TOWARDS THE MAGNETIC FIELD OF M81

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Abstract. We present calculations showing how both transient effects associated with nonaxisymmetric seed fields, and an interaction with a companion, can produce BSS type magnetic structure in a spiral galaxy.

Key words: Spiral Galaxies – M81 – Magnetic Fields

1. Introduction

An outstanding problem of galactic dynamo theory is to explain the bisymmetric spiral (BSS) magnetic field that is observed in the spiral galaxy M81. Such a field corresponds to a dominant azimuthal dependence $e^{im\phi}$ with $m = 1$, where ϕ is the azimuthal angle. Linear mean field theory with isotropic alpha tensor predicts that axisymmetric modes ($m = 0$) will be excited more readily than nonaxisymmetric, although the difference in excitation conditions decreases as the ratio of disc thickness to radius becomes small (Ruzmaikin et al. 1988, Moss & Brandenburg 1992).

A number of mechanisms may play a role in producing the observed field geometry. For example, growth times for galactic dynamos are not very short compared to galactic lifetimes, and the observed approximate equipartition between turbulent kinetic and magnetic energy densities in galaxies suggests that galactic dynamos are at least mildly nonlinear. Thus transient effects, associated with growth to saturation from small seed fields, may be important, and the eventually stable field configurations may not be those currently observed.

Further, M81 belongs to a group of galaxies, and may have been perturbed by the other group members. Recently Thomasson & Donner (1992) have proposed a model where the spiral structure of M81 is caused by a tidal interaction with the companion galaxy NGC3077. In this model large scale nonaxisymmetric velocities are produced, which could assist nonaxisymmetric field generation.

In this paper we focus attention on these two possibilities. Other mechanisms may also be important: for example Rüdiger & Elstner (1992) predict that plausible anisotropies in the alpha tensor will favour nonaxisymmetric field generation, but we will not discuss such alternatives further here. A more detailed discussion from a slightly different viewpoint is given in Moss et al. (1993).

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2. The Model

We consider a thick disc mean field galactic model, in which the turbulent coefficients α and η (turbulent magnetic diffusivity) are functions of distance from the galactic plane, and solve the mean field dynamo equation

$$\partial \mathbf{B}/\partial t = \nabla \times (\mathbf{u} \times \mathbf{B} + \alpha \mathbf{B} - \eta \nabla \times \mathbf{B}) \tag{1}$$

in a sphere of radius R. We use

$$\alpha = \frac{\alpha_0 z}{1 + \alpha_B \mathbf{B}^2} \left(1 + \alpha_1 - 2\alpha_1 e^{-(z/d)^2}\right), \tag{2}$$

introducing a simple 'alpha-quenching' nonlinearity, and

$$\eta = \eta_0 \left(1 - \eta_1 e^{-(z/d)^2}\right), \tag{3}$$

where $z = r\cos\theta$ (r, θ, ϕ are spherical polar coordinates) and α_1, η_1 are constants. We take $\eta_1 > 0$, ie the diffusivity in the disc is smaller than in the halo, and η_0 is the value of η high in the halo. C_α is defined as $\alpha_0 R/\eta_0$. For the axisymmetric azimuthal velocity we adopt a modification of the rotation law given by Rohlfs & Kreitschmann (1980), omitting the inner peak for numerical reasons. See Moss et al. (1993) for further details.

3. Interaction with a Companion

From the two dimensional model of the encounter of NGC3077 with M81 proposed by Thomasson & Donner (1992) we calculated the smoothed velocity components $u_r(r,\phi)$, $u_\phi(r,\phi)$. We then somewhat arbitrarily extended these velocities to $|z| > 0$ by writing

$$u_{rm}(r,\theta) = u_{rm}(r,\pi/2)\sin\theta; \quad u_{\phi m}(r,\theta) = u_{\phi m}(r,\pi/2)\sin^2\theta, \tag{4}$$

where $u_{rm}(r,\pi/2)$, $u_{\phi m}(r,\pi/2)$ are the parts of the Thomasson & Donner velocities with sin/cos mϕ dependence. We neglected the time dependence of the velocity field. Typical non-circular velocities are of order tens of km/sec. We always used the Rohlfs & Kreitschmann values for the circular (axisymmetric) component, although this differs slightly from the rotation curve used by Thomasson & Donner, in order to facilitate comparison with our other computations.

To isolate the effects of the interaction, we first took a pre-existing stable S0 solution of (1) and 'switched on' the velocities (4) (remembering that the system may not have had enough time to reach such a state.) We ignored any alpha-effect in the nonaxisymmetric parts of the dynamo equation, and so the $m > 0$ field is purely the kinematic effect of the nonaxisymmetric parts of the velocities (4). Our 'standard' physical parameters were $\eta_0 = 5 \times 10^{27}\mathrm{cm}^2\mathrm{sec}^{-1}$, $R = 15\,\mathrm{kpc}$, and $\alpha_1 = -1$, $\eta_1 = 0.95$, $d = 0.2$. Thus in the disc plane $\eta = 2.5 \times 10^{26}\mathrm{cm}^2\mathrm{sec}^{-1}$, and the alpha effect vanished in the far halo. The unit of time τ is R^2/η_0, which is thus approximately 1.3×10^{10} years. $M = E_{\mathrm{nax}}/(E_{\mathrm{ax}} + E_{\mathrm{nax}})$ is the ratio of the energies in the part of the field with $m > 0$ to the total energy.

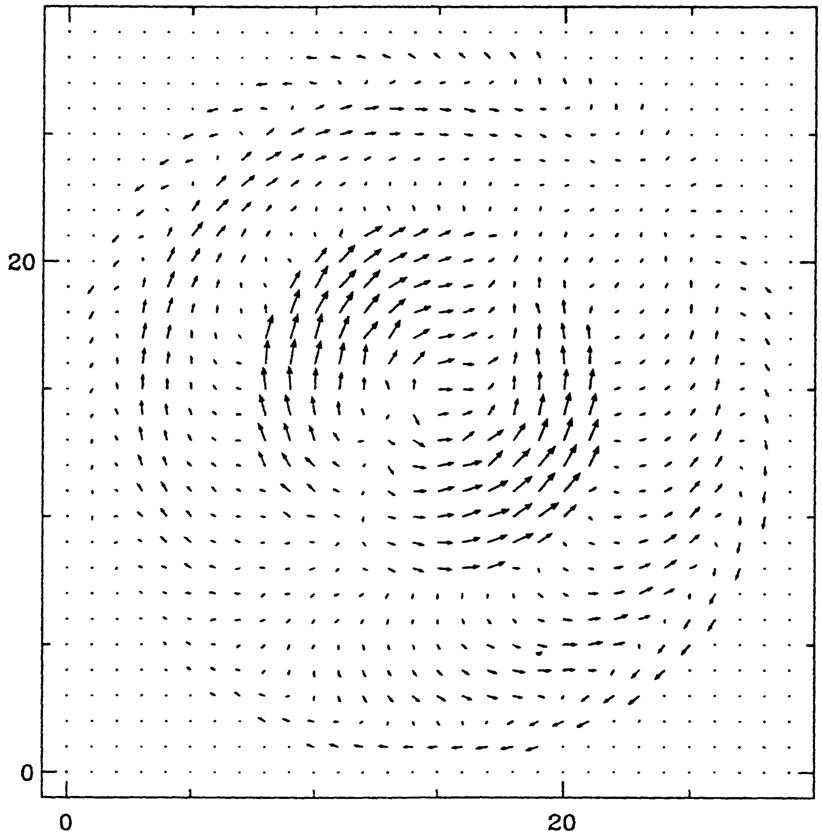

Fig. 1. Field vectors in the plane $z = 0$ for the interaction model of Section 3

The nonaxisymmetric field grows rapidly until $M \approx 0.09$. This figure is quite insensitive to modest changes in the model, such as taking $\eta_0 = 2 \times 10^{27}\mathrm{cm}^2\mathrm{sec}^{-1}$, $\eta_1 = 0.95$, or $\eta_0 = 5 \times 10^{27}\mathrm{cm}^2\mathrm{sec}^{-1}$, $\eta_1 = 0.98$, so that $\eta = 10^{26}\mathrm{cm}^2\mathrm{sec}^{-1}$ in the disc. A vector plot of the field in the plane $z = 0$ is given in Fig. 1.

4. Transient Effects

We now discuss solutions of the full mean field dynamo equation (1), without imposed nonaxisymmetric velocities, starting from an arbitrary seed field. This seed contained a mixture of A0, S0, A1 and S1 parts. E_0 is the total initial energy in approximate units of the equipartition energy, and q is the value of $E_{\mathrm{nax}}/E_{\mathrm{ax}}$ at $\tau = 0$. P is $(E^{(\mathrm{S})} - E^{(\mathrm{A})})/(E^{(\mathrm{S})} + E^{(\mathrm{A})})$, where $E^{(\mathrm{S})}$ and $E^{(\mathrm{A})}$ are the energies in the parts of the field symmetric and antisymmetric respectively with respect to the plane $z = 0$. The evolution of the solution with the standard parameters and $E_0 = 10^{-12}$, $q = 10^4$, $C_\alpha = 40$ is shown in Fig. 2.

Saturation has occurred by $\tau \approx 0.6$, and a significant nonaxisymmetric field survives until $\tau \approx 0.9$. The eventual field geometry is S0, but for $0.6 < \tau < 1.1$ the axisymmetric field is predominantly of A0 type. This is a quite robust feature of our models. Increasing E_0 to 10^{-6} hastens the transition to $M = 0$ (see Fig. 3a),

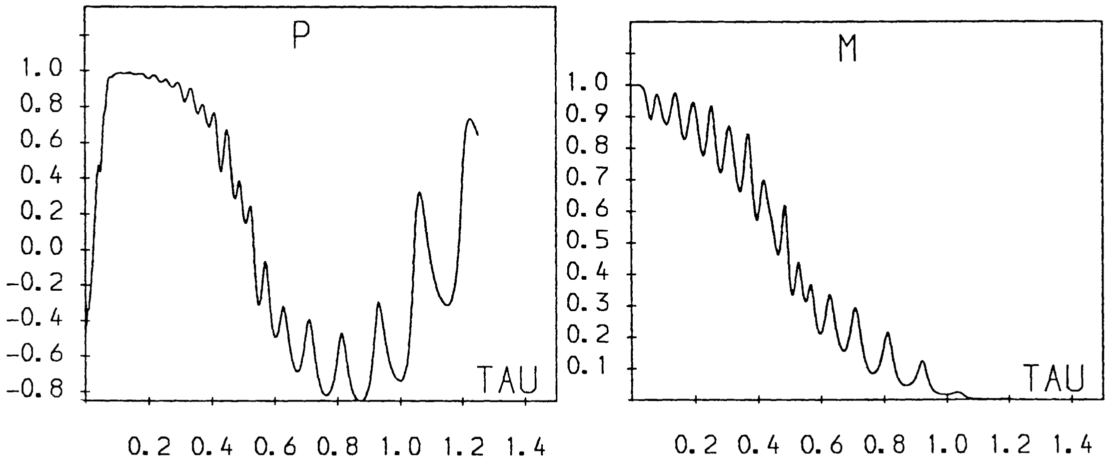

Fig. 2. $P(\tau)$ and $M(\tau)$ for the 'standard' parameters described in Section 2 and $C_\alpha = 40$, $E_0 = 10^{-12}$, $q = 10^4$

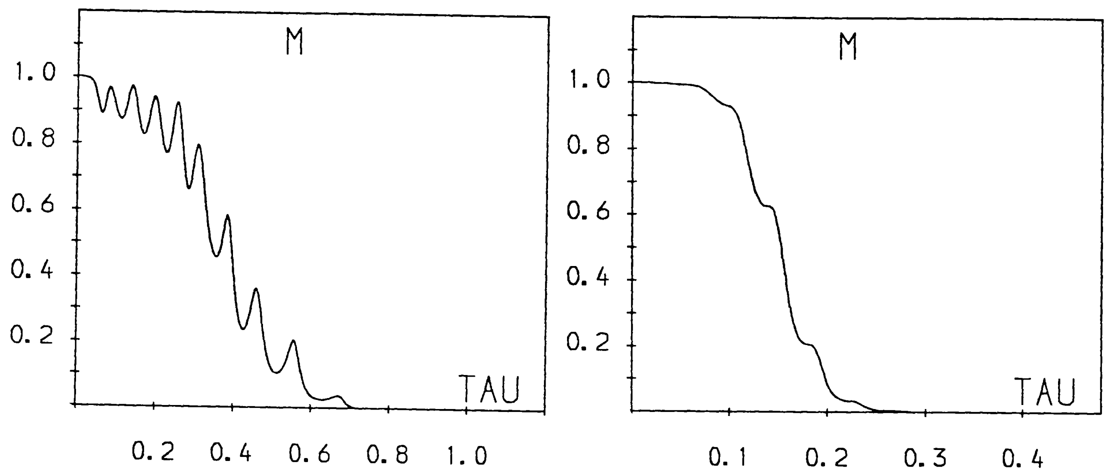

Fig. 3. $M(\tau)$ for the same parameters as Fig. 2 except: a) $E_0 = 10^{-6}$, b) $d = 0.4$, $C_\alpha = 15$

as does increasing C_α for given E_0. In comparison, for $C_\alpha = 30$, saturation occurs at $\tau \approx 0.9$ and $M > 0.1$ until $\tau > 1.2$. The influence of disc thickness is illustrated in Fig. 3b, which is for a calculation with $d = 0.4$. The transition to $M = 0$ is now rapid and occurs before saturation of the dynamo.

Returning to the calculation shown in Fig. 2, we note that for $\tau = O(1)$ the $m > 0$ field is concentrated in $r > 0.8R$. The structure of the field in the outer regions of the disc has considerably steeper gradients than, for example, a simple sine wave. This feature may be connected with nonlinear effects, as discussed in Poezd et al. (1992). In Fig. 4 we plot B_ϕ against ϕ at $r = 0.98R$ at $\tau = 1.15$. Here we have used our standard set of parameters except that $C_\alpha = 30$.

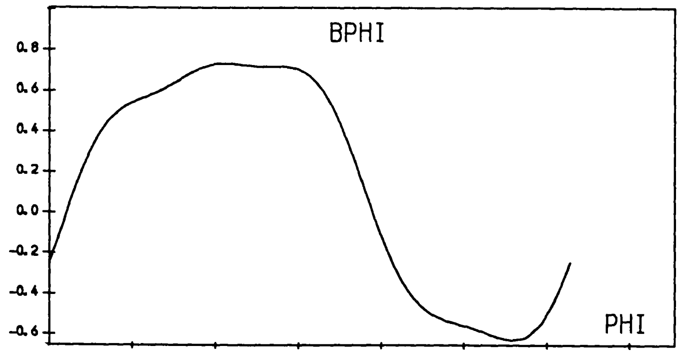

Fig. 4. B_ϕ as a function of ϕ on the range $(0,2\pi)$ for a model with the same parameters as in Fig. 2, except that $C_\alpha = 30$, at $r = 0.98\,R$, $\tau = 1.15$

5. Conclusions

We have discussed two effects that may separately contribute to BSS structure in galaxies such as M81. A more realistic model would include both these and perhaps others (eg nonaxisymmetric α and η, anisotropic α). For example, in a calculation similar to that shown in Fig. 2, but including the nonaxisymmetric velocities introduced in Section 3, the solution was similar to that shown in Fig. 2 until $M \approx 0.15$, when the effect of the interaction became important. The solution then retained a significant nonaxisymmetric part at large τ, with $M \approx 0.11$. Thinner (and thus more realistic) discs may further enhance nonaxisymmetric structure.

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