GALACTIC DYNAMOS AND DYNAMICS

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Abstract. We discuss some aspects of the interrelationship between the dynamo problem for galaxies and their dynamics. First, we consider the generation of magnetic fields in the presence of fountain flows and galactic winds. Next, we discuss the distortion of a steady magnetic field by tidal effects and other transient spiral features. Finally, we give an expression for the amplitude of density waves generated by large-scale non-axisymmetric fields.

Key words: Interstellar gas dynamics – Interactions of galaxies – Density waves

1. Introduction

Dynamo models for the origin of galactic magnetic fields are making progress towards greater realism. Hitherto, the dynamo theory for galaxies has made much use of analogies from the more advanced theory of planetary and stellar dynamos. However, unlike those systems, which are hydrostatically supported by gas pressure, galaxies are dynamically supported, vertically by kinetic pressure and radially by centrifugal forces. We contend that galactic dynamo theory should take greater account of the dynamical processes specific to galaxies. In this paper we give some examples of the interconnections between galactic dynamics and magnetic fields.

2. Dynamo Activity and the Vertical Equilibrium of Interstellar Gas

2.1. Dynamo Action by Fountain Flows

During recent years a view of the interstellar medium has developed where a large fraction of the gas mass is in the form of a diffuse partially ionised intercloud medium with a temperature of 10^4 K, forming a thick disc with an exponential scale-height which is about 1 kpc. Such a thick disc has been detected at least in the Milky Way (Reynolds 1991) and NGC 891 (Rand et al. 1990, Dettmar et al. 1991). Since the thermal scale-height is much smaller than 1 kpc, perhaps the most plausible scenario is that the thick disc is produced and maintained by superbubbles and fountain flows driven by correlated type II supernovae (with some support provided by cosmic-ray pressure and disordered magnetic fields). In this type of picture a galactic wind driven by Alfvén waves and cosmic rays may be expected to set in at some height above the galactic plane (Breitschwerdt et al. 1991).

Because of these large-scale convective motions the parameters of the turbulence thought to be responsible for dynamo action in galaxies need to be reconsidered

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F. Krause et al. (eds.), The Cosmic Dynamo, 333–337.

(cf. Shapiro 1991). According to the simplest mean-field theory the turbulent diffusivity $\eta = u\ell/3$ and the magnitude of the α-effect $\alpha = |B|\ell^2/h$. Here u and ℓ are the amplitude and correlation length of the turbulent velocities, h is the density scale-height, and the local angular velocity of turbulent elements is given by the second Oort parameter $|B|$ (see the discussion of Parker 1971). The strength of the ω-effect is measured by the local shear rate, which we write as $2A$, where A is the first Oort parameter. (For a disc with the rotational velocity V constant with radius r, $A = -B = V/2r$).

The estimates for thick discs will be compared with the thin-disc estimates of Ruzmaikin et al. (1989). The local strengths of the α- and ω-effects are measured by the dimensionless numbers $R_\alpha = \alpha h/\eta$ and $R_\omega = 2Ah^2/\eta$ (considered as functions of radius). The strength of the $\alpha\omega$-effect depends on $R_\alpha R_\omega = 18A|B|h^2/u^2$. Clearly, a thicker disc will increase this number. On the other hand the velocities associated with fountain flows are probably larger than what has been assumed for thin discs. In consequence, the value of $R_\alpha R_\omega$ changes only slightly.

The ratio of the strengths of the α- and the ω-effects is given by $R_\alpha/R_\omega = (|B|/2A)(\ell/h)^2$. Estimating the ratio ℓ/h would require proper modelling of the vertical flows. In a turbulently supported disc it is plausible that it should be close to one. Since the thin-disc models have used $\ell/h = 0.25$, the α-effect will be somewhat enhanced.

2.2. Disc Thickness and Galactic Winds

The influence of fountain flows should be most clearly evident in the vertical structure of the magnetic field. In particular, the strong vertical magnetic field observed far above the disc plane in NGC 4631 poses a problem (Hummel et al. 1991a).

From disc dynamo models the ratio between the vertical and the azimuthal field may be estimated as $B_z/B_\varphi \approx (hR_\alpha/rR_\omega)^{1/2}$ (Ruzmaikin et al. 1989). Thus models with a thicker disc should have a larger vertical field. Here we consider the possibility that the vertical field of NGC 4631 might be due to a very thick disc.

The details of our models are described in Brandenburg et al. (1993). We determine the magnitude of α and η by applying the estimates of the preceding section at one scale-height above the disc plane. For the turbulent velocity we take $u = 40$ km s^{-1}, which is perhaps a typical value at 1 kpc above the disc of the Milky Way (Danly et al. 1992). We consider two models with the scale-heights 1.5 and 3 kpc, corresponding to the ratio of scale-heights of the radio continuum emission in NGC 891 and NGC 4631 (Hummel et al. 1991b). For the thicker disc we also give a model which includes a radial wind. In order to isolate the effect of disc thickness we always use the rotation curve of NGC 891.

The results are shown in Fig. 1. In judging their relevance to observed fields the highly schematic nature of the models should be stressed. Nevertheless, it appears that for NGC 891 the spatial distribution of synchrotron emission and the polarisation indicative of a field mostly parallel to the plane are reasonably well reproduced in our model (a). However, we do not see the signs of a slight flaring of the field at larger radii suggested by the observations.

For NGC 4631 it is not possible to obtain a predominantly vertical polarisation

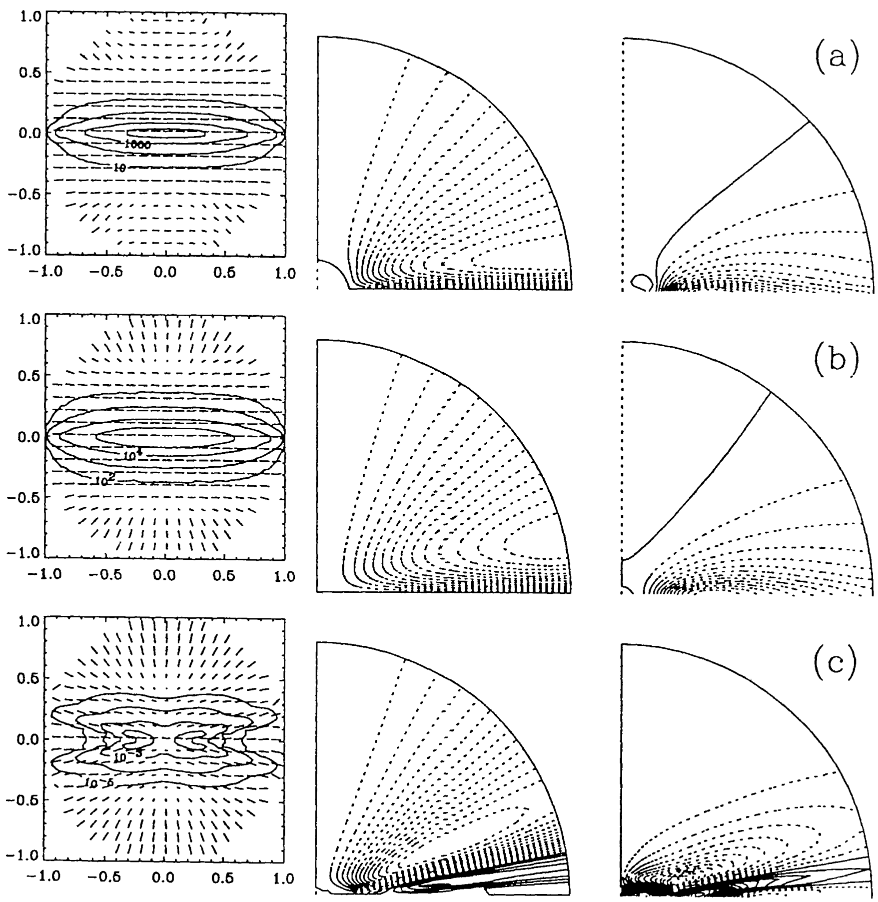

Fig. 1. ***Left column:*** **Distribution of the degree of polarisation (line segments) and total emission (contours) of synchrotron radiation;** ***middle column:*** **poloidal field lines;** ***right column:*** **contours of constant toroidal field.** ***Model (a):*** **$h = 0.1$, no wind;** ***model (b):*** **$h = 0.2$, no wind;** ***model (c):*** **$h = 0.2$, terminal wind speed 200 $\mathrm{km\,s^{-1}}$. Length unit 15 kpc, parameters $C_\Omega = 60/h$ and $\xi = 0.5h$. For definition of the parameters and further details of the model, see Brandenburg et al. (1993).**

at large heights above the plane simply by making the disc thicker. On the other hand, a purely axisymmetric wind can produce a distribution of polarisation similar to that observed by removing the toroidal field component without affecting the field along the wind velocity vector. We note that if our estimate of α is significantly too small, a central dipolar field might be generated by the α^2 mechanism as in the models of Donner & Brandenburg (1990). However, since this effect should be confined to the central, rigidly rotating part of the galaxy it is doubtful whether it can be consistent with the large observed radio continuum size of NGC 4631.

Thus the dynamo models suggest that the magnetic field of NGC 891 can essentially be explained by dynamo action in a thick disc, whereas in NGC 4631 a galactic wind plays a crucial rôle. This conclusion is in agreement with evidence from Hα emission (Rand et al. 1992) and spectral index variations (Hummel et al. 1991b) showing a stronger influence of a wind in NGC 4631. Further models and several other turbulent effects are discussed by Brandenburg et al. (1992, 1993).

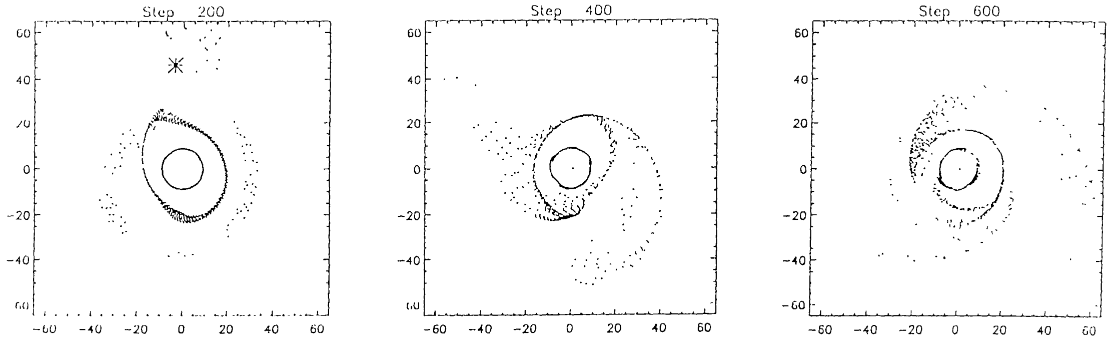

Fig. 2. Displacements of particles from the initial radii 5, 10, 15 kpc for a tidal model of M 81. The present epoch is at time-step 600, corresponding to 400 Myr.

3. Spiral Structure and Magnetic Fields

3.1. Field Distortion by Transient Spiral Arms

The streaming motions associated with transient spiral arms will tend to carry along a weak magnetic field. In particular, tidal perturbations may be expected to induce global distortions of the field. An especially interesting example is M 81, which shows signs of interactions, since it also represents the best observational case for a bisymmetric spiral field (Krause et al. 1989).

Thomasson & Donner (1993) have recently presented a model where the spiral pattern of M 81 was generated by an interaction with its companion NGC 3077. To the extent that the magnetic field can be treated as frozen into the gas, the effect of this tidal perturbation on the field is reflected in the displacements of particles. In Fig. 2 the distortion of rings of particles at several radii is shown. In the region where the signatures of a bisymmetric spiral field have been detected (6–12 kpc) the distortion of a ring is large and unsymmetric. At larger radii the ring is completely disrupted, and at smaller radii the distortion is small and symmetric.

The basic conclusion from the particle simulations presented here is that a strong tidal effect on the field is predicted in the relevant radial interval. The results of a dynamo calculation incorporating a simplified representation of the velocity field from this model are given in Moss et al. (1993), but a proper confrontation with observations would require a full gas dynamic simulation.

It is worth pointing out another consequence of gas motions in transient spiral arms. From Fig. 2 it is evident that the particle rings are drawn out into tails in the arms (the effect is more clearly seen in Toomre 1981). Along lines of sight cutting through these tails the magnetic field would exhibit reversals. This effect may be of importance in interpreting the field reversals in the Milky Way. For another possible cause of reversals, see Brandenburg et al. (1993).

3.2. Wave Generation by Non-axisymmetric Magnetic Fields

A magnetic field with $m = 1$ symmetry will produce a Lorentz force with a $m = 2$ component. This force will give rise to a steady density wave in the gas at Lindblad resonances and an evolving spiral pattern at corotation resonances (Goldreich & Tremaine 1979, Donner 1979).

For a tightly wrapped magnetic field with wave number K the Lorentz force is almost radial and its $m = 2$ component has the amplitude $F_r = KB_\varphi^2/8\pi$. The square of the amplitude of the relative density perturbation in the wave emitted at a Lindblad resonance is given by $\Delta^2 = (\pi k/c^2\mathcal{D})\,(F_r/\rho)^2$, where k is the wave number, c the speed of sound, ρ the gas density and $\mathcal{D}$ is determined by the rotation curve and the pattern speed of the field. For an inner Lindblad resonance and a constant velocity rotation curve we obtain approximately $\Delta = 1.5\,(kr)^{1/2}(Kr)\,(b_\varphi^2/8\pi)\,/\,(\rho cV)$.

We apply this to M 81 assuming that the magnetic field represents a steady $m = 1$ mode with an inner Lindblad resonance near 4 kpc. The ordered field strength is about $4\,\mu$G (Krause et al. 1989). The wave numbers are obtained from the pitch angles of the field and the spiral pattern. For H I the pitch angle is 15° (Rots 1975); we take the same value for the magnetic field. With $c = 10\ \mathrm{km\,s^{-1}}$ and $\rho = 1\ \mathrm{atom\,cm^{-3}}$ we find $\Delta \approx 0.4$. Since this estimate is quite sensitive to several uncertain parameters, it is not clear whether it is consistent with the observed spiral pattern of M 81. However, the effect is potentially important in putting limits on large-scale non-axisymmetric magnetic fields in spiral galaxies.

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