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Galactic spiral patterns and dynamo action

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Abstract. The theory of mean-field galactic dynamos is generalized by allowing for a finite response time of the mean electromotive force (emf) to variations in the mean magnetic field and small-scale turbulence. A non-axisymmetric forcing of the dynamo by a spiral pattern (either stationary or transient) is invoked. The resulting magnetic spiral arms are phase-shifted from the spiral arms of the pattern by an angle $15° - 40°$, opposite to the sense of galactic rotation. Our findings may help to explain the phase shift between material and magnetic arms observed in NGC 6946 and other galaxies.

Keywords. magnetic fields – MHD – galaxies: magnetic fields – galaxies: spiral

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The large-scale (or mean or regular) magnetic field in spiral galaxies, traced by polarized radio emission and Faraday rotation, is typically concentrated in magnetic spiral arms akin to the familiar material spiral arms. Magnetic arms may trace the material arms or be phase-shifted images of them, lagging them in the sense of the galactic rotation. The magnitude of the phase shift is $\sim 40°$ in NGC 6946 (Frick *et al.* 2000).

The telegraph equation for the mean magnetic field (Blackman & Field 2002; Chamandy, Subramanian & Shukurov 2012a), neglecting Ohmic terms, is given by

$$\tau \frac{\partial^2 \overline{\boldsymbol{B}}}{\partial t^2} + \frac{\partial \overline{\boldsymbol{B}}}{\partial t} = \boldsymbol{\nabla} \times \left(\overline{\boldsymbol{U}} \times \overline{\boldsymbol{B}} + \alpha \overline{\boldsymbol{B}}\right) + \eta_{\mathrm{t}} \nabla^2 \overline{\boldsymbol{B}} + \tau \boldsymbol{\nabla} \times \left(\overline{\boldsymbol{U}} \times \frac{\partial \overline{\boldsymbol{B}}}{\partial t}\right), \tag{0.1}$$

where $\boldsymbol{U}$ and $\boldsymbol{B}$ are, respectively, the velocity and magnetic fields, and an overbar represents a volume average over scales larger than the turbulence but smaller than the system. Here α and η_{t} are turbulent transport coefficients, and τ is the characteristic response time of the mean emf to changes in the mean magnetic field and small-scale turbulence. It is estimated that $\tau \approx \tau_{\mathrm{c}}$, the correlation time of the turbulence (Brandenburg & Subramanian 2005). Eq. (0.1) reduces to the standard mean-field dynamo equation in the limit $\tau \to 0$. To model the nonlinear dynamo regime, when the energy of the magnetic field approaches equipartition with the turbulence, α is approximated as the sum of kinetic and magnetic parts $\alpha_{\mathrm{k}} + \alpha_{\mathrm{m}}$ (Pouquet, Frisch & Leorat 1976), with α_{m} governed by an evolution equation deriving from magnetic helicity balance (Shukurov *et al.* 2006). The equations are solved numerically, and in some cases, semi-analytically (Chamandy, Subramanian & Shukurov 2012b), using the thin-disk and no-z approximations (Subramanian & Mestel 1993). Non-axisymmetric forcing of the dynamo is implemented by modulating α_{k} along a spiral, presumably (but not necessarily) co-spatial with the material spiral (Mestel & Subramanian 1991).

For an α-spiral with n arms, the mean magnetic field azimuthal modes $m = kn$, with $k = 1, 2, 3, ...$, are enslaved to (grow along with) the dominant axisymmetric mode $m = 0$, outcompeting other non-axisymmetric modes as they do so. The $m = n$ mode has the highest amplitude among $m \neq 0$ modes. Enslaved modes resulting from forcing by a steady rigidly rotating α-spiral are stationary, corotate with the material spiral, and are

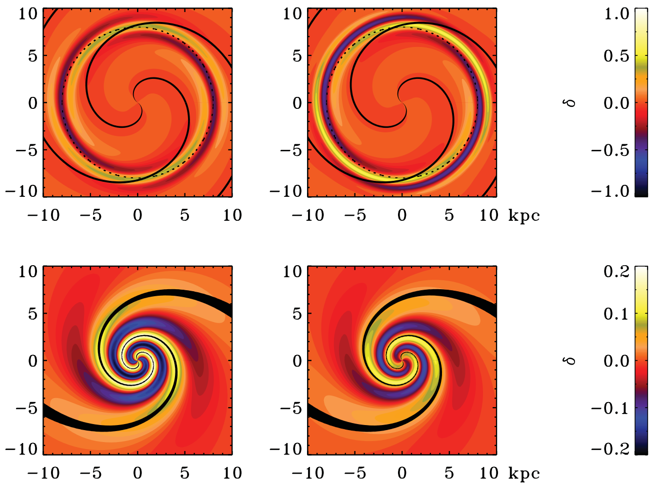

Figure 1. Ratio δ of non-axisymmetric to axisymmetric part of the azimuthal component of $\overline{\boldsymbol{B}}$, for steady (top) and transient (bottom) spirals, and for $\tau \to 0$ (left) and $\tau = \tau_{\rm c}$ (right). The maximum of $\alpha_{\rm k}$ is shown as a black line, while $r_{\rm cor}$ is shown as a dotted circle in top panels.

strongly peaked about the corotation radius $r_{\rm cor}$. This results in magnetic arms that are more tightly wound than the α-arms, as seen in Fig. 1 (top). The τ effect enhances the magnetic arms, and gives them a negative (in the sense of the rotation) phase shift (of up to $-40°$) with respect to the α-arms. Asymptotic (semi-analytical) as well as numerical solutions reveal a phase shift $\approx -(1-2)\Omega\tau$, which is quite natural: by the time the dynamo responds to the enhancement of α along the spiral arm, the latter has already rotated by an angle $\approx \Omega\tau$.

Galactic spirals may be transient and effectively winding up (e.g. Quillen *et al.* 2011). Therefore, the opposite extreme to steady rigidly rotating patterns is also explored: α-spirals that wind up with the differentially rotating gas. In effect, every radius then becomes a corotation radius, which is near to the radius at which non-axisymmetric modes are peaked in the rigidly rotating case. Indeed, strong non-axisymmetric modes extending over ≈ 10 kpc in radius and lasting for a few hundred Myr are found. Magnetic arms trace α-arms for $\tau \to 0$ and are phase-shifted from them by $\approx -(15° - 25°)$ for $\tau = \tau_{\rm c}$. This can be seen in Fig. 1 (bottom), which shows snapshots of the magnetic arms at 73 Myr after the sudden onset of an $\alpha_{\rm k}$ 'bar'. This model is thus able to account for certain features of magnetic arms observed in nearby spiral galaxies.

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