs in the steady state of the dynamo, to yield (Ruzmaikin et al., 1988)

$$B_0 \simeq (4\pi\rho v \Omega l)^{1/2} . \tag{7}$$

Note that $\Omega l \simeq 3\,\mathrm{km\,s^{-1}}$ near the Sun, so the two forms, (6) and (7), result in magnitudes of B_0 that differ by a factor of order unity.

Reversals can, but not necessarily will occur at $r = R_{\rm rev}$. Solutions with alternating magnetic field can only arise if the initial (seed) field had reversals, and a unidirectional initial field would result in a unidirectional magnetic field in the steady state. We show in Fig. 1 $\gamma_0(r)$, $B_0(r)$ and $U(r)$ as obtained for a model of the Milky Way. Since $U(r)$ has many zeros, the occurrence of reversals in the Milky Way is quite plausible.

These results have been confirmed by a numerical solutions of the thin-disc dynamo equation (3) (Poezd et al., 1993). The numerical solutions do exhibit persistent reversals, but their number depends on the initial conditions. In particular, a reversal at $r \approx 7\,$kpc occurs for almost all configurations of the initial Galactic magnetic field; with allowance for the accuracy of the model, it can be identified with that observed between the Orion and Sagittarius arms. The other reversals, both in the inner and the outer Galaxy, do not occur for certain initial conditions. The time evolution of the signed amplitude of magnetic field, starting from a chaotic

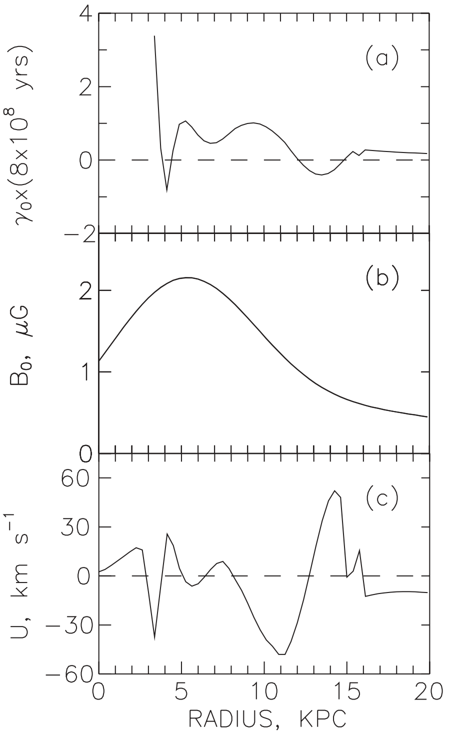

Fig. 1. Radial profiles, for the Milky Way, of (**a**) the local growth rate, (**b**) the equipartition magnetic field from (6), and (**c**) the function $U(r)$ defined in (4) Poezd et al. (1993). The model is based on the CO rotation curve of Clemens (1985) and gas density distribution of Gordon and Burton (1976), and the disc scale height $h(r) = 150\,\mathrm{pc}[1 + (r/4\,\mathrm{kpc})^2]^{1/2}$. The radius of the solar orbit was adopted to be 10 kpc

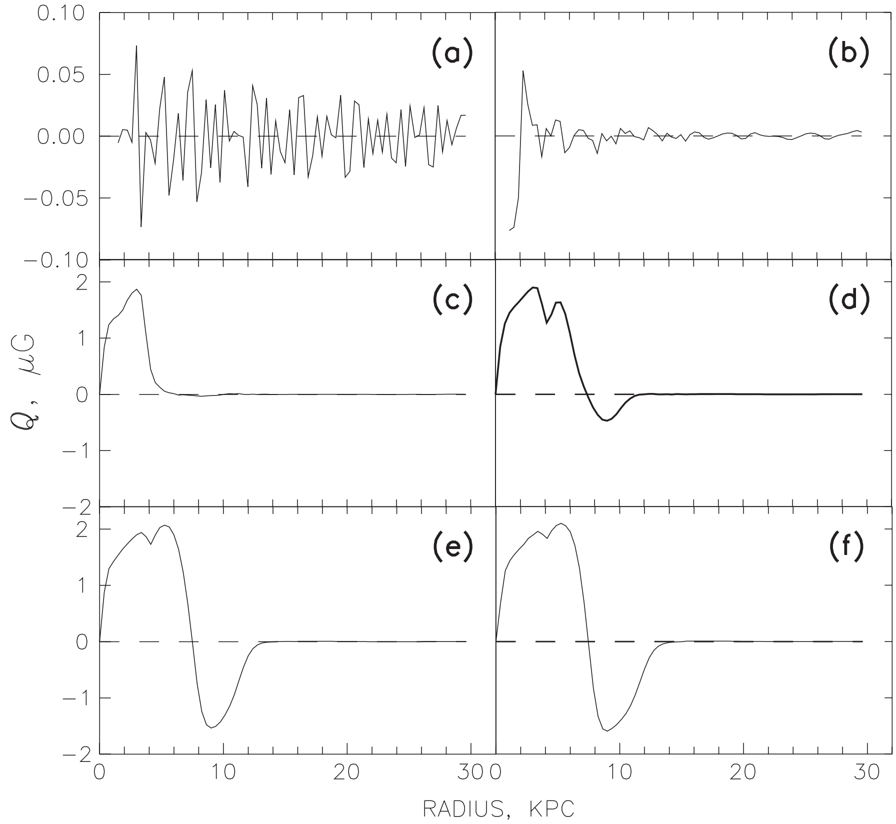

Fig. 2. Time evolution of the signed magnetic field strength in the Milky Way, according to Poezd et al. (1993), at the following times: (**a**) $t = 0$, the chaotic seed magnetic field; (**b**) 5.5×10^8 yr, (**c**) 2.2×10^9 yr, (**d**) 5.3×10^9 yr, (**e**) 8.1×10^9 yr, and (**f**) 9.6×10^9 yr. Parameters of the Milky Way model are as in Fig. 1

initial condition, is illustrated in Fig. 2. This evolution ends with just one reversal in the inner Galaxy.

The conclusion is that the regular magnetic field in the Milky Way can possess a number of reversals at rather well defined positions, but their occurrence depends on the unknown details of the initial magnetic field; as a result, the exact number of reversals is difficult to predict.

A similar nonlinear dynamo model was developed for M 31 (Poezd et al., 1993), where $U(r)$ has just one zero at $r \simeq 10\,\mathrm{kpc}$, i.e., within the synchrotron ring where we are confident that no reversals occur. The absence of the reversal can be explained by the lower growth rate of magnetic fields in M 31, so that the sign-constant (leading) mode had had enough time to become dominant before nonlinear effects have become important.

4 Localized Reversals

The above models rely on the interpretation of reversals as a global phenomenon, i.e., an *assumption* that they extend over the whole Galaxy. This is, however, not the only possibility. Since our knowledge of magnetic field of the Milky Way is limited to a relatively narrow neighbourhood of the Sun (of a size 3–5 kpc in radius and, say, 10 kpc in azimuth), it cannot be excluded that the reversed magnetic field is restricted to this neighbourhood (Shukurov, 2000). This possibility is corroborated by the magnetic structure in the disc of the galaxy M 51 (Berkhuijsen et al., 1997). As shown in Fig. 3, the regular magnetic field in the disc of M 51 is reversed in a region about 3 by 8 kpc in size elongated along the azimuth. The reversal occurs in the range of galactocentric radius 3–6 kpc centred on the corotation radius of the spiral pattern, and extends in azimuth from 280° to 20°. We suggest that the Sun can be located within a similar region with reversed magnetic field. We note that the Sun is located not far from the corotation radius of the Milky Way.

A dynamo model that clarifies the origin of such a localized region with reversed large-scale magnetic field was developed by Bykov et al. (1997) who solved numerically an equation analogous to (3), but written for nonaxisymmetric magnetic field, $Q(r,\phi)$:

$$\frac{\partial Q}{\partial t} + \Omega\frac{\partial Q}{\partial \phi} = \gamma_0 Q\left(1 - \frac{Q^2}{B_0^2}\right) + \lambda^2\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r} rQ\right) + \frac{1}{r^2}\frac{\partial^2 Q}{\partial \phi^2}\right] , \qquad (8)$$

where ϕ is the galactocentric azimuth and the other notation is as in (3). Now B_0 is modulated by a two-armed, logarithmic spiral pattern with the pitch angle of $p_s = -15°$. Since B_0 appears only in the nonlinear term of (8), the spiral pattern becomes important only at the nonlinear stage of magnetic field evolution in this model. Equation (8) was solved for $0 < r < 20$ kpc, with boundary conditions $Q(0) = Q(20\,\mathrm{kpc}) = 0$. The initial conditions represented a superposition of an axisymmetric and bisymmetric magnetic fields. In an axisymmetric disc (i.e., with the spiral modulation of B_0 neglected), the bisymmetric field rapidly decays. However, the spiral pattern can trap a bisymmetric magnetic field and preserve it near the corotation radius for a time exceeding the galactic lifetime. The radial extent of the region with reversed magnetic field is controlled by the balance of the local dynamo action and advection by the galactic differential rotation, and is estimated as

$$\delta r \simeq \frac{r_c}{|\sin p_s|^{1/2}}\left(\frac{v}{3V_0}\,\frac{l^2}{hr_c}\right)^{1/4} , \qquad (9)$$

where r_c is the corotation radius, V_0 is the rotational velocity, a constant for a flat rotation curve. For typical values of parameters, $\delta r \simeq 0.2 r_c$, i.e., the trapped bisymmetric field can extend over a few kiloparsecs along radius. Equation (9) indicates that the following conditions are favourable for such a magnetic configuration to persist: smaller pitch angle of the spiral arms p_s, thinner gas disc (smaller h), weaker rotational shear (smaller V_0), and also a stronger spiral pattern. The region with reversed magnetic field would be broader in radius if the rotation curve were rising (rather than flat) near the corotation radius.

The possibility that the global magnetic structure of the Milky Way is similar to that shown in Fig. 3 has to be verified observationally. This would require a careful

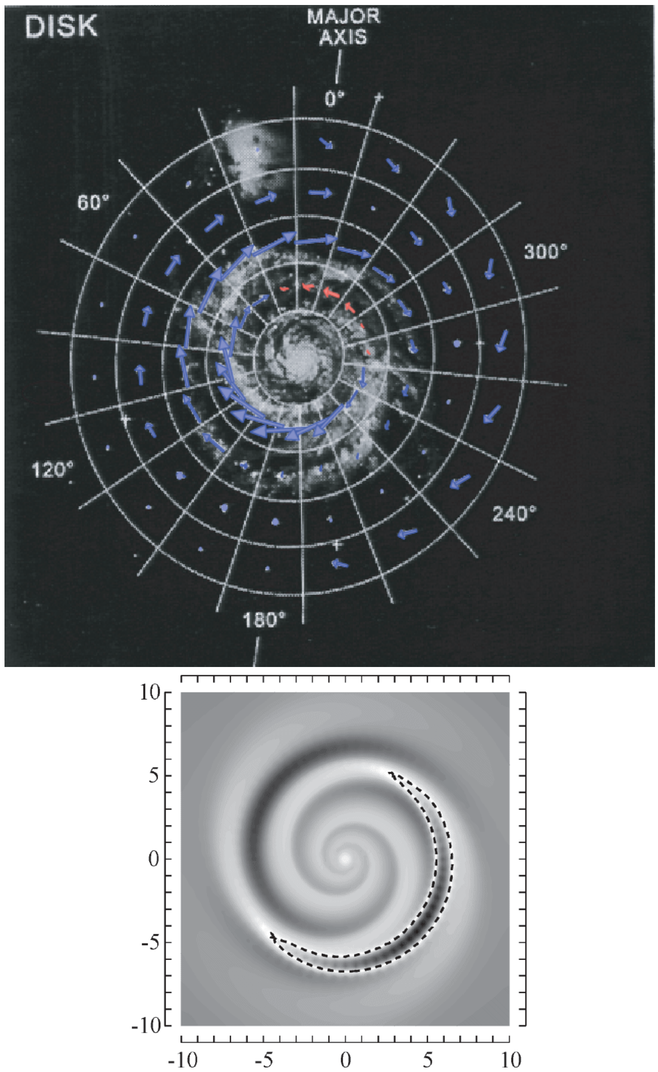

Fig. 3. *Upper panel:* The global magnetic structure in the disc of the galaxy M 51. Arrows represent the direction and strength of the regular magnetic field on a polar grid shown superimposed on an optical image of the galaxy (Berkhuijsen et al., 1997). The grid radii are 3, 6, 9, 12 and 15 kpc. The length of the arrows is proportional to $\mathcal{R} = Bn_eh$ in the inner two rings and to $3\mathcal{R}$ in the two outer rings. *Lower panel:* Magnetic field strength $|Q|$ from the dynamo model for the disc of M 51 (Bykov et al., 1997) is shown with shades of grey (darker shade means stronger field). This structure represents a bisymmetric magnetic field trapped by the spiral pattern near the corotation radius. Magnetic field is reversed within the zero-level contour shown dashed; scale is given in kpc. The magnetic structure rotates rigidly in the anticlockwise direction together with the spiral pattern visible in the shades of grey

study of Faraday rotation measures in all directions along the Galactic equator, so that the position of a magnetic field reversal(s) can be established confidently in all directions.

5 Magnetic Arms

The classical picture of the interaction of the large-scale magnetic field with galactic spiral arms was proposed by Roberts and Yuan (1970). Their two-dimensional model with magnetic field frozen into the interstellar gas predicted an enhancement of magnetic field within the arms and alignment of magnetic field with the arms, both resulting from gas compression (see Sect 3.2). This can be described as a passive behaviour of magnetic field, where it does not affect gas dynamics significantly, but rather responds to variations in gas density and velocity. However, nonthermal pressure components (including magnetic pressure) have been shown to lead, in three dimensions, to a more complicated picture with vertical motions of order $20\,\mathrm{km\,s^{-1}}$ and height-dependent displacements between maxima in gas (and magnetic field) and stellar densities (Martos and Cox, 1998; Gómez and Cox, 2002). It is not surprising that an active magnetic field produced by dynamo action is capable of an even more complicated behaviour.

The influence of the galactic spiral pattern on the dynamo can enhance the generation of nonaxisymmetric magnetic fields via parametric resonance (where with intrinsic oscillation frequency of the dynamo field is a multiple of the frequency of periodic variation in the dynamo control parameters produced by the travelling spiral pattern). This aspect of the global interaction between magnetic fields and the spiral pattern has been reviewed in Beck et al. (1996), and we refer the reader to that paper for details and references. Another, local aspect of the interaction is the position of gas ridges relative to those in the regular and total magnetic field. The fine structure of magnetized spiral arms has become accessible to observations only recently (Fletcher et al., 2005), and detailed models have not yet been developed.

Here we discuss in more detail the so-called magnetic arms, first observed in the galaxy IC 342 (Krause, 1993) and later identified as an unusual physical phenomenon in the galaxy NGC 6946 (Beck and Hoernes, 1996). We show, in the left-hand panel of Fig. 4, a map of polarized radio emission from NGC 6946 (a tracer of the large-scale magnetic field strength) superimposed on the galaxy's image in the Hα spectral line (a tracer of ionized gas). It is evident that the large-scale magnetic field is stronger *between* the gaseous spiral arms of this galaxy, i.e., where the gas density (both total and ionized) is lower. This behaviour is just opposite to what is expected of a frozen-in magnetic field that scales with a power of gas density. Spiral arm branches that may be of similar nature have been observed in NGC 2997 (Han et al., 1999). The spiral structures in gas and magnetic field in M 51 show a complicated, partially interlaced structure (Fletcher et al., 2005). It appears that the phenomenon of magnetic arms can be of general significance and some of its aspects can be common among spiral galaxies in general.

NGC 6946 remains the best studied case of magnetic arms. A quantitative morphological analysis of the spiral patterns visible in seven images in various wavelength ranges from the infrared to the radio was performed using wavelet techniques (Frick et al., 2000, 2001). Five arms and major arm segments have

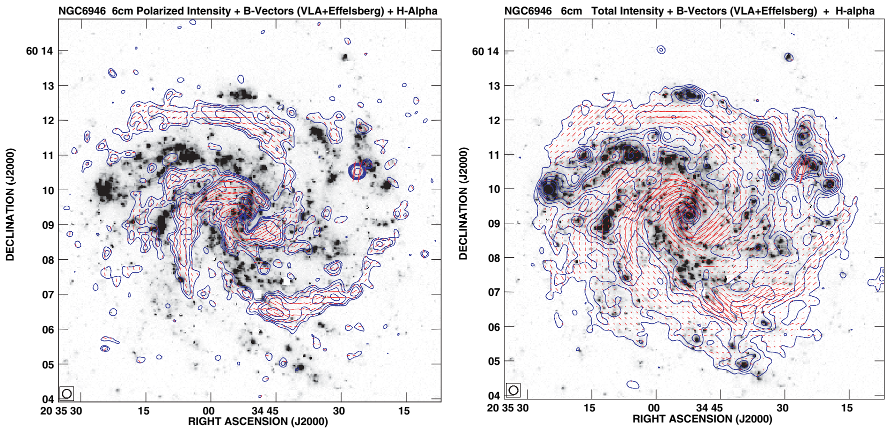

Fig. 4. *Left panel:* Magnetic arms in the galaxy NGC 6946: polarized intensity at the wavelength $\lambda = 6\,\mathrm{cm}$ (blue contours), a tracer of the large-scale magnetic field, superimposed on the galactic image in the Hα spectral line of ionized hydrogen (grey scale). Red dashes indicate the orientation of the B-vector of the polarized emission (parallel to the direction of intrinsic magnetic field if Faraday rotation is negligible), with length proportional to the fractional polarization. The spiral arms visualized by Hα are the sites where gas density is maximum. The large-scale magnetic field is evidently stronger between the arms where gas density is lower. *Right panel:* As in the left panel, but for the total synchrotron intensity, a tracer of the total magnetic field comprising both the regular and turbulent parts. The total field is enhanced in the gaseous arms. Given that the large-scale field concentrates between the arms, this means that the turbulent field is significantly stronger in the arms, a distribution very different from that of the large-scale field. The size of the beam in the radio maps is shown in the bottom left of each frame (see Chap. 3)

been identified, best visible in red light (emitted by the old stellar population) and polarized radio emissions at wavelengths 3.5 and 6.2 cm (tracers of the large-scale magnetic field). The stellar and magnetic arms are interlaced even in very fine detail, so their physical connection is evident. Each major optical arm branch has a magnetic counterpart. The arms can be reasonably approximated by logarithmic spirals, with the optical and magnetic counterparts having similar pitch angles; this implies that the phase shift between the stellar and magnetic spiral patterns is roughly independent of galactocentric radius. Total radio intensity, and H I and Hα line emissions exhibit more patchy and disordered distributions, although most features found in polarized emission and red light can also be found in the neutral and ionized hydrogen maps.

The phenomenon of magnetic arms confirms in a spectacular manner that the large-scale magnetic field is not frozen into the interstellar gas, and therefore cannot be primordial. If so, mean-field dynamo theory appears to be an appropriate framework to address the origin of magnetic spiral arms. The only alternative to the dynamo theory proposed up to date are slow magnetohydrodynamic density waves discussed in Sect. 5.2.

5.1 The Effects of Spiral Arms on the Galactic Dynamo

Two types of dynamo effects have been considered in relation to the phenomenon of magnetic arms (Moss, 1998; Shukurov, 1998; Rohde et al., 1999), discussed here and in Sect. 5.2. It was argued that dynamo number can be smaller within the gaseous spiral arms (e.g., because turbulence can be stronger there, thus providing larger turbulent magnetic diffusivity), resulting in a weaker magnetic field. In order to clarify and illustrate these arguments, consider a simple model of dynamo nonlinearity (known as α-quenching) where exponential growth of magnetic field $\boldsymbol{B}$ is saturated through the suppression of the α-effect, so that the effective dynamo number D_B decreases with B as

$$D_B = \frac{D}{1 + B^2/B_0^2} \ ,$$

where D is given in (5) and B_0, in (6) or (7). Replacing D by D_B in the expression for the field growth rate γ_0 given in (5), we obtain the following estimate of magnetic field strength in the steady-state, $\gamma_0 = 0$:

$$B \simeq B_0 \sqrt{\frac{D}{D_{\rm cr}} - 1} \ .$$

where $D_{\rm cr} \simeq -\pi^3/4 \approx -8$ is the critical dynamo number obtained from $\gamma_0 = 0$ in (5) (for $B = 0$), and the estimate for B is applicable if $D \approx D_{\rm cr}$ and $D/D_{\rm cr} > 1$. Within this simple framework, the ratio of the steady-state strengths of the regular magnetic field in the gaseous spiral arms and between them is given by (Shukurov, 1998)

$$\frac{B_{\rm a}}{B_{\rm i}} \simeq \frac{B_{0\rm a}}{B_{0\rm i}} \left(\frac{D_{\rm a}/D_{\rm cr} - 1}{D_{\rm i}/D_{\rm cr} - 1} \right)^{1/2} \ , \tag{10}$$

where subscripts ‘a’ and ‘i’ refer to gaseous arms and interarm regions.

It seems plausible that the turbulent kinetic energy density is larger in the arms (because gas density and star formation intensity are larger in the arms), and so $B_{0\rm a} > B_{0\rm i}$. Therefore, the regular magnetic field can be stronger between the arms, $B_{\rm a} < B_{\rm i}$, only because of the term in brackets in (10). Equation (5) shows that the local dynamo number depends on the scale height of the gas h, turbulent speed v, angular velocity Ω and the local shear rate G which may include not only shear due to differential rotation but also that arising from streaming velocities associated with the galactic spiral arms.

Therefore, we need to know how all these variables are affected by the spiral arms in order to understand the nature of magnetic arms. The available observational and theoretical knowledge of the effects of the spiral arms on the interstellar medium is yet insufficient for any firm conclusions to be made; relevant discussion can be found in Shukurov (1998) and Shukurov and Sokoloff (1998). To illustrate the nature of the problem, consider the scale height of gas disc, h. In hydrostatic equilibrium, h can be estimated as

$$h \simeq \frac{v^2 + V_A^2}{g} \,,$$

where v is the turbulent speed, $V_A = B_{tot}/(4\pi\rho)^{1/2}$ is the Alfvén speed based on the total magnetic field $B_{tot} = (B^2 + \sigma_B^2)^{1/2}$ and g is the acceleration due to gravity. It might seem plausible that the disc scale height is larger in the arms because both v and V_A are larger there. An arm-interarm contrast of a factor of two in v and V_A would result in a factor of four contrast in h. Such a variation in the disc scale height seems to be unrealistically large. It can be argued (Shukurov, 1998; Shukurov and Sokoloff, 1998) that the contrast in h is reduced away from the corotation radius as the passage time of a spiral arm becomes shorter than the sound crossing time over the disc scale height. The above estimate of h can be oversimplified also because of the multi-phase nature of the interstellar medium where the filling factor of the hot gas can be significantly different within the arms and between them, thus reducing the arm-interarm contrast in total pressure in the interstellar gas, and hence in h. We discuss relevant simulations of the multi-phase interstellar medium in Sect. 5.3, which lead to an opposite conclusion that h can be slightly larger between the arms. Altogether, it seems to be reasonable to assume that h is not affected much by the spiral arms.

Thus, it is reasonable to assume that the ratio h/v is smaller in the gaseous arms, mainly because the turbulent velocity v is larger there, and then it does not seem implausible that the dynamo number can be reduced within the arms, with the arm-interarm contrast estimated in Shukurov (1998) and Shukurov and Sokoloff (1998) as

$$\frac{D_a}{D_i} \simeq \frac{1}{4} \,.$$

Then (10) shows that the steady-state magnetic field is stronger between the gaseous arms provided (Shukurov, 1998)

$$|D_a| < \frac{1 - B_{0i}^2/B_{0a}^2}{1 - \rho_i/\rho_a} \simeq \frac{5}{4} D_{cr} \tag{11}$$

for $B_{0a}/B_{0i} \simeq 4$ and $\rho_a/\rho_i \simeq 4$. This indicates that magnetic arms can occur between the gaseous arms in galaxies with weak dynamos, i.e., where $|D|$ small enough to satisfy the inequality (11). A mild enhancement of the turbulent velocity suppresses significantly the dynamo action in the arms of such galaxies. In contrast, galaxies with a strong dynamo, where (11) is not satisfied, must have the strongest large-scale magnetic field in the gaseous arms. Numerical simulations of non-linear mean-field dynamos in a disc with v enhanced in the arms (Rohde and Elstner, 1997) support this explanation of interlaced magnetic arms, and confirm (10) by showing that B_a/B_i indeed decreases when the dynamo number decreases (see Fig. 4 in Rohde and Elstner, 1997).

The suppression of the dynamo number within the gaseous arms can be due to several reasons. The definition of the dynamo number from which the expression for D in (5) has been obtained is

$$D = \frac{\alpha G h^3}{\beta^2} \,,$$

where $\alpha = -\frac{1}{3}\tau\langle \boldsymbol{v}\cdot\nabla\times\boldsymbol{v}\rangle$ is the so-called α-coefficient of the mean-field dynamo theory, τ is the correlation time of the random velocity field $\boldsymbol{v}$, and $\beta = \frac{1}{3}\tau\langle \boldsymbol{v}^2\rangle$

is the turbulent magnetic diffusivity. Different authors suggest different causes for the arm-interarm variation in D. A possible set of relevant estimates is presented above, following Shukurov (1998), and Shukurov and Sokoloff (1998) continued in Sect. 5.3. Rohde et al. (1999) maintain that there is no clear observational evidence for the modulation of the turbulent intensity by the spiral pattern, and therefore assume similar modulation for the turbulent correlation time. These authors assume that τ is larger within the gaseous arms than between them (unfortunately, such an assumption can hardly be verified as the correlation time is not an observable quantity; on the contrary, it is perhaps more plausible that τ is shorter in the arms because of the higher supernova rate), again resulting in a reduced D in the gaseous arms. The idea discussed in this section only relies on the appropriate modulation of the dynamo number by the spiral pattern, whatever is the eventual cause of this modulation.

The effects discussed in this section are most efficient near the corotation radius where the spiral arms do not move with respect to the gas, and so the dynamo has enough time to produce stronger large-scale magnetic field between the gaseous arms. Away from the corotation radius, the passage time of the spiral arms through a volume element can become shorter than the dynamo regeneration time $\gamma_0^{-1} = (10^8\text{–}10^9)$ yr and the azimuthal modulation of the large-scale magnetic field is averaged out. However, the interlaced magnetic and gaseous arms are expected to occur in galaxies with weak dynamos, i.e. with weak differential rotation, where the effects of azimuthal advection are minimized. Nevertheless, magnetic arms in NGC 6946 extend over a radial range broad enough for the effects of differential rotation to be potentially important. Numerical studies of the galactic mean-field dynamo model with the rotation curve of NGC 6946 and dynamo number reduced in the gaseous arms confirm that interlaced gaseous and magnetic arms persist over a broad radial range (Rohde et al., 1999). Hence, it appears that dynamo action in NGC 6946 is strong enough to balance the shearing of magnetic arms by differential rotation. Nevertheless, the situation is not completely satisfactory and we discuss in the next section an alternative explanation of magnetic arms based on travelling wave phenomena.

5.2 Dynamo Waves and Magnetohydrodynamic Density Waves

Unlike the basic axisymmetric magnetic mode, the nonaxisymmetric dynamo modes in a thin disc are oscillatory (Ruzmaikin et al., 1988), i.e., they represent dynamo waves propagating in the azimuthal direction. The spiral pattern also travels in the azimuthal direction, and so periodically modulates the dynamo parameters as described above. If this modulation is in resonance with the dynamo wave itself, the spiral pattern can facilitate the generation of this dynamo mode (Chiba and Tosa, 1990). The effect is weaker than it was first expected to be (Beck et al., 1996), but still can contribute to the support of magnetic arms (Moss, 1998). For a two-armed spiral pattern in both gas density and magnetic field strength, the dynamo mode with the azimuthal wave number $m = 1$ is to be in the resonance (then $\boldsymbol{B}$ has a bisymmetric pattern, but the field strength $|\boldsymbol{B}|$ has a two-armed structure). Numerical simulations indicate that resonance effects can indeed maintain the magnetic $m = 1$ mode interlaced with the gaseous arms if the turbulent magnetic diffusivity is enhanced within the gaseous arms (Moss, 1998) – an assumption consistent with reduced dynamo number in the arms. The resonance occurs if the oscillation frequency of the magnetic mode in the inertial frame ω is close to $2\Omega_{\rm p}$, where $\Omega_{\rm p}$ is the angular velocity of the spiral pattern. However, the spiral pattern of NGC 6946, where the number of both gaseous and magnetic arms is different at different radii, would be difficult to explain since it seems implausible that several dynamo modes can be in resonance simultaneously (Moss, 1998). We also note that it not clear whether or not the magnetic field in the magnetic arms of NGC 6946 is consistent with the $m = 1$ symmetry.

Another theory advanced to explain magnetic arms, in NGC 6946 in particular, interprets them as the slow magnetohydrodynamic density waves in the self-gravitating galactic disc (Fan and Lou, 1996; Lou et al., 1999) (see also Lou and Fan, 2002, 2003 and references therein). This theory generalizes the density wave theory, devised to explain the galactic spiral structure, by including the large-scale magnetic field. The perturbations in gas surface density and magnetic field in the slow mode have a significant phase shift, and therefore its magnetic field is maximum away from gas density maxima, as in magnetic arms. This could be an attractive model for magnetic arms, but it appears to encounter significant difficulties. Its early versions could explain the existence of magnetic arms only in a rigidly rotating part of the galaxy, but theory has been later extended to the case of a flat rotation curve (Lou and Fan, 2002). Another limitation is that all models of magnetohydrodynamic density waves assume that the large-scale magnetic field is purely azimuthal and has a unique (and unrealistic) radial profile $B_\phi \propto r^{-1}$ or $r^{-1/2}$. Yet another difficulty is that the ratio of the amplitude of magnetic field in the magnetic arms to the mean magnetic field at a given radius, predicted by this theory, scales with galactocentric radius as $r^{-1/2}$; the amplitude of the stellar spiral arms has the same scaling (Lou and Fan, 2002). Arm strengths in magnetic field and stellar surface density in NGC 6946 have been estimated by Frick et al. (2000). Their results indicate that the mean relative intensity of magnetic spiral arms remains rather constant with galactocentric radius at a level of 0.3–0.6. On the contrary, the relative strength of the stellar arms systematically grows with radius from very small values in the inner galaxy to 0.3–0.7 at $r = 5$–$6\,$kpc, and then decreases to remain at a level of 0.1–0.3 out to $r = 12\,$kpc. The distinct magnitudes and radial trends in the strengths of magnetic and stellar arms in NGC 6946 do not seem to support the idea that the magnetic arms are due to MHD density waves.

However, the most important difficulty of the density wave theory of magnetic arms is of a more fundamental nature. All the existing models of magnetohydrodynamic density waves devised to explain magnetic arms are two-dimensional, with the galactic disc assumed to be infinitely thin and the perturbed magnetic field to be strictly horizontal (Lou and Fan, 2003; Lou and Zou, 2004 and references therein). A similar approximation is perfectly acceptable in theory of hydrodynamic density waves but becomes inadequate when magnetic fields are included (M. Tagger, private communication). The two-dimensional density wave models exclude the Parker instability (or magnetic buoyancy) from the analysis since this effect essentially involves vertical magnetic fields. As shown by Foglizzo and Tagger (1994, 1995), the slow branch of magnetohydrodynamic waves becomes unstable in three dimensions and transforms into a non-propagating Parker mode. This implies that the nature of the solutions applied to explain magnetic arms in this theory changes fundamentally in three dimensions; therefore, the application of this theory to magnetic arms observed in spiral galaxies is questionable.

To summarize, the nature of magnetic arms is still unclear. Galactic dynamo theory does provide mechanisms to maintain stronger large-scale magnetic field between the gaseous arms, but the development of detailed prognostic models is hampered by our insufficient knowledge of the effects of the spiral pattern on the global parameters of the interstellar medium.

5.3 Numerical Simulations of the Multi-phase Interstellar Medium

Observational evidence for the arm-interarm contrast in various parameters of the interstellar gas is still fragmentary and incomplete because of the relatively low resolution and sensitivity of the observations. However, recent numerical models of interstellar medium have become realistic enough as to shed some light on this problem (Vázquez-Semadeni et al., 2000).

The effects of the mean gas density and magnetic field on the overall parameters of the interstellar gas were recently studied with the aim to clarify the arm-interarm variation in the overall parameters of interstellar medium (Shukurov et al., 2004). These simulations are based on three-dimensional, non-ideal equations of magnetohydrodynamics with rotation, density stratification in the galactic gravity field, heat sources due to supernova explosions and UV heating, and radiative cooling (see Korpi et al., 1999a,b for details). The simulations were performed in a relatively small Cartesian box with the horizontal and vertical (z) dimensions of $0.25 \times 0.25 \times 1\,\mathrm{kpc}$ (with the midplane in the centre), modest spatial resolution of about 4 pc, and closed boundary conditions in z. The model reproduces the multi-phase structure of the interstellar medium and its stratification reasonably well. Results have been obtained for three values of the gas midplane density, assumed to model conditions within spiral arms, between them, and on average in the Solar vicinity of the Galactic disc. The three models with low, intermediate and high density are referred to as Interarm, Average and Arm. Results of the simulations are presented in Table 1.

An unexpected result of these simulations is that the density scale height is significantly larger in the Interarm model, although both thermal and turbulent pressures are a factor of about 3 larger in the Arm model. The reason for this is that the filling factor of the hot gas, together with the mean gas temperature, is significantly higher in the Interarm case, even though the SN rate is lower. An apparent reason is that the cooling rate has a stronger net dependence on gas density than the SN energy injection rate.

This conclusion is opposite to what was expected from the qualitative estimates of Sect. 5.1. An immediate implication of these simulations is that the arm-interarm contrast in gross parameters of the interstellar gas can be sensitive to quite fine details of the gas dynamics, multi-phase structure, and energy balance.

Another surprising feature of the results presented in Table 1 is that the filling factor of the hot gas is lower than expected by a factor of 2–3. This can be attributed to the geometry of the magnetic field in our models; it is uniform initially, and therefore effective in confining expanding bubbles of hot gas. The initial mid-plane field strength, $6\,\mu\mathrm{G}$, is close to that of the *total* field in the Solar vicinity, but the field

Table 1. Three models of interstellar medium driven by supernova explosions, each with a different initial mid-plane gas density, ρ_0, devised to reproduce physical conditions in the interarm regions, on average in the gas layer and within the gaseous arms (Shukurov et al., 2004). The mean temperature, pressures, root mean square velocity and filling factor are all calculated within $|z| < 0.2\,\mathrm{kpc}$, where z is the vertical distance, with the disc midplane at $z = 0$. The filling factor is for the hot gas, of a temperature $T > 10^5\,\mathrm{K}$; supernova rate and the spatial distribution of the supernovae are also obtained as the result of these simulations, and they are given in the last two lines. All the models include an imposed azimuthal magnetic field of a strength $6\,\mu\mathrm{G}$.

	Unit	Interarm	Average	Arm
Initial midplane density, ρ_0	$10^{-24}\,\mathrm{g\,cm^{-3}}$	0.7	1.4	2.9
Density Gaussian scale height	kpc	0.23	0.20	0.16
Mean temperature	$10^4\,\mathrm{K}$	35	7.8	3.4
Mean thermal pressure	$10^{-14}\,\mathrm{dyn\,cm^{-2}}$	42	68	120
Rms vertical velocity	$\mathrm{km\,s^{-1}}$	23	20	20
Mean turbulent pressure	$10^{-14}\,\mathrm{dyn\,cm^{-2}}$	39	63	110
Hot gas filling factor		0.12	0.07	0.04
SN II rate	$\mathrm{kpc^{-2}\,Myr^{-1}}$	11	38	111
SN II Gaussian scale height	kpc	0.30	0.16	0.14

is implausibly well ordered. A more realistic simulation would initialize the model with a ratio of turbulent to ordered magnetic energies of about 3. The dependence of the results on the strength of the initially uniform magnetic field is illustrated in Table 2. The filling factor of the hot gas is sensitive to the field strength and increases to 0.2 as the field becomes weaker. The density scale height marginally increases with magnetic field strength, but this effect is much less pronounced than the suppression of the hot phase; magnetic field strongly suppresses turbulence in the hot gas. Thus, magnetic field can affect the disc-halo connection and the global structure of the ISM in crucial, diverse and unexpected ways. This aspect of the ISM dynamics has not yet been fully explored. Incidentally, this implied that the problem of magnetic arms is intrinsically nonlinear, with the large-scale

Table 2. The effect of magnetic field on the multi-phase interstellar medium illustrated with three runs with varying initial magnetic field, B. All variables are as defined in Table 1. All runs have $\rho_0 = 0.7 \times 10^{-24}\,\mathrm{g\,cm^{-3}}$ (the Interarm model)

Initial Magnetic Field Strength, B	μG	0	6
Density scale height	kpc	0.20	0.23
Mean thermal pressure	$10^{-14}\,\mathrm{dyn\,cm^{-2}}$	50	42
Rms vertical velocity	$\mathrm{km\,s^{-1}}$	43	23
Mean turbulent pressure	$10^{-14}\,\mathrm{dyn\,cm^{-2}}$	54	39
Hot gas filling factor		0.19	0.12

magnetic field responding to the interstellar gas variations between gaseous arms and interarm regions, which in turn depend on the magnetic field itself.

6 Conclusions

The galactic dynamo theory has been impressively successful in explaining the gross features of galactic magnetic fields at scales exceeding a few kiloparsecs. It can be expected that the current controversy regarding the nonlinear behaviour of mean-field dynamos (Chap. 9 and references therein) will be resolved without affecting its main conclusions. The reason for this expectation is that the large-scale magnetic fields generated by the mean-field dynamo depend remarkably weakly on the detailed properties of the dynamo system (such as the poorly known α-coefficient) (Ruzmaikin et al., 1988). As argued by F. Krause and Rädler (1980), the *form* of the mean-field dynamo equations is generic: any system capable of maintaining a large-scale magnetic field independently of external electric currents must be governed by equations similar to the classical mean-field dynamo equations. The specific physical nature of the system only affects the coefficients of this system, e.g., the α-coefficient. Then, given that the form of the solutions is only weakly sensitive to the form of α, we expect the results of galactic dynamo theory to remain robust.

Improvements in the quality of radio polarization observations have revealed detailed properties of interstellar magnetic fields at scales intermediate between the global galactic scales of 10 kpc and the turbulent scale of 0.1 kpc, which can be conveniently called mesoscales. As might be expected, the details often obscure the simple and symmetric overall structure prominent in observations with lower resolution or in smoothed data. One of the outstanding mesoscale magnetic features are magnetic arms whose understanding is still far from being complete and confident.

Systematic studies of galactic magnetic structures at intermediate scales can advance our understanding of the nature of the cosmic magnetism as strongly as similar studies of the global magnetic structures. As argued above, two types of mesoscale magnetic structures, magnetic reversals and magnetic arms, are compatible with galactic dynamo theory and confirm it to a certain extent. In the framework of the dynamo theory, magnetic reversals carry information about early stages of galactic evolution and/or interaction of galactic magnetic fields with the spiral pattern. In order to understand the nature of magnetic arms, we need a much better understanding of the effects of the spiral pattern on the interstellar medium.

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