NUMERICAL MODELS OF 3-D GALACTIC DYNAMOS

J.S. PANESAR, N. MOORE and A.H. NELSON
Physics Department, University of Wales College of Cardiff
P.O. Box 913, Cardiff CF1 3TH, UK

Abstract. We describe here the results of 3-D numerical simulations of an $\alpha\omega$-dynamo in galaxies with differential rotation, small scale turbulence, and a shock wave induced by a stellar density wave. A non-linear quenching mechanism for the dynamo instability is used, and with the model parameters employed the field achieves a steady state which closely resembles observed fields in galaxies. The magnetic field vectors are parallel to the plane in the disc, with the magnetic intensity decreasing away from the plane. The vectors are also nearly parallel to the spiral arms in the disc, and the field direction is axisymmetric about the galactic centre, but with significant increase of intensity in the arms. The magnetic intensity rises steeply towards the centre of the galaxy, where the field becomes dominated by the vertical component. Nowhere in the parameter range covered is the bi-symmetric field mode dominant.

Theoretical models of the galaxy fields have been based on the kinematic dynamo theory originally developed by Parker (1971) and expounded in detail by Moffatt (1978) and Krause and Rädler (1980). This mean-field theory involves an induction equation with a dynamo term of the form $\nabla \times (\alpha \mathbf{B})$ to yield a reasonable approximation to the evolution of the mean magnetic field. The coefficient α and the turbulent resistivity η are related to the turbulent velocity field u by the expressions

$$\eta = \tau \left\langle u^2 \right\rangle /3 \quad \text{and } \alpha = -\tau \left\langle \mathbf{u} \cdot \nabla \times \mathbf{u} \right\rangle /3$$

where τ is the characteristic timescale of the turbulence (given by l/u where l is the characteristic length scale of the turbulence cells), and the <> brackets denote averages over many turbulence cells.

The 3-D grid which we use is cylindrical in shape with a total thickness of 2kpc and a radius of 20kpc. The grid size is (20x60x14) in the (r, ϕ, z) directions respectively, which yields rather modest resolution, particularly in the z-direction. This grid size is dictated by the limitations of processing power available.

The galaxy model used has the following features:

1) A thin gas disc with half scale height h varying from 150pc at $r = 0$, through 400pc at $r = 10kpc$, to 800pc at $r = 20kpc$ (Ruzmaikin et al. 1985).

2) Velocity field

   i) Angular velocity $V(r) = V_c \left(1 + (r/a)^2\right)^{-3/4}$ with $a = 4kpc$, i.e. differential rotation outside $r = a$, but near rigid rotation inside $r = a$. This yields different characters of dynamo inside and outside $r = a$. Inside $r = a$ we have an α^2 dynamo, while outside $r = a$ we have an $\alpha\omega$-dynamo.

   ii) We apply a spiral shock perturbation to the above rotational velocity, obtained from a hydrodynamic simulation of the response of the gas to a spiral modulation of a stellar galactic potential (Johns and Nelson 1986).

3) Resistivity $\eta = 0.33kpc(km/sec)$, corresponding to $\eta = lu/3$ with $l = 100pc$ and $u = 10km/sec$.

F. Krause et al. (eds.), The Cosmic Dynamo, 345–348.

4) α varies in time in response to the varying magnetic intensity (see next point), but its initial value also varies with r, according to the formula

$$\alpha_i = l^2\Omega/h, \quad \text{where} \quad \Omega = rV.$$

This takes acount of the variation in r of the rate of generation of helicity by the Coriolis force acting on rising and falling turbulence cells (Ruzmaikin et al. 1988), and yields a variation of α_i from 5.32 km/sec at $r = 0$ to 0.5 km/sec at $r = 10$ kpc.

5) We use the following expression for α

$$\alpha = \alpha_i / \left(1 + B^2/(\mu_0 \rho u^2)\right).$$

where ρ is the gas density (modified by the shock). This is intended to represent the tendency for the magnetic field to suppress turbulence, and ensures suppression of the instability which generates the field when the field approaches equipartition with the turbulent energy density. Here ρ is taken to vary as a gaussian in z, and with the azimuthal variation obtained from the spiral shock.

6) The initial field has a broad spectrum of random amplitude wave modes in B_r and B_ϕ, with B_z zero. The direction of $\mathbf{B}$ (via the signs of B_r and B_ϕ) switches randomly from grid point to grid point in the z direction. The rms field strength in this initial field is $10^{-15}T$.

After the dynamo has been switched on the field strength grows rapidly to about $10^{-10}T$ ($1\mu G$) in approximately 10^9 years, after which it settles into a quasi-steady state (see Fig. 1).

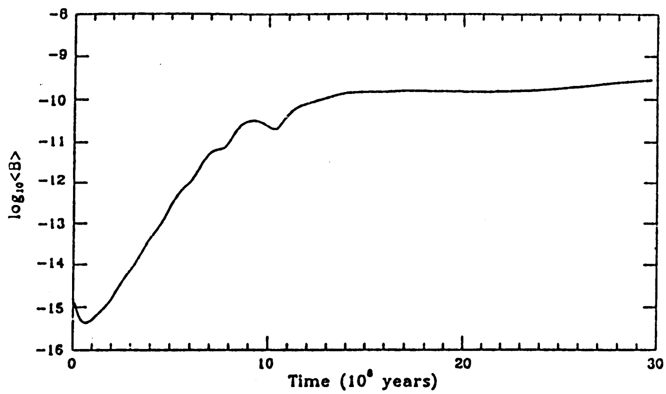

Fig. 1 Mean B as a function of time

https://doi.org/10.1017/S007418090017439X Published online by Cambridge University Press

The spectrum of **B** changes dramatically, with the higher order modes decreasing to insignificance relative to the dominant $m = 0$ axisymmetric mode. The dominance of this mode can be seen in the plot of field vectors parallel to the plane (Fig.2).

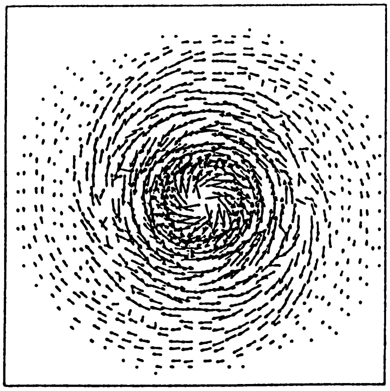

Fig. 2 **B** *vectors in* (r, ϕ) *plane near* $z = 0$ *(arrow lengths are logarithmic in B)*

At constant r the field direction is independent of ϕ, while the direction oscillates in sign with varying r. Note that the field vectors plotted here have lengths which are proportional to the log of the field intensity rather than the field intensity itself. Without this the vectors at the centre would completely dominate Fig. 2 and the field in the disc would not be visible. The next most significant azimuthal mode in the spectrum is the $m = 2$ mode which is just visible in the outer part of the disc in Fig. 2 as a doubly periodic azimuthal modulation of the field intensity. There is also a small $m = 1$ component present in the spectrum, but this is too weak to be visible in the field plots. In all of our runs the $m = 1$ mode is dominated by $m = 0$. The only way we have found to obtain a visible $m = 1$ bisymmetric field in the final steady state is to start off with $m = 1$ as the only mode in the initial conditions (an initially straight field parallel to the plane for instance).

Figs 3a and 3b show the vertical structure of the field. Fig. 3a shows the contours of the toroidal field component B_ϕ in the (r,z) plane. In the outer part of the disc the reversal of field direction with r and the confinement of the strong field to the plane can be seen. At the galaxy centre the sign of B_ϕ reverses across the $z = 0$ plane, while further out B_ϕ is symmetric about the $z = 0$ plane. This suggests that there is an odd, dipole field at the centre (where the α^2 dynamo is strongest) and an even, quadrupole field in the outer disc (where the $\alpha\omega$-dynamo is strongest). This is corroborated by the field vector plots for the poloidal field (B_r, B_z) in the (r,z) plane shown in Fig. 3b. At the centre the field is obviously dipole, while further out it is quadrupole (to obtain sufficient dynamic range the vectors here also have lengths proportional to the log of the field intensity).

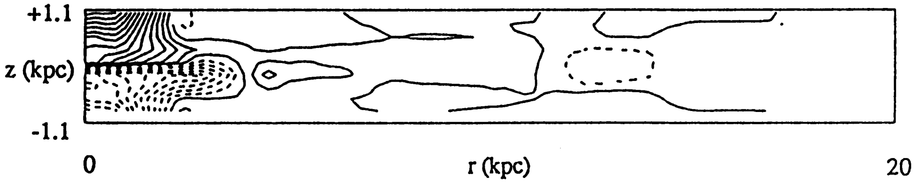

Fig. 3a Contours of B_ϕ in (r,z) plane near $\phi = 0$ (broken lines denote negative values)

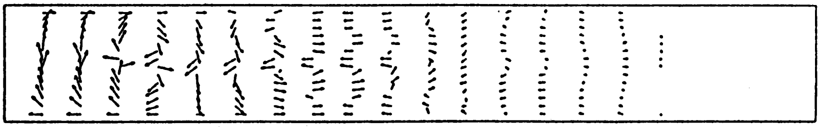

Fig. 3b **B** *vectors in the (r,z) plane near $\phi = 0$ (arrow lengths are logarithmic in B, and the box is the same as in 3a)*

These calculations show that, using reasonable justifiable parameters, kinematic dynamo models based on the mean-field dynamo equation can reproduce the gross features of galaxy magnetic fields. In particular the field is confined to a region close to the plane in the outer part of the disc by the non-linear quenching mechanism and we obtain simultaneously a strong vertical, dipole field at the centre and a quadrupole field in the outer disc.

We have varied the pattern speed of the spiral shock wave imposed on the velocity and density field in order to search for the parametric resonance enhancement of the bi-symmetric $m = 1$ mode reported by Chiba & Tosa (1990), and Mestel & Subramanian (1991). However we have found no part of this parameter space in which the final amplitude, or the linear phase growth rate for the $m = 1$ mode is not dominated by the axisymmetric $m = 0$ mode.

References

Chiba, M., Tosa, M.: 1990, *Mon. Not. R. astr. Soc.* **244**, 714.
Johns, T.C., Nelson, A.H.: 1986, *Mon. Not. R. astr. Soc.* **220**, 165.
Krause, F., Beck, R., Hummel, E.: 1989, *Astr. Astrophys.* **217**, 17.
Krause, F., Rädler, K.-H.: 1980, *Mean-field electrodynamics and Dynamo Theory*, Pergamon
Mestel, L., Subramanian, K.: 1991, *Mon. Not. R. astr. Soc.* **248**, 647.
Moffatt, H.K.: 1978, *Magnetic Field Generation in Electrically Conducting Fluids*, CUP.
Parker, E.N.: 1971, *Astrophys. J.* **163**, 255.
Ruzmaikin, A.A., Sokoloff, D.D., Shukurov, A.M.: 1985, *Astr. Astrophys.* **148**, 335.
Ruzmaikin, A.A., Shukurov, A.M., Sokoloff, D.D.: 1988, *Magnetic Fields of Galaxies*, Kluwer, Dordrecht.