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Magnetic fields and spiral structure of galaxies

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Abstract

We discuss the relation between spiral arms and magnetic arms in galaxies. Consequences of different properties of the ISM in arms and interarms for the dynamo induced magnetic field are illuminated. By means of kinematic global MHD simulations the role of gravitational induced time dependent spiral flows on the induction process is investigated.

1 Introduction

Observations of polarized radio emission show large scale magnetic fields in nearby spiral galaxies. The large scale fields are mainly axisymmetric with modifications corresponding to the optical spiral structure. The symmetry with respect to the equator appears symmetric. The field strength is nearly in equipartition with the turbulence in the ISM. All these properties can be well explained with models for turbulent mean field dynamos (Beck et al. 1996). In a first approximation most of the models assumed a simple axisymmetric rotation for the mean flow and axisymmetric turbulence coefficients α and η. With this simplifying assumptions one could explain the first occurrence of axisymmetric magnetic fields with equatorial symmetry. Under reasonable assumptions for the α-effect and the turbulent diffusivity the resulting dynamo modes have a growth time of about 0.1 to 1 Gyr. This time can be much smaller for models with additional flows like galactic fountains (cf. Elstner et al. 1995). It seems that more complicated mean flows can seriously change the dynamo properties, similar to the meridional flow driven solar dynamo models. The most obviously deviation in spiral galaxies are flows induced by the spiral structure. Here we find a huge variety of different realizations like strong bars, strong and weak density varying spirals and more small scale variations in the flocculent galaxies. In grand design spirals or bars we see a strong correlation between magnetic field structure and the optical spiral arms up to the details of the shape of the arms. In several galaxies a phase shift between optical and magnetic arms is observed. The explanation of these essentially non-axisymmetric properties demands fully three dimensional models with more realistic mean flows and possible variations of the turbulence properties in arms and interarms.

2 The pitch angle problem

Let us first consider the constraints on dynamo models for the realization of the observed pitch angle for the magnetic field. The observed values range from 10° to 40°. The evolution of the large scale magnetic field is described by the induction equation

$$\frac{\partial \bar{\mathbf{B}}}{\partial t} = \mathrm{rot}\ (\bar{\mathbf{u}} \times \bar{\mathbf{B}} + \alpha \bar{\mathbf{B}} - \eta_T \,\mathrm{rot}\, \bar{\mathbf{B}}). \tag{1}$$

Defining the dynamo numbers

$$C_\alpha = \frac{\alpha H}{\eta_T}$$

and

$$C_\Omega = \frac{\Omega H^2}{\eta_T} = \frac{u_\varphi H^2}{r_\Omega \eta_T}$$

with disk height H, outer rotation velocity u_φ and turnover radius r_Ω one can estimate the pitch angle p by

$$\tan p \approx \sqrt{\frac{C_\alpha}{C_\Omega}} \quad \widehat{=} \quad 10^\circ - 30^\circ.$$

Here we assumed $u_\varphi = 200$ km s^{-1}, r$_\Omega = 3$ kpc and $\alpha = 1$ - 10 km s^{-1}. But it is very unlikely to have the unquenched α in the final regime. For the critical dynamo number $D_{crit} \approx 10$ the estimation reduces to

$$\tan p \approx \frac{\sqrt{D_{crit}}}{C_\Omega} = \frac{3 r_\Omega \eta_T}{u_\varphi H^2},$$

which leads only to 10° for a turbulent diffusivity of 1 kpc km s^{-1}.

The situation becomes even worse when the turnover radius has a much smaller value. To achieve these high values for the turbulent diffusivity one has to consider the collective action of supernovae explosions in superbubbles. For single explosions the values for $\eta_T = 0.01 - 0.1$ kpc km s^{-1} are to small (cf. Ferrière 1998 and Ziegler 1996).

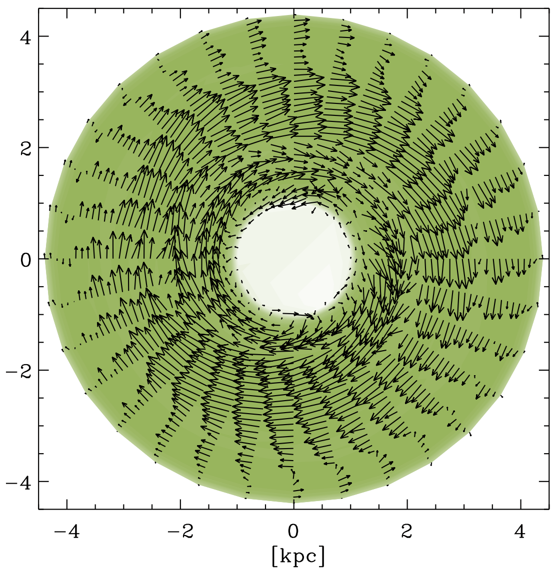

Figure 1: Large scale magnetic field in the midplane at the final state of a global simulation with magneto-rotational instability.

Maintaining turbulence by the magneto-rotational instability does not improve the situation (Dziourkevitch et al. 2004). Global simulations resulted in the saturated regime (no further growth of the magnetic field) with a rather small pitch angle of about 1° (see Fig. 1).

The strong diffusion of cosmic rays may provide a fast enough diffusion process. Supernovae explosions as source for the cosmic rays together with the Parker instability could give a dynamo process with the desired properties (Hanasz et al. 2004).

3 Interarm fields

One basic field property is a concentration of the large scale magnetic field between the optical arms as it is well studied for NGC6946 (Beck and Hoernes 1996). It finds a natural explanation within the dynamo models due to different properties of the ISM in arms and interarms. If we agree with a supernovae driven turbulence, a stronger action should be seen in the arms. The turbulence coefficients entering the induction equation are determined by two independent parameters the turbulence velocity and the correlation time. The turbulence diffusivity is given by

$$\eta_T = \tau u'^2$$

and α can be written as

$$\alpha = \tau^2 \Omega u'^2 C_{strat} H^{-1},$$

where C_{strat} is a measure for the stratification of density or turbulence velocity. For an $\alpha\Omega$-dynamo the dynamo number

$$D = C_\alpha C_\Omega = \frac{\Omega H^2 C_{strat}}{u'^2}$$

is a reasonable measure for the dynamo activity. Here we see that a large turbulence velocity would lead to a smaller dynamo number. On the first glance one could expect a weaker field in the more active spiral arms. Notice also that the dynamo number in that regime is only dependent on the turbulence velocity. But the situation changes if we consider the $\alpha^2\Omega$ regime, where the α effect also contributes to the toroidal field generation. Here we can describe the dynamo effectivity better by

$$D = C_\alpha C_\Omega - C_\alpha^2 = \frac{\Omega H^2 C_{strat}}{u'^2} - \tau^2 \Omega^2 C_{strat}^2$$

This leads to the situation that *only* a variation of the correlation time results inherently in a change of the dynamo number. For galaxies we should have the case with a dominating $C_\alpha C_\Omega$ term but not negligible C_α^2 term. Otherwise the pitch angle would be to small. More star formation activity in more dense arms increases not necessarily the turbulence velocity. But the occurrence of collective supernovae explosions in superbubbles should be raised in the arm regions. That translates into a larger correlation time or length. For the dynamo it results in a smaller dynamo number in the arms (the $\alpha\Omega$ term is reduced by the α^2 term). Indeed observations of turbulence velocity in NGC6946 do not show any difference between arms and interarms.

The numerical solution of the induction equation in Rohde et al. (1999) confirm this result. In this phenomenological model the turbulence velocity stratification was calculated from a density stratification in analogy to our galaxy. The correlation time remaines as the only free parameter in the model. It is varied by a factor 2−3 in a form of a logarithmic

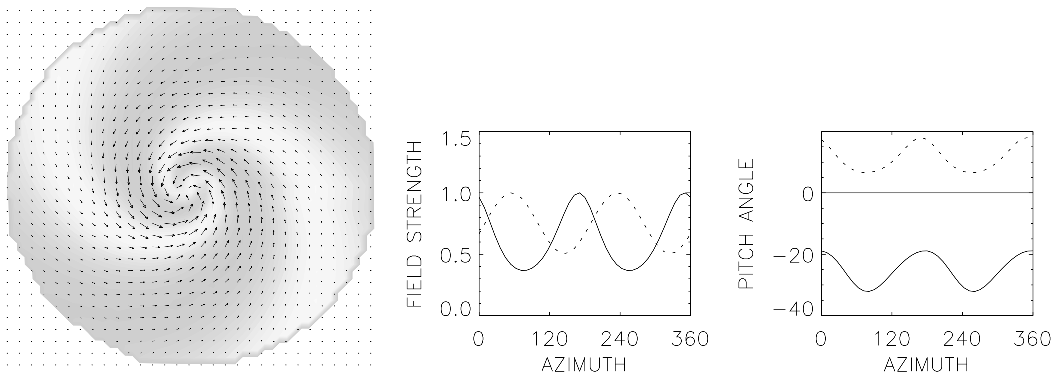

Figure 2: LEFT: Magnetic field geometry in the galactic mid-plane for an azimuthal variation of $\tau_{\rm corr} = 0.01 \ldots 0.02$ Gyr. The optical spiral arms (enlarged $\tau_{\rm corr}$) are shown by light shades. MIDDLE: $\bar{\mathbf{B}}^4$, where $\bar{\mathbf{B}}$ is the normalized regular magnetic field strength (solid) compared with the profile in correlation time (dotted, also normalized). RIGHT: The field shows a concentration between the gaseous spiral arms. We show $\bar{\mathbf{B}}^4$ to allow a comparison with the polarized intensity. Magnetic pitch angle (solid) compared with the normalized magnetic field strength (dotted). The absolute value of the magnetic pitch angle is largest between the "magnetic arms", i.e. in the gaseous (optical) arms. Both plots are given for the galactic mid-plane at $r = 6$ kpc.

spiral. The resulting variation of the field strength for the mean magnetic field turns out to be consistent with the observations.

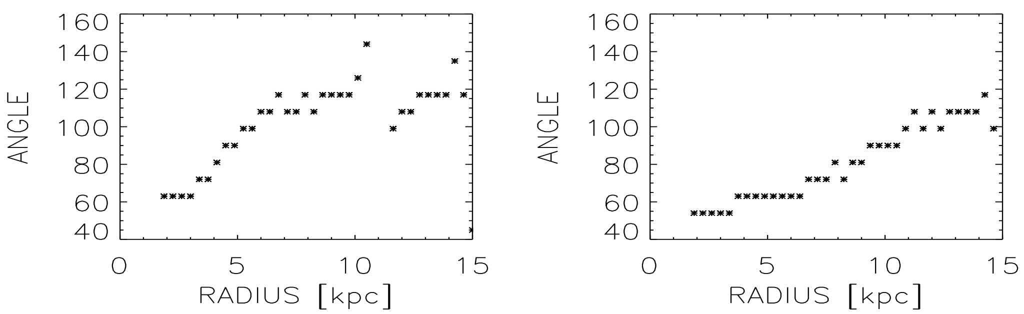

Figure 3: Shift of the magnetic field maximum to the preceding spiral arm for a corotation radius 5kpc (LEFT) and 10kpc (RIGHT).

Another interesting result of this model is a possible determination of the corotation radius for the spiral pattern. Inside the corotation radius the magnetic field maximum is slightly shifted in direction to the preceding spiral arm and vice versa outside. This is illustrated in Fig. 3.

4 2D density wave flows

Let us now consider more complex mean flows (cf. Rohde et al. 1998). First we add to the mean rotation described by a Brandt law

$$v_\varphi = r\Omega = r\Omega_0 \left(1 + \left(\frac{r}{r_\Omega}\right)^2\right)^{-1/2}. \tag{2}$$

radial and azimuthal velocity disturbances due to density waves,

$$\begin{aligned} u_r &= \chi u_0 \cos\left(m_\mathrm{p}(\varphi - \Omega_\mathrm{p} t) + K\tfrac{r}{R_\mathrm{max}}\right) f(r) \\ u_\varphi &= u_0 \sin\left(m_\mathrm{p}(\varphi - \Omega_\mathrm{p} t) + K\tfrac{r}{R_\mathrm{max}}\right) f(r) \end{aligned} \tag{3}$$

with $m_\mathrm{p} = 1, 2$ for a one and two-armed spiral galaxy, respectively. The frequency Ω_p gives the drift of the spiral pattern and K its radial wave number. Density wave theory predicts $\chi = -2\Omega/K^2(\Omega_\mathrm{p} - m\Omega)$. In order to avoid boundary effects the function $f(r)$ reduces the flow to zero at the radial boundaries. The parameters for the nonlinear model are set to $v_\varphi = 180$ km s^{-1}, $u_0 = 20$ km s^{-1}, $C_\Omega = 41.85$ and $C_\alpha = 4.65$.

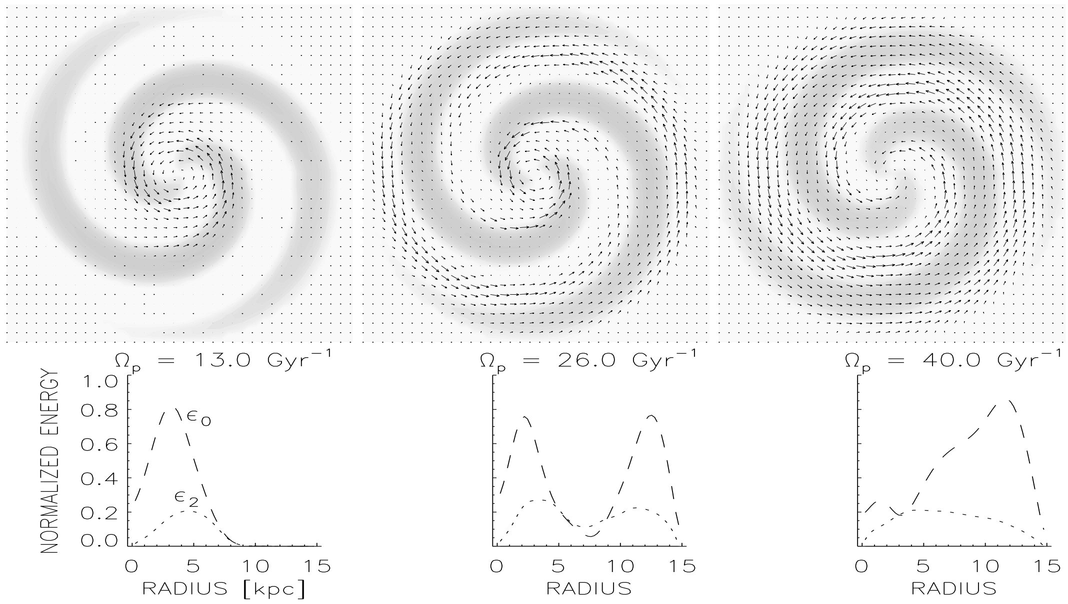

Figure 4: Magnetic field in the equatorial plane of a *two-armed* spiral galaxy model for different pattern velocity $\Omega_\mathrm{p} = 13$ (LEFT), 26 (MIDDLE) and 40 (RIGHT) Gyr^{-1}. Regions with radial velocity directed inwards (spiral arms) are shown in grey scale.

It turns out that these flows make the dynamo action more difficult. The flow pattern rotates with a velocity Ω_p. The solutions for three different pattern velocities corresponding to corotation radii 10 kpc, 5 kpc and 3 kpc are shown in Fig. 4. The radial energy distribution for the m=0−2 modes are plotted below the fields. Especially at the corotation radius the field is suppressed. For $\Omega_p = 26\ \mathrm{Gyr}^{-1}$ a resonance for the m=2 mode occurs. Therefore the largest fraction of magnetic energy for the m=2 mode was found in this model. The field has its maximum at the inner edge of the spiral arm.

5 3D mean flows

Here we take the mean flow for the gas from a sticky particle simulation (Elstner et al. 2000). We follow the magnetic field evolution in 3D time dependent gas flow driven by the gravitational force. We consider a spiral model and a bar forming galaxy. The setup for the two models differs by a more massive disk and a weaker bulge component for the bar forming galaxy.

5.1 A spiral model

It turns out that the 3D gas flow in this model is unable to amplify the magnetic field significantly without any turbulent dynamo. Assuming a uniform turbulence in arms and interam regions the magnetic field is concentrated in the spiral arms. It is well aligned with the arms. The field is smoothly distributed without any reversals for that calculation with a turbulent diffusivity of 1 kpc km s^{-1} (Fig. 5 D). Varying the turbulence diffusivity with the spiral structure in analogy to the model presented in section 3, we got only a slight shift of the fields but no clear interarm fields (Fig. 5 B).

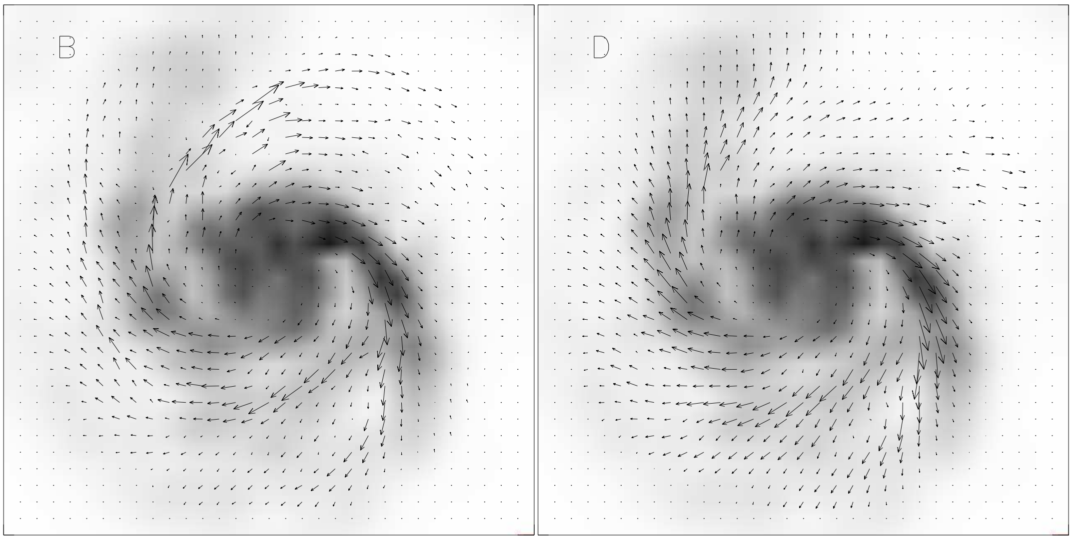

Figure 5: Magnetic field in the equatorial plane and density in grey scale

Increasing the diffusivity, the inductive effect of the flow is reduced and we get a nice interarm magnetic field with a structure reasonable coupled to the density spirals. For a lower diffusivity the growing radial outflow downstream the spiral arms induces a radial magnetic field with the same sign as the azimuthal field in contrast to the inductive process of the galactic differential rotation, where azimuthal and radial field have opposite signs. This leads to local field reversals. After some time these structures disappear by diffusion. The situation in that model is typical for a stationary density wave flow. Computations with a reduced turbulent diffusivity of 0.1 kpc km s^{-1} do not show a noticeable reduction of the pitch angle, as it would occur in models with differential rotation only.

5.2 A bar model

The bar galaxy has a different behaviour of the magnetic field spirals (cf. Otmianowska-Mazur et al. 2002). Here magnetic arms are build up with the optical ones but remain slightly behind the optical arms with further evolution in time. Therefore temporarily interarm magnetic fields are found without any modification of turbulence with the spiral structure. Again a reduction of the diffusivity gives sharper structures but no essential change of the pitch angle. Magnetic fields follow mainly the spiral shape. Without any α-effect an amplification of the field over the whole simulation time scale of about 1 Gyr occurred for a diffusivity of 0.1 kpc km s^{-1}. Because of the large vertical diffusion time of 10 Gyr, we can not decide if the field amplification is due to a dynamo maintained by the flow which is driven only by gravitation. However, a test with the vertical component of the flow set to zero gave only a decay of the field.

6 Conclusions and discussion

The main results of the numerical models are:

- Correlation of magnetic arms with optical spiral arms is mainly achieved by the flow and to some extent also by the dependence of turbulence on the spiral structure.
- In spiral galaxies magnetic arms induced by a density wave flow coincide with the optical arms. The pitch angle of the magnetic field within the arms is similar to the arms independently of the diffusivity. The interarm regions have weaker magnetic fields and sometimes negative pitch angles and reversals in contradiction to the observations.
- The magnetic fields in interarms could only be found with spiral dependent turbulence. But the pitch angle of the field is determined by the diffusivity only.
- For long living spiral pattern the shift of magnetic arm to optical arms could be used as a tracer for the pattern velocity.
- The shear of the non-axisymmetric flow is more effective in barred galaxies. Interarm fields are a common phenomenon in galaxies with a bar in contrary to spirals.

The explanation of the correlation of the large scale magnetic field structure with the optical spirals is still an unresolved problem. Mean field dynamos with sufficient large turbulence diffusivity depending on the properties of the ISM reproduce nicely interarm magnetic fields but the pitch angle of the magnetic field does not automatically coincide with the pitch angle of the optical spiral arms. A possible way out could be the effect of the flow connected with the spiral structure. Indeed, including more realistic flows into dynamo models, at least for the field in the arms the pitch angle problem can be relaxed. Difficulties still occur with negative pitch angles in the interarms , which are not observed. Galaxies with stationary density wave flows show a strong concentration of magnetic fields in the arms. That can also be seen in recent simulations of Gómez and Cox(2004).

The situation is different for spirals driven by an inner bar. Here we observed temporarily interarm fields. Negative pitch angles disappeared fast. It remaines open how the situation is in more time dependent spiral structures induced by mergers or local gravitational instabilities, where the flow is determined by the spiral formation process. In that case magnetic field observations should be another window into the gasdynamical evolution process of galaxies.

The flocculent Galaxy NGC4414 is an interesting example, with very weak deviations of the rotation (Soida et al. 2002). This galaxy has a magnetic field with a large pitch angle and therefore serves as a counterexample for the statement, that the pitch angle in galaxies is always caused by induction processes of spiral flows. A highly diffusive process like cosmic ray diffusion together with a strong α effect could help to understand the magnetic field in that galaxy.

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