Global Magnetic Structures in Spiral Galaxies: Evidence for Dynamo Action

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Abstract. Observational evidence for dynamo action in spiral galaxies is reviewed, and the capabilities of various theories in explaining the basic features of galactic magnetic fields are discussed. Mean-field dynamo models appear to be unique in providing a coherent explanation of a wide variety of magnetic features in spiral galaxies.

Reliable modelling of global magnetic structures, such as the magnetic ring in M31, requires detailed knowledge of the rotation curve, the magnitude and radial profile of turbulent and noncircular systematic velocities, the scale height of the warm ionized layer, the total gas density, the turbulent scale and their variations with galactocentric radius. More detailed models involving the effects of the spiral arms on magnetic field require the knowledge of the arm-interarm contrasts in the above quantities.

1 Introduction

Energy density of interstellar magnetic fields is comparable to kinetic energy density of interstellar turbulence, so magnetic can fields significantly affect the turbulent motions. Systematic motions at a speed in excess of 10–30 km s$^{-1}$ are too strong to be affected by interstellar magnetic fields. However, regular magnetic fields revealed by polarized radio emission can be a sensitive tracer of the regular motions (e.g., Beck et al., 1999). Theory and observations of galactic magnetic fields are now advanced enough to provide useful constraints on the kinematics and spatial structure of interstellar gas.

There are two basic approaches to the origin of global magnetic structures in spiral galaxies — one of them asserts that the observed structures represent a primordial magnetic field twisted by differential rotation, and the other that it is due to turbulent dynamo action. The simplicity of the former theory is appealing, but it fails to explain the strength, geometry and apparent lifetime of galactic magnetic fields (Ruzmaikin et al., 1988a,b; Beck et al., 1996; Kulsrud, 1999; see below). Furthermore, there are no mechanisms known to produce cosmological magnetic fields of required strength and scale (Beck et al., 1996). Dynamo models appear to be much better consistent with the observational and theoretical knowledge of interstellar gas, and almost all models of magnetic fields in specific galaxies have been formulated in terms of dynamo theory. It seems to be very plausible that galactic magnetic fields are generated by some kind of dynamo action, i.e., that they are produced in situ. The most promising is the mean-field turbulent dynamo. The aim of this paper is to justify these statements. MHD density waves (Lou & Fan, 1996, 1998, 2000) can add further structure to the global magnetic fields, but this theory cannot explain the origin of the regular magnetic field and relies on a background field supported by an unspecified source.

2 Dynamo control parameters

Dynamo action is the conversion of kinetic energy of plasma motion into magnetic energy independently of any external electric currents. The dynamo needs a weak seed magnetic field to be launched, but it does not rely on the seed as soon as the amplification has started, so the process is called
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self-excitation. The field amplification is exponential in time. Without dynamo action, velocity shear can amplify an external magnetic field only slowly, linearly in time; the field eventually decays as soon as reconnection and magnetic buoyancy overcome the slow amplification.

Two types of turbulent dynamo can be distinguished: one is the mean-field dynamo briefly described below, and the other is the so-called fluctuation dynamo. The mean-field dynamo generates both regular and random magnetic fields. The fluctuation dynamo produces purely random magnetic fields with vanishing mean (regular) component and, contrary to a rather widespread misconception, acts independently of any overall rotation and \( \alpha \)-effect. The only ingredient needed is a random (even not necessarily turbulent) motion of conducting fluid with a magnetic Reynolds number exceeding \( R_{\text{m, cr}} \approx 100 \). The fluctuation dynamo contributes to turbulent magnetic fields in the interstellar medium producing magnetic filaments \( l \approx 100 \) pc in length and \( lR_{\text{m, cr}}^{1/2} \approx 10 \) pc in thickness (Sokoloff et al., 1990; Subramanian, 1999). The distinction between mean-field and fluctuation dynamos can be viewed as merely a mathematical convenience, and unified models have been developed (Subramanian, 1999; Brandenburg, 2000).

Mean-field turbulent dynamo action needs two ingredients, rotation and deviation of the velocity field from mirror symmetry. The latter arises naturally in a rotating, stratified system such as the gas disk of a spiral galaxy. Correspondingly, the mean-field dynamo is controlled by two dimensionless parameters quantifying the differential rotation and the so-called \( \alpha \)-effect,

\[
R_\omega = \frac{Gh^2}{\beta}, \quad R_\alpha = \frac{\alpha h}{\beta}, \quad (1)
\]

where \( r \) is the galactocentric radius, \( \Omega \approx 25 \text{ km s}^{-1} \text{ kpc}^{-1} \) is the angular velocity of rotation obtained from the rotation curve, \( G = r d\Omega/dr \) is a measure of differential rotation, \( h \approx 500 \) pc is the scale height of the ionized layer (presumably, of the warm interstellar medium), \( \beta \approx \frac{2}{3} tv \approx 0.3 \text{ kpc km s}^{-1} \) is the turbulent magnetic diffusivity, \( \alpha \approx \frac{2}{3} \Omega/h \approx 1 \text{ km s}^{-1} \) is the helical (mirror-asymmetric) part of the turbulent velocity \( v \approx 10 \text{ km s}^{-1} \), and \( l \approx 100 \) pc is the turbulent scale (see, e.g., Ruzmaikin et al., 1988a,b). It is possible that magnetic buoyancy plays significant role in galactic dynamos; then \( \alpha \) is a function of magnetic field \( B \) (Parker, 1992; Moss et al., 1999).

In spiral galaxies, the typical values of the control parameters are \( R_\omega \approx -10 \) and \( R_\alpha \approx 1 \) at \( r \approx 1-2 \) kpc, so \( |R_\omega| \gg R_\alpha \) and then the dynamo (the \( \omega \)-dynamo) is controlled by a single parameter known as the dynamo number

\[
D = R_\alpha R_\omega \approx 10 \frac{h^2}{v^2} \frac{d\Omega}{dr}. \quad (2)
\]

Mean-field dynamo action is also possible with rigid rotation; then it is called \( \alpha^2 \)-dynamo and its control parameter is \( R_\alpha^2 \).

This theory describes self-excitation of a large-scale or regular magnetic field whose spatial and temporal scales significantly exceed those of turbulent motions, \( l \approx 100 \) pc and \( l/v \approx 10^7 \) yr, respectively. The regular field is in fact that magnetic field which produces polarized radio emission observed at a linear resolution of 1–3 kpc typical of the present-day observations of nearby galaxies.

The regeneration (\( e \)-folding) rate of the regular magnetic field \( \gamma \) is related to the magnetic diffusion time along the smallest dimension of the gas layer and to the dynamo number (if \( |R_\omega| \gg R_\alpha \)). The following expression is acceptable as a rough estimate:

\[
\gamma \approx \frac{\beta}{h^2} \left( \sqrt{\frac{|D|}{D_\text{cr}}} - 1 \right) \approx (1-10) \text{ Gyr}^{-1} \quad \text{for } |D| \gtrsim D_\text{cr}, \quad (3)
\]

where \( D_\text{cr} \) is a certain critical dynamo number which weakly depends on the vertical profile of \( \alpha \); \( D_\text{cr} \approx 10 \) is a reasonable approximation. Magnetic field can be amplified \( \gamma > 0 \) if differential rotation and stratification are strong enough to yield \( |D| \geq D_\text{cr} \). In spiral galaxies, this condition is normally satisfied out to a large radius; it is therefore not surprising that regular magnetic fields have been detected in all galaxies where observations have sufficient sensitivity and resolution (Wielebinski & Krause, 1993; Beck et al., 1996; Beck, 2000).
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3 Observational evidence of dynamo action in spiral galaxies

3.1 Magnetic pitch angle

Regular magnetic fields observed in spiral galaxies have field lines in the form of a spiral with a pitch angle in the range $p = \pm (10^\circ - 30^\circ)$, with negative values indicating a trailing spiral (e.g., Beck et al., 1996). The value of the pitch angle is a useful diagnostic of the mechanism maintaining the magnetic field (Krasheninnikova et al., 1989).

Consider the simplest form of mean-field dynamo equations appropriate for a thin galactic disk (see Ruzmaikin et al., 1988a,b):

$$
\dot{B}_r = -(\alpha B_\phi)' + \beta B_\phi'',
\dot{B}_\phi = G B_r + \beta B_\phi''
$$

where $\mathbf{B} = (B_r, B_\phi, B_z)$ is the regular magnetic field written in cylindrical coordinates $(r, \phi, z)$, dot denotes time derivative, and dash derivative with respect to $z$, the vertical coordinate; $B_z$ can be obtained, e.g., from $\nabla \cdot \mathbf{B} = 0$. 
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Any regular magnetic field maintained by the dynamo must have a non-zero pitch angle: for $B_r \equiv 0$ (a purely azimuthal magnetic field), equation for $B_\phi$ in (1) reduces to a diffusion equation $\dot{B}_\phi = \beta B_r/\rho$ which only has decaying solutions, $B_\phi \propto \exp(-\beta t/h^2)$. The same applies to a purely radial magnetic field.

Consider exponentially growing solutions, $B_r, B_\phi \propto \exp(\gamma t)$, and replace $\partial / \partial z$ by $1/h$ and $\partial^2 / \partial z^2$ by $-1/h^2$ to obtain two algebraic equations, $(\gamma + \beta/h^2) B_r + \alpha B_\phi/h = 0$, $-GB_r + (\gamma + \beta/h^2) B_\phi = 0$, which have non-trivial solutions only if the determinant vanishes, which yields $(\gamma + \beta/h^2)^2 \approx -\alpha G/h$, and Eq. (2) follows with $D_{cr} = 1$. The resulting estimate of the magnetic pitch angle is given by

$$\tan p = \frac{B_r}{B_\phi} \approx -\sqrt{\frac{\alpha}{-Gh}} \approx -\frac{l}{h} \sqrt{\frac{\Omega/r}{|d\Omega/dr|}} = -\sqrt{\frac{R_\alpha}{|R_\omega|}}. \quad (6)$$

For $l/h \approx 1/4$ and a flat rotation curve, $(\Omega/r)/(d\Omega/dr) = -1$, we obtain $p \approx -15^\circ$, and this is the middle of the range observed in spiral galaxies. More elaborate treatments discussed by Ruzmaikin et al. (1988a) confirm this estimate of $p$ and yield a more accurate value of $D_{cr}$.

If the steady state is established by reducing $R_\alpha$ to its critical value as to obtain $R_\alpha R_\omega = D_{cr}$, then the pitch angle in the nonlinear steady state becomes

$$\tan p \approx -\frac{D_{cr}}{|R_\omega|}. \quad (7)$$

The magnetic pitch angle in M 31 determined from observations and dynamo theory is shown in Fig. 1. Although the model curves show noticeable differences from the observed pitch angles, the general agreement is encouraging. The situation is typical: magnetic pitch angles of spiral galaxies are a direct indication that the regular magnetic field is not frozen into the interstellar gas and has to be maintained by the dynamo (Beck, 2000).

Twisting of a horizontal primordial magnetic field by galactic differential rotation leads to a tightly wound magnetic structure with magnetic field direction alternating with radius at a progressively smaller scale $\Delta r \approx R/|G|t$ with $p_r \approx -(|G|t)^{-1}$, where $R \approx 10$ kpc is the scale of variation in $\Omega$ (see Moffatt, 1978, Sect. 3.3; Howard & Kulsrud, 1997; Kulsrud, 1999 for a detailed discussion). The winding-up proceeds until a time $t_0 \approx 5 \times 10^9$ yr such that $|G|t_0 \approx |C_\omega|^{1/2}$, where $C_\omega = GR^2/\beta = R_\alpha R_\omega^2 h^2 \approx 10^3-10^4$. At later times, the alternating magnetic field rapidly decays because of diffusion and reconnection. The resulting maximum magnetic field strength achieved at $t_0$ is given by

$$B_{\text{max}} \approx B_0|C_\omega|^{1/2}, \quad (8)$$

where $B_0$ is the external magnetic field; the magnetic field reverses at a small radial scale $\Delta r \approx R|C_\omega|^{-1/2} \approx 100$ pc. The magnetic pitch angle at $t_0$ is of the order of $|p| \approx |C_\omega|^{-1/2} \approx 1^\circ$, i.e., much smaller than observed. This picture cannot be reconciled with observations (cf. Kulsrud, 1999). It can be argued that streaming motions could make magnetic lines more open and parallel to the galactic spiral arms. However, then magnetic field will reverse on a small scale not only along radius, but also along azimuth. Such magnetic structures are quite different from what is observed. The moderate magnetic pitch angles observed in spiral galaxies are a direct indication that the regular magnetic field is not frozen into the interstellar gas and has to be maintained by the dynamo (Beck, 2000).
MHD density waves can produce non-zero magnetic pitch angle only in non-axisymmetric magnetic structures (Lou & Fan, 1998); an axisymmetric MHD wave suggested to explain the magnetic ring in M31 (Lou & Fan, 2000) can only have vanishing radial magnetic field, \( p = 0 \).

### 3.2 Even (quadrupole) symmetry of magnetic field in the Milky Way

One of the most convincing arguments in favour of the galactic dynamo theory comes from the symmetry of the observed regular magnetic field with respect to the Galactic equator in the Milky Way. As shown by wavelet analysis of the Faraday rotation measures of extragalactic radio sources, the horizontal components of the local regular magnetic field definitely have even parity being similarly directed on both sides of the midplane (Frick et al., 2000b). This symmetry is naturally explained by dynamo theory where even parity is strongly favoured against odd parity because the even field has twice larger scale in the vertical coordinate. Because of the difference in scale, the even field is subject to weaker destruction by magnetic diffusion, so the dynamo can regenerate even fields more efficiently (see Ruzmaikin et al., 1988a,b).

Primordial magnetic field twisted by differential rotation can have even vertical symmetry if it is parallel to the disk plane. However, then the field is rapidly destroyed by twisting and reconnection as described in Sect. 3.1. If, otherwise, the primordial field is parallel to the rotation axis and amplified by the vertical rotational shear \( \partial \Omega / \partial z \) (which is weak in galaxies anyway), it can avoid catastrophic decay (Moffatt, 1978, Sect. 3.11), but then it will have odd parity in \( z \), which is ruled out by the observed parity of the Milky Way field.

The derivation of the regular magnetic field of the Milky Way from Faraday rotation measures of pulsars and extragalactic radio sources, RM, is complicated by the contribution of local magnetic perturbations, so it is difficult to decide which features of the RM sky are due to the regular magnetic field and which are produced by localized magneto-ionic perturbations (e.g., supernova remnants). Therefore, the same observational data have lead different authors to different conclusions (see Frick et al., 2000b, for a recent review). Odd parity of the Galactic magnetic field has been suggested by Andreassian (1980, 1982) and, for the inner Galaxy, by Han et al. (1997). As stressed by Frick et al. (2000b), quantitative methods of analysis are especially appropriate in this case.

Unfortunately, it is difficult to determine the parity of magnetic fields in external galaxies. In galaxies seen edge-on, the disk is depolarized, whereas Faraday rotation in the halo is weak. Beck et al. (1994) found weak evidence of even magnetic parity in the lower halo of NGC 253. The arrangement of polarization planes in the halo of NGC 4631 (Beck, 2000) is very suggestive of odd parity, but this does not exclude even parity in the disk. In galaxies inclined to the line of sight, the amount of Faraday rotation produced by an odd (antisymmetric) magnetic field differs from zero because Faraday rotation and emission occur in the same volume; as a result, emission originating at the far half of the galactic layer will have small or zero net rotation, whereas emission from the near half will have significant rotation produced by the unidirectional magnetic field in that half. Therefore, Faraday rotation measures produced by even and odd magnetic structures of the same strength only differ by a factor of two (Krause et al., 1989a; Sokoloff et al., 1998) and it is difficult to distinguish between the two possibilities.

An interesting method to determine the parity of magnetic field in an external galaxy has been suggested by Han et al. (1998). These authors note that the contribution of the galaxy to the RM of a background radio source will be equal to the intrinsic RM of the galaxy if the magnetic field has even parity. For odd parity, the galaxy will not contribute to the RM of a background source, whereas any intrinsic RM will remain. The implementation of the method requires either a statistically significant sample of background sources or an extended single background source.

### 3.3 Azimuthal structure

Non-axisymmetric magnetic fields in a differentially rotating object are subject to twisting and enhanced dissipation as described in Sect. 3.1. The dynamo can compensate for the losses, but axisymmetric magnetic fields are still easier to maintain (Rädler, 1986). A few lowest non-axisymmetric
modes with azimuthal wave numbers

\[ m \lesssim \frac{R}{h} |R_\omega|^{-1/4} \approx 2 \]  

(9)

can be maintained in thin galactic disks where \( h \ll R \) (Ruzmaikin et al., 1988a, Sect. VI.7). However, the dominance of non-axisymmetric modes in most galaxies would be difficult to explain.

Early interpretations of Faraday rotation in spiral galaxies indicated strong dominance of bisymmetric magnetic structures \((m = 1)\), \( B \propto \exp i \phi \) with \( \phi \) the azimuthal angle (Sofue et al., 1986), and this was considered as a severe difficulty of the dynamo theory and an evidence of the primordial origin of galactic magnetic fields. Despite effort, dynamo models could not explain the apparent widespread dominance of bisymmetric magnetic structures. However, what seemed to be a difficulty of the dynamo theory has turned out to be its advantage as observations with better sensitivity and resolution and better interpretations have led to a dramatic revision of the observational picture. The present-day understanding is that modestly distorted axisymmetric magnetic structures occur in most galaxies, wherein the dominant axisymmetric mode is mixed with weaker higher azimuthal modes (Beck et al., 1996; Beck, 2000). Among nearby galaxies, only M 81 remains candidate for a bisymmetric magnetic structure (Krause et al., 1989b); the interesting case of M 51 is discussed below. Deviations from precise axial symmetry can result from the spiral pattern, asymmetry of the parent galaxy, etc. Dominant bisymmetric magnetic fields can be maintained by the dynamo action near the corotation radius due to a linear resonance with the spiral pattern (Mestel & Subramanian, 1991; Subramanian & Mestel, 1993; Moss, 1996) or nonlinear trapping of the field by the spiral pattern (Bykov et al., 1997).

Twisting of a horizontal magnetic field by differential rotation generally produces a bisymmetric magnetic field, \( m = 1 \). A twisted primordial magnetic field can result in an axisymmetric configuration near the galactic centre if the initial state is asymmetric (Sofue et al., 1986; Nordlund, 2000), with a maximum of the primordial field displaced from the disk’s rotation axis where the gas density is normally maximum. The requirement that magnetic fields in most spiral galaxies are axially symmetric within large radius (in fact, the whole galaxy) would need a systematic strong asymmetry in the initial state, with distinct initial distributions of magnetic field and gas density, which would be difficult to explain.

### M 33

A bisymmetric magnetic structure has been suggested for M 33 by Buczilowski & Beck (1991). Recent results of Fletcher et al. (2000) indicate that magnetic field in M 33 can represent an axisymmetric structure distorted by a two-armed spiral pattern. New observations are needed to decide between these possibilities. The magnetic spiral, as well as the optical spiral pattern, is rather open with \( p \approx -40^\circ \).

A dynamo model for M 33 was suggested by Starchenko & Shukurov (1989) who obtained WKB asymptotics for the growth rates of axisymmetric and non-axisymmetric modes of the mean-field \( \alpha \omega \)-dynamo neglecting any nonlinear effects and the spiral structure. They concluded that M 33 is likely to support two lowest magnetic modes \((m = 1, 2)\) because its rotation is rather close to a rigid one. More specifically, the bisymmetric mode can grow in M 33 provided \( Q = |d \ln \Omega / d \ln r| (v/\Omega)(h/l)^2 \lesssim 25 \), which seems to be the case. As shown by Eq. (6), weaker differential rotation with \( R_\alpha \approx |R_\omega| \) naturally leads to a more open magnetic spiral. These results need to be reconsidered and developed further using more advanced dynamo models.

### 3.4 A composite magnetic structure in M 51 and magnetic reversals in the Milky Way

A striking example of a complicated magnetic structure that can hardly be explained by any mechanism other than the dynamo is provided by the galaxy M 51 (Berkhuijsen et al., 1997). As shown in Fig. 2, the regular magnetic fields in the disk is reversed in a region about 3 by 8 kpc in size extended along azimuth at galactocentric radii \( r = 3–6 \) kpc. A significant deviation from axial symmetry in the disk has been detected out to \( r = 9 \) kpc, although it is too weak to result in magnetic field reversal. Furthermore, the regular magnetic field in the halo of M 51 has a structure distinct from that in the
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Fig. 2. **Left panel:** Magnetic structure in the disk of M 51 obtained from radio polarization observations at \( \lambda \lambda 2.8, 6.2, 18.0 \) and 20.5 cm smoothed to a resolution of \( \approx 3.5 \) kpc; arrows indicate the direction and strength of the regular magnetic field on the polar grid shown superimposed on the optical picture (see Berkhuijsen et al., 1997, for detail). The grid radii are 3, 6, 9, 12 and 15 kpc. Note reversed magnetic field at azimuthal angles 300°–0 in the inner ring. **Right panel:** Magnetic field strengths from the nonlinear dynamo model of Bykov et al. (1997) is shown with shades of grey (darker shade corresponds to stronger field). Magnetic field is reversed within the zero-level contour shown dashed; scale is given in kpc. The model is based on the rotation curve of M 51 (Tully, 1974), with the pitch angle of the spiral arms −15° and corotation radius 6 kpc. The magnetic structure rotates rigidly together with the spiral pattern visible in the shades of grey.

disk — the halo field is nearly axisymmetric and directed oppositely to that in the disk in most of the galaxy. An external magnetic field should have a rather peculiar form to be twisted into such a configuration!

A nonlinear dynamo model based on the rotation curve of M 51, developed by Bykov et al. (1997), shows that a region with reversed magnetic field can occur in the disk near the corotation radius of the spiral pattern. Near the corotation, non-axisymmetric (bisymmetric) magnetic field can be trapped by the spiral pattern and maintained over the galactic lifetime. The effect is favoured by a smaller pitch angle of the spiral arms, thinner gaseous disk, weaker rotational shear and stronger spiral pattern. A disk dynamo solution of Bykov et al. (1997) arguably similar to the structure observed in M 51 is shown in Fig. 2.

Distinct azimuthal magnetic structures in the disk and the halo can be readily explained by dynamo theory as non-axisymmetric magnetic fields can be maintained only in the thin disk but not in the quasispherical halo where \( h \approx R \) and \( |R_\omega| \gg 1 \) in Eq. (8). Moreover, dynamo action in the disk and the halo can proceed almost independently of each other producing distinctly directed magnetic fields (Sokoloff & Shukurov, 1990).

Another case of a regular magnetic field with unusual radial structure is the Milky Way where magnetic field reversals are observed in the inner Galaxy between the Orion and Sagittarius arms at \( r \approx 7.9 \) kpc (Simard-Normandin & Kronberg, 1980; Rand & Kulkarni, 1989; Rand & Lyne, 1994; Frick et al., 2000b) and, possibly, in the outer Galaxy between the Orion and Perseus arms at \( r \approx 10.5 \) kpc (Agafonov et al., 1988; Frick et al., 2000b; see, however, Vallée, 1983). The reversals were first interpreted as an indication of a global bisymmetric magnetic structure (Sofue & Fujimoto, 1983), but it has been shown that dynamo-generated axisymmetric magnetic field can have reversals at the appropriate scale (Ruzmaikin et al., 1985; Poezd et al., 1993). Both interpretations presume that the
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reversals are of a global nature, i.e., they extend over the whole Galaxy to all azimuthal angles (or radii in the case of the bisymmetric structure). This leads to a question why reversals at this radial scale are not observed in any other galaxy (Beck, 2000). Poezd et al. (1993) argue that the lifetime of the reversals is sensitive to subtle features of the rotation curve and the geometry of the ionized gas layer (see also Belyanin et al., 1993) and demonstrate that they are more probable to survive in the Milky Way than in M 31.

However, the observational evidence of the reversals is restricted to a relatively small neighbourhood of the Sun, of at most 3–5 kpc along azimuth. It is therefore quite possible that the reversals are local and arise from a magnetic structure similar to that in the disk of M 51 as shown in Fig. 2. The reversed field in the Solar neighbourhood has the same radial extent of 2–3 kpc as in M 51 and occurs near the corotation radius. This possibility has not yet been explored; its observational verification would require careful analysis of pulsar Faraday rotation measures.

3.5 The radial magnetic structure in M 31

An important evidence in favour of galactic dynamos is the magnetic ring in M 31 (Beck, 1982), predicted by dynamo theory (Ruzmaikin & Shukurov, 1981). The dynamo model of Ruzmaikin & Shukurov (1981) was based on the double-peaked rotation curve of Rubin & Ford (1970), Deharveng & Pellet (1975) and Haud (1981) shown in Fig. 1, where rotational shear is strongly reduced at \( r = 2–6 \) kpc. As a result, \( R_\omega \) is small and even positive in this radial range, so \( |D| \gtrsim D_{cr} \) and the dynamo cannot maintain any regular magnetic field at \( r = 2–6\) kpc.

An attractive aspect of this theory is that both magnetic and gas rings are attributed to the same feature of the rotation curve. Angular momentum transport by viscous stress leads to matter inflow at a rate \( \dot{M} = 2\pi\sigma v(r/\Omega) d\Omega/dr \simeq 0.1 \, M_\odot \, \text{yr}^{-1} \), where \( \nu \simeq \beta \) is the turbulent viscosity, resulting in the radial inflow at a speed \( v_r = \dot{M}/2\pi r \sigma \) with \( \sigma \) the gas surface density. In the nearly-rigidly rotating parts, \( v_r \) is reduced and matter piles up outside this region producing gas ring. Gravitational torques from spiral arms can further enhance the inflow (see Moss et al., 2000, for a discussion), so the total radial velocity is expected to be of order 1 km s\(^{-1}\) at \( r = 10 \) kpc.

The double-peaked rotation curve of M 31 is consistent with the existence of both magnetic and gas rings. The situation is different with the more recent rotation curve of Braun (1991) which does not have a double-peaked shape (Fig. 1). The difference between the two rotation curves arises mainly from the fact that Braun allows for significant displacements of spiral arm segments from the galactic midplane: this results in a revision of the segments’ galactocentric distances for regions away from the major axis. We note that the CO velocity field at the major axis (Loinard et al., 1995) is compatible with a double-peaked rotation curve.

With Braun’s rotation curve, the magnetic field can concentrate into a ring mainly because the gas is in the ring and \( B \propto \rho^{1/2} \) as shown in Eq. (4). The dynamo model of Moss et al. (1998) based on the rotation curve of Braun (1991) has difficulties in reproducing a magnetic ring as well pronounced as implied by the observed amount of Faraday rotation — see Fig. 3. This has lead to an idea that magnetic field can be significant at \( r = 2–6 \) kpc in M 31. This has prompted Han et al. (1998) to search for magnetic fields at \( r = 2–6 \) kpc that could have escaped detection because of reduced density of cosmic ray electrons at those radii. These authors have found that two out of three background polarized radio sources seen through that region of M 31 have Faraday rotation measures compatible with the results of Moss et al. (1998) shown with solid and long-dashed lines in Fig. 3. They further conclude that this indicates an even symmetry of the regular magnetic field. This is encouraging, but a statistically representative sample of background sources has to be used to reach definite conclusions because of their unknown intrinsic RM.

With a double-peaked rotation curve, a primordial magnetic field with a uniform radial component could have been twisted to produce a magnetic ring by virtue of Eq. (8). In this case the primordial and dynamo theories have similar problems and possibilities regarding the magnetic ring in M 31.

Lou & Fan (2000) attribute the magnetic ring in M 31 to an axisymmetric mode of MHD density waves. Because of the axial symmetry of the wave, the magnetic field in the ring must be purely azimuthal, \( p = 0 \), in contrast to the observed structure with a significant pitch angle (Fig. 1). Fur-
3.6 Strength of the regular magnetic field

Interstellar regular magnetic fields are close to energy equipartition with interstellar turbulence. This directly indicates that the regular magnetic field is coupled to the turbulent gas motions. (Note that $\Omega$ does not differ much from the turbulent velocity $v$ in Eq. (4).) To appreciate the importance of this conclusion, consider primordial magnetic field twisted by differential rotation. Its maximum strength given by Eq. (8) as $B_{\text{max}} \approx 10^2 B_0$ is controlled by the strength of the primordial field $B_0$, and so this theory, if applicable, would result in stringent constraints on extragalactic magnetic fields.

The theory of MHD density waves relates magnetic field excess in spiral arms to the enhancement in stellar density, $\Delta B_\text{arm}/\langle B \rangle = \Delta \Sigma_\text{arm}/\langle \Sigma \rangle$ (Lou & Fan, 1998), where $\Sigma$ is the stellar surface density and angular brackets denote azimuthal averaging. Arm intensities in magnetic field and stellar surface density in NGC 6946 have been estimated by Frick et al. (2000a) who applied wavelet transform techniques to radio polarization maps at $\lambda\lambda 3.5$ and 6.2 cm and to the galaxy image in broadband red light. 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.

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