GALACTIC SPIRAL ARMS AND DYNAMO CONTROL PARAMETERS

A. SHUKUROV
Department of Mathematics, University of Newcastle upon Tyne, U.K.[1]
D. SOKOLOFF
Department of Physics, Moscow State University, Moscow, Russia[2]

Summary: *We discuss the effects of galactic spiral arms on the α-coefficient, turbulent diffusivity and turbulent energy density of the interstellar turbulence. We argue that the α-coefficient and the dynamo number are larger in the interarm regions, whereas the kinetic energy density of turbulence is larger in the arms; the turbulent magnetic diffusivity can be only weakly affected by the spiral pattern.*

Key words: Galactic spiral arms, interstellar turbulence, galactic magnetic fields, mean-field dynamos

1. INTRODUCTION

Both theory and observations of galactic magnetic fields have now reached a stage advanced enough as to address fine properties of interstellar magnetic fields such as the azimuthal and radial structure of the large-scale magnetic field, the role of the galactic environment (galactic winds, fountain flows, star formation), statistical parameters of random magnetic fields, etc. (see *Beck et al., 1996; Zweibel and Heiles, 1997* for recent reviews). The origin of bisymmetric magnetic structures (first pinpointed as strongly nonaxisymmetric structures having an azimuthal wave number $m = 1$) was one of the early problems of this kind, actively studied for about fifteen years. Although this problem still has not been properly resolved, it has lost its acuteness because both theory and observations converge to the opinion that purely bisymmetric structures are rather an exception than a rule among galaxies. Various nonlinear combinations of different azimuthal modes appear to be more natural from both theoretical and observational viewpoints (*Beck et al., 1996; Bykov et al., 1997; Moss et al., 1998a*).

Detailed properties of the nonaxisymmetric components of the large-scale magnetic fields are sensitive to the galactic spiral arms. Until very recently, the understanding of the interaction between galactic magnetic fields and spiral density waves was based on the classical paper of *Roberts and Yuan (1970)*. Since the magnetic Reynolds number based on ambibolar diffusivity is very large in the interstellar medium (at least 10^6—see *Ruzmaikin et al., 1988*), galactic magnetic fields were long considered to be frozen into the interstellar gas at *all* scales. An immediate consequence of this was that interstellar magnetic fields must be sensitive to just one parameter of the interstellar gas, its density. This viewpoint must be reconsidered now.

[1] Address: Newcastle upon Tyne, NE1 7RU (Anvar.Shukurov@Newcastle.ac.uk)
[2] Address: Moscow 119899 (sokoloff@dds.srcc.msu.su)

The large-scale component of the magnetic field is subject to turbulent magnetic diffusion and so it cannot be considered frozen into the interstellar gas over the galactic lifetime. Therefore, interstellar large-scale magnetic fields are sensitive not only to the gas density, but also to velocity shear, angular velocity of the overall rotation, r.m.s. turbulent velocity and other kinematic parameters of the ambient medium.

2. THE DYNAMO PARAMETERS

Among the parameters that control mean-field dynamo action, the following may be different within galactic spiral arms and in the interarm regions: (i) the α-coefficient, (ii) the turbulent magnetic diffusivity β and (iii) the saturation level of the mean field, B_0. Models of the mean-field dynamo in galaxies are quite robust with respect to plausible changes of these parameters. The ultimate reason for the success of simple galactic dynamo models is that galactic discs are thin. Because of this, the basic, local dynamo equations (retaining only derivatives across the galactic disc) have a simple spectrum with only one (quadrupole) mode having positive growth rate in the main part of the disc. Hence, order of magnitude estimates of the dynamo parameters based on simple physical considerations both match the accuracy of astronomical observations and are sufficient to construct reliable models of galactic dynamos.

It is most often sufficient to use the following estimates:

$$\alpha \simeq \frac{l^2\Omega}{h}\,, \quad \beta \simeq \tfrac{1}{3}\tau v^2\,, \quad B_0^2 \simeq 8\pi E_{\rm k}\left(\left|\frac{D}{D_{\rm cr}}\right| - 1\right)\,, \tag{1}$$

where v is the r.m.s. turbulent velocity, l and τ are the correlation length and time of the turbulence, respectively, Ω is the angular velocity of galactic rotation, h is the scale height of the ionized gas layer, $E_{\rm k} = \frac{1}{2}\rho v^2$ with ρ the density of the interstellar gas, and

$$D = \frac{\alpha h^3}{\beta^2}\, r\frac{d\Omega}{dr} \simeq -10\left(\frac{h\Omega}{v}\right)^2 \tag{2}$$

is the dynamo number. In order to obtain the last estimate, we used Eq. (1) and assumed that the galactic rotation curve is flat, that is $\Omega \propto r^{-1}$ at a sufficient galactocentric distance r from the centre. We assume that $\tau \simeq l/v$. The last estimate of Eq. (1) applies for $|D|$ only slightly exceeding its critical value $|D_{\rm cr}| \approx 10$ and describes the standard behaviour of a nonlinear solution near a simple bifurcation (see *Moss et al., 1998b; Shukurov, 1998*).

The advantage of Eqs (1) and (2) is that they include only those parameters of interstellar turbulence which can be more or less reliably determined from observations and models of the interstellar medium. More detailed expressions for the dynamo parameters involve unobservable quantities which cannot be well constrained without a reliable theory of interstellar turbulence.

We do not discuss here nonaxisymmetric regular motions (the so-called streaming velocities) which are associated with the spiral arms. This part of the regular velocity field is well known from density wave models and it directly contributes to the induction term in the mean-field dynamo equation.

The dynamo number and the saturation level of the large-scale magnetic field do not depend on l. However, this parameter is important for random magnetic fields, so we discuss l below together with other relevant parameters.

3. CONSTRAINTS ON DYNAMO PARAMETERS IMPLIED BY OBSERVATIONS AND MODELLING

Equations (1) and (2) lead to the following widely adopted average values of the relevant parameters, based on the estimates $l \simeq 0.1\,\mathrm{kpc}$, $v \simeq 10\,\mathrm{km\,s^{-1}}$, $\rho \simeq 1.7\times10^{-25}\,\mathrm{g\,cm^{-3}}$ (0.1 particle per cm^3), $h \simeq 0.5$–$1\,\mathrm{kpc}$ and $\Omega \simeq 20\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ (see details in *Ruzmaikin et al., 1988*):

$$\alpha \simeq 0.4\text{--}0.2\,\mathrm{km\,s^{-1}}\,, \qquad \beta \simeq 10^{26}\,\mathrm{cm^2\,s^{-1}}\,,$$

$$B_0^2 \simeq (1.5\,\mu\mathrm{G})^2\left(\left|\frac{D}{D_{\mathrm{cr}}}\right| - 1\right)\,, \qquad D \simeq -(10\text{--}40)\,.$$

The resulting estimate of B_0 is comfortably close to the observed strength of the large-scale galactic magnetic fields (1–5 μG), and the value of the dynamo number is close enough to the dynamo threshold to make the last estimate of Eq. (1) applicable.

The above range of h reflects a recent observational revision of the semi-thickness of the Galactic ionized layer. This layer is intrinsically connected with the warm phase of the interstellar medium. The neutral component of the warm interstellar medium, believed to be the site of the dynamo activity, has the scale height of 0.5 kpc. However, it was found by *Reynolds (1991)* that the vertical distribution of free thermal electrons near the Sun has a component whose scale height is about 1 kpc. In external galaxies, the ionized layer was observed to have two components, one with the conventional scale height of $h \simeq 0.5\,\mathrm{kpc}$ and the other with $h \simeq 1\,\mathrm{kpc}$ (*Wang et al., 1997*). It is not quite clear which of the two components hosts the mean-field dynamo.

The effects of the galactic spiral arms on the above parameters are not well understood and here we propose only an exploratory qualitative discussion. The quality of modern observations is, in general, not sufficient to determine reliably the arm-interarm contrast of the above parameters. Therefore, we rely mostly on theoretical models, but mention supporting observational evidence wherever possible.

The turbulent velocity v is expected to be enhanced in the arms because of gas compression in galactic shocks, more active star formation in the arms and other factors. *Rohlfs and Kreitschmann (1987)* note that the velocity dispersion of neutral hydrogen is about $12\,\mathrm{km\,s^{-1}}$ in the 3-kpc arm and $6\,\mathrm{km\,s^{-1}}$ in the interarm regions of the Milky Way. CO observations of the galaxy M51 (*García-Burillo et al., 1993*) indicate that the spectral line widths are larger in the arms than between them, but only an uncertain part of this difference can be attributed to the arm-interarm contrast in turbulent velocity. An enhancement of v by a factor of two in the arms seems to be compatible with their observations. This value of the arm-interarm contrast in v is supported by simulations of density waves in a cloudy interstellar medium by *Roberts and Hausman (1984)* who conclude that the velocity dispersion of neutral hydrogen clouds in the arms is about twice that between the arms. Hence we adopt $v_a/v_i \simeq 2$; subscripts 'a' and 'i' henceforth refer to arms and interarm regions, respectively.

The density contrast between spiral arms and the interarm space is typically $\rho_a/\rho_i \simeq 3$ (see e.g., *Roberts and Hausman, 1984*). It may be important to note that the maxima in density and velocity dispersion are shifted in phase, so that the contrast in E_k is smaller than 10; with this reservation, one may adopt $E_{ka}/E_{ki} = 10$. We stress that this is an upper limit.

It is usually assumed that the ionized gas is in hydrostatic equilibrium, so that the gas scale height is given by $h \simeq (v^2 + V_A^2)/g$, where V_A is the Alfvén velocity and g is the vertical acceleration due to gravity (we take into account that thermal and turbulent pressures are equal to each other, that is the sound speed c_s is equal to v, and the magnetic and cosmic ray pressures are also assumed to be equal to each other). The Alfvén velocity is determined by the total magnetic field. The energy density of random magnetic fields, $b^2/8\pi$, is about three times larger than that of the large-scale magnetic field in galaxies. Assuming that $b^2/8\pi \simeq E_k$, we obtain $V_A \simeq v$. Then assumption of *detailed* hydrostatic equilibrium, if applicable, would yield a perplexing result $h_a/h_i \simeq (v_a/v_i)^2 \simeq 4$.

However, the assumption of hydrostatic equilibrium may be applicable only in average over the galaxy, but cannot be used to estimate localised azimuthal variations in h. The reason is that hydrostatic equilibrium can be established only if the sound crossing time for one scale height h is shorter than the time scale of variations in any relevant parameters. The sound crossing time is $h/c_s \simeq (0.5\text{–}1) \times 10^8$ years. The passage time of the spiral density wave is $\tau_p \simeq d/(V \sin p)$, where d is the width of a spiral arms, V is the linear velocity of the arms relative to the gas and p is the pitch angle of the spiral arm. For $d = 2\,\mathrm{kpc}$, $V = 100\,\mathrm{km\,s^{-1}}$ and $p = 15°$, we obtain $\tau_p \simeq 0.8 \times 10^8$ years. Thus, $h/c_s \simeq \tau_p$, so the spiral density waves affect only the *mean* hydrostatic equilibrium of the interstellar gas. A conservative upper limit is $h_a \simeq c_s\tau_p \simeq 0.8\,\mathrm{kpc}$, whereas $h \simeq 0.5\text{–}1\,\mathrm{kpc}$ in average. As we can see, the effect is negligible. We conclude that $h_a/h_i = 1$ is a plausible estimate.

An estimate of the arm-interarm contrast in the turbulent magnetic diffusivity can be obtained assuming that $\tau \propto \nu_{SN}^{-1}$, where ν_{SN} is the supernova rate, a quantity proportional to the star formation rate. Since the latter scales as ρ^n with $n = 1\text{–}2$, we obtain $\beta_a/\beta_i \simeq (v_a/v_i)^2(\rho_a/\rho_i)^{-n} \simeq 1.3\text{–}0.4$. Thus, the azimuthal variation in the turbulent diffusivity may be quite weak.

The azimuthal variations of the total pressure p in the interstellar medium are determined by the variations in E_k and magnetic pressure. Assuming again that $b^2/8\pi \simeq E_k$ and that cosmic ray and magnetic pressures are equal to each other, we obtain $p_a/p_i \simeq E_{ka}/E_{ki} \simeq 10$. A strong contrast in the total pressure is compatible with azimuthally uniform gas scale height because hydrostatic equilibrium is maintained only on average, but not locally.

Observational estimates of the turbulence correlation scale l are scarce. Various statistical analyses of fluctuations in v and ρ in the Milky Way imply $l \simeq 50$–$150\,\mathrm{pc}$ in average, but tell nothing about the arm-interarm contrast in l. We suggest the following estimate based on the idea that the main source of interstellar turbulence is supernova explosions. Then l is determined by the radius of a supernova remnant when it expands to a balance between internal and external pressures. The equation of adiabatic expansion of a remnant filled with hot gas then predicts that l scales as (*Chevalier, 1974; McKee and Ostriker, 1977; Lozinskaya, 1992*)

$$l \propto \rho^{-0.16} p^{-0.20} \,.$$

Then

$$\frac{l_a}{l_i} \simeq \left(\frac{\rho_a}{\rho_i}\right)^{-0.16} \left(\frac{p_a}{p_i}\right)^{-0.20} \simeq 0.5 \,.$$

Combining the above results we arrive at the following estimates of the arm-interarm contrast for the dynamo parameters:

$$\frac{\beta_a}{\beta_i} \simeq 1.3\text{–}0.4 \,, \qquad \frac{\alpha_a}{\alpha_i} \simeq \left(\frac{l_a}{l_i}\right)^2 \simeq 0.25 \,, \qquad \frac{D_a}{D_i} \simeq \left(\frac{v_a}{v_i}\right)^{-2} \simeq 0.25 \,.$$

Albeit simplistic, these estimates lead to rather unexpected conclusions: the α-effect is expected to be stronger between the arms, whereas turbulent magnetic diffusivity can be only weakly affected by the arms. As a result, the dynamo number is larger between the arms. As discussed by *Shukurov (1998)*, this can result in stronger regular magnetic fields in the interarm regions, although the kinetic energy density of turbulence is larger in the arms.

Acknowledgements: D.S. acknowledges financial support from the Organizing Committee and RFBR project 96–02–16252. The authors are grateful to the Royal Society and PPARC (grant GR/L30268) for financial support.

Manuscript received: 25th February, 1998; *Revisions accepted: 6th June, 1998*

References

Beck, R., Brandenburg, A., Moss, D., Shukurov, A. and Sokoloff, D., 1996: Galactic magnetism: recent developments and perspectives. *Ann. Rev. Astron. Astrophys.*, **34**, 155–206

Bykov, A., Popov, V., Shukurov, A. and Sokoloff, D., 1997: Anomalous persistence of bisymmetric magnetic structures in spiral galaxies. *Mon. Notic. roy. Astron. Soc.*, **292**, 1–10

Chevalier, R.A., 1974: The evolution of supernova remnants. 1. Spherically symmetric models. *Astrophys. J.* **188**, 501–516

García-Burillo, S., Combes, F. and Gerin, M., 1993: CO in Messier 51. II. Molecular gas dynamics. *Astron. Astrophys.*, **274**, 148–164

Lozinskaya, T.A., 1992: *Supernovae and Stellar Wind in the Interstellar Medium.* American Institute of Physics, New York

McKee, C.F. and Ostriker, J.P., 1977: A theory of the interstellar medium: three components regulated by supernova explosions in an inhomogeneous substrate. *Astrophys. J.*, **218**, 148–169

Moss, D., Korpi, M., Rautiainen, P. and Salo, H., 1998a: The evolution of dynamo maintained magnetic fields in a barred spiral galaxy. *Astron. Astrophys.*, **329**, 895–905

Moss, D., Shukurov, A., Sokoloff, D.D., Berkhuijsen, E.M. and Beck, R., 1998b: The nature of the magnetic belt in M31. *Astron. Astrophys.*, in the press

Reynolds, R.J., 1991: Ionized disk/halo gas—Insight from optical emission lines and pulsar dispersion measures. In: *The Interstellar Disk-Halo Connection in Galaxies, Proc. IAU Symp. 144,* ed. H. Bloeman. Kluwer, Dordrecht, pp. 67–76

Roberts, W.W. and Hausman, M.A., 1984: Spiral structure and star formation. I. Formation mechanisms and mean free paths. *Astrophys. J.*, **277**, 744–767

Roberts, W.W. and Yuan, C., 1970: Application of the density-wave theory to the spiral structures of the Milky Way system. III. Magnetic field: large-scale hydromagnetic shock formation. *Astrophys. J.*, **161**, 877–902

Rohlfs, K. and Kreitschmann, J., 1987: Kinematics and physical parameters of neutral hydrogen in the inner Galaxy. *Astron. Astrophys.*, **178**, 95–105

Ruzmaikin, A.A., Shukurov, A.M. and Sokoloff, D.D., 1988: *Magnetic Fields of Galaxies.* Kluwer, Dordrecht

Shukurov, A., 1998: Magnetic arms in spiral galaxies. *Mon. Notic. roy. Astron. Soc.*, submitted

Wang, J., Heckman, T.M. and Lehnert, M.D., 1997: On the dynamical and physical state of the "Diffuse Ionized Medium" in nearby spiral galaxies. *Astrophys. J.*, **491**, 114–133

Zweibel, E.G. and Heiles, C., 1997: Magnetic fields in galaxies and beyond. *Nature,* **385**, 131–136