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Large scale galactic magnetic fields : Need for a new theory of generation

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1. Introduction

A large number of spiral galaxies have now been observed to possess large scale galactic magnetic fields. Almost toroidal unidirectional field was observed in M31 with Effelberg 100-m radio telescope (Beck 1982). Fields in other galaxies have been observed using the VLA and Parks 64m dish (Safue *et al.* 1986; Beck & Gräve 1987).

The strength and the form of the magnetic field is deduced from the measurement of linearly polarized synchrotron emission.

Three types of magnetic field structures have been identified :

a) Axisymmetric Spiral Structure (ASS) :

ASS is found to be dominant in M31 and IC 342 for example (Beck 1982; Kraus *et al.* 1989a). Here, the spiral like magnetic field lines point along the same direction at all angular positions; all spiralling towards the centre or spiralling outwards from the centre.

b) Bisymmetric Spiral Structure (BSS)

In the BSS form, field lines spiral in form one half of the disc and spiral out from the other half. The form is roughly what would result if a fiield line running along the diameter of the disk were to be distorted by the differential rotation of the disk.

Such spiral patterns are observed in M81 and M51 and possibly in M33. M51 shows beautiful patterns almost parallel to the spiral arms (Krause *et al.* 1989a; 1989b). See figure 1 for the magnetic field pattern for M51.

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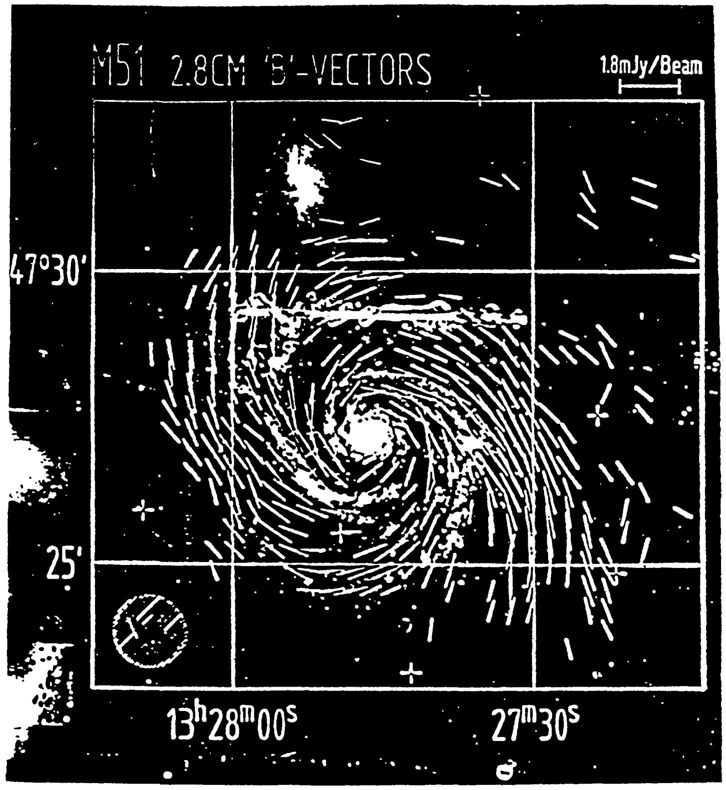

Figure 1. Global bisymmetric magnetic field pattern for M51.

c) The 'zero' cases

These types of galactic fields show high degree of polarization but low rotation measure. The field is ordered but without a uniform direction. This means that frequent reversals have to occur within the telescope beam.

The examples are M83, NGC 6946 and our own galaxy (Sukumar and Allen 1989; Beck *et al.* 1990)

It is significant to note, however, that in all galaxies the field lines are roughly parallel to the optical spiral arms.

The most popular and until recently the most widely accepted theory for the magnetic field generation is the Kinematical Dynamo Theory (KDT) promoted by Parker (1979) Zeldovich *et al.* (1983) and Ruzmaikin *et al.* (1988). However, recent work by Kulsrud and Anderson (1992, 1993) has pointed out some serious problems with this (kinematic dynamo) theory which render it invalid. This will be discussed later in more detail. There is, therefore, a strong need to advance a new point of view and a new theory for the generation of large scale magnetic field. In Section 2, we give a critique of the KDT and in Section 3, we present an alternate scenario for the GMF motivated by some observational data on the galactic plasma density distribution as indicated by HII distribution.

2. Failure of the kinematic dynamo theory

Two competing models had been proposed for the generation of the galactic magnetic fields (By generation we do not mean the question of generation of cosmic fields, which serve as seed fields for the galactic field generation / amplification).

a) Primordial field model :

According to this model, the primordial magnetic field is trapped by a proto-galaxy and twisted to a bisymmetric form by differential rotation.

This leads, however, to the problem of 'overwinding' of the field lines, as they would get wound into a tighter and tighter bisymmetric spiral with the passage of time, which is contrary to observations. This 'overwinding' has been sought to be countered by allowing the magnetic field lines to diffuse into the halo (Sawa and Fujimoto, 1980). Kulsrud on the other hand, has attempted to overcome the overwinding through friction against the neutrals.

It may be mentioned, however, that it is not clear how an axistymmetric spiral could be generated by this "primordial field hypothesis".

b) The Kinematical Dynamo Theory :

The other theory, and by far the most popular one for the generation of the galactic field is the kinematic dynamo theory. The generation of magnetic field in this theory is supposed to occur through coupling to turbulent velocity fields, so that the energy of the latter is used up in the building up of the magnetic field energy associated with the generation of the magnetic field. The dynamo is kinematical because the back reaction of this generation on the velocity field is disregarded. Nor is the velocity field sought to be replenished or maintained by its sources. To be self consistent the dynamo ought to be dynamical and the full set of dynamical equations must be used incorporating both the gravitational field as well the back reaction of the growing magnetic field on the velocity fields.

The kinematical dynamo theory has recently suffered a severe setback because of a recent work by Kulsrud & Anderson. It has been shown by these authors that the small scale turbulent magnetic fields grow much faster (on the time scale $\sim 10^4$ years) as compared to the large scale average fields (which grow on the time scale of 10^8 years), so that after a relatively short time (compared to the growth time of the mean fields) the turbulent fields dominate the large scale mean fields. The latter thus gets obliterated in the dominating presence of the small scale turbulent fields. Furthermore, when the back reaction of the magnetic field on the vorticity field is taken into account in the dynamical framework the situation becomes worse because the effect is to suppress the vorticity field scale by scale until equipartition is achieved between the magnetic and the vorticity fields. The kinematic theory assumed tacitly that the small scale turbulent fields remain small as they were supposed to get dissipated through resistivity on being cascaded down to the resistive scales. It has been argued by Kulsrud & Anderson that the kinematic dynamo fails to work because of these factors.

If that is so, then it is necessary to look for other sources of free energy to build the large scale magnetic field from, which, in particular, are not susceptible to the fragility of the above kind. One obvious source of free energy is the gravitational field, both the self gravitation of the neutral component as well as gravitational field of the central bulge. If the plasma disk of the galaxy has somewhere an inverted density distribution with respect to the bulge gravity, then such a distribution being Rayleigh - Taylor unstable, could lead to the growth of the spiral magnetic field modes in the disk. We describe in Sec. 3 a theory of the large scale magnetic field generation due to such a mechanism which has been developed by Pandey & Varma (1996). It may be mentioned that such a mechanism would not be susceptible to the kind of problems raised by Kulstrud and Anderson for the kinematic dynamo because it is not derived from average properties of any kind of turbulence, but from a steady inverted density gradient under the gravitational field of the bulge. Moreover, the treatment is fully dynamical.

3. Largescale galactic field : A new possible theory

With the failure of the kinematic dynamo theory one has to look, as mentioned above, for other scenarios and free energy sources for the generation of the mean magnetic field which is an observational fact. It may be noted that the reason for the fragility of the kinematic fast dynamo is that both the large scale mean field and the small turbulent magnetic fields are generated by the same dynamo mechanism. So, whatever amplifies the mean field would also *a fortiori* amplify the small scale turbulent fields. One should therefore look for a mechanism which does not depend, for the required free energy, on any turbulent fields but rather on some zero order density or velocity field gradients in the galactic plasma.

There are two possibilities.

a. Other sources of free energy with steady gradients in either velocity or density fields.

b. Self-organization of magnetic field from the small scale turbulent fields to large scale ordered magnetic field.

While the second possibility is a very attractive one, and promises to yield a rather general mechanism for the generation of the field, it is still a rather difficult one to explore. We shall investigate the first possibility and make use of the plasma density gradient as a free energy source.

It is well known that the plasma disk of the galaxy is produced by inoization of the neutral hydrogen by star light and cosmic rays. The distribution of HII regions in a galaxy, which essentially consist of inonized hydrogen, would be a good indicator of the plasma density distribution in the galaxy. It is known (Hodge 1969) that the radial density distribution of the number of HII regions in most galaxies studied, typically peaks at about 2kpc decreasing to about a tenth of its peak value by about 10kpc. Figure 2 gives the mean profiles of HII region radial distribution by galaxy type. SBb galaxies show a sharp density gradient compared to SBc galaxies. Therefore, assuming that the plasma density is also distributed similarly one has here an inverted density distribution with respect to the bulge gravity in the region upto roughly 2-3kpc, which is Rayleigh-Taylor unstable. One has therefore, a source of free energy which could be exploited to grow the bisymmetric (and other) modes of the large scale magnetic field. A limitation of this scenario ought to be pointed out, however. The scenario relies on the distribution of HII regions as observed 'today', which may not be true in the distant past which era is relevant for the initial growth of the magnetic field. One would nevertheless believe that for as long as stars have existed in the galaxy, there would exist distributions of HII regions not too different from what is seen 'today' and the mechanism being suggested would be relevant at least from some distant time in the past.

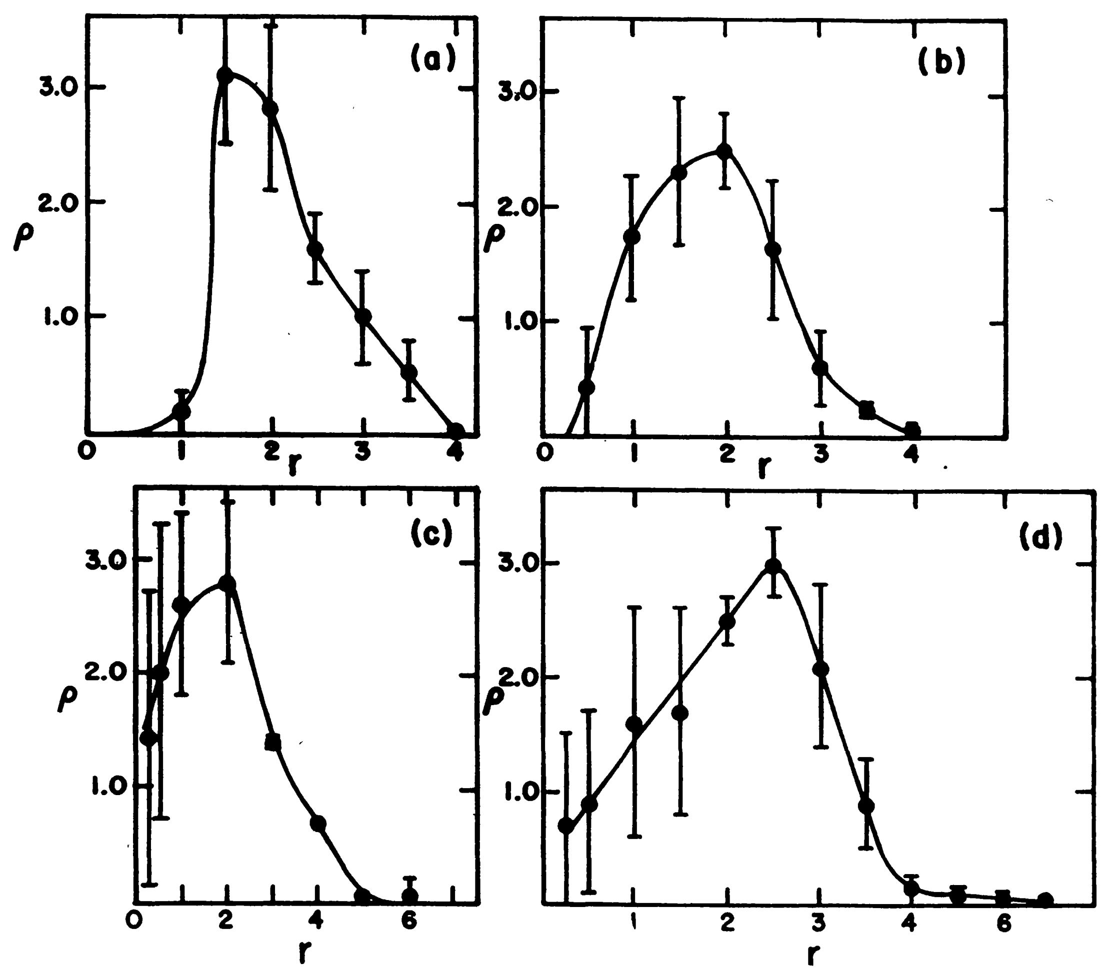

Figure 2. Density distribution of HII regions for various galaxy types. a) SBb (3 galaxies), b) Sb (3 galaxies), c) SC (11 galaxies), and d) SBc (6 galaxies). (Figure adapted from P.W. Hodge).

It is also known that the intergalactic space is permeated by a magnetic field at least of order 10^{-9} gauss, so also would be the galactic plasma 'initially', which is also under the action of the bulge gravity. This leads to the gravitational drift V_g of both the ions and the electrons. (The ion gyro-radius in a field of 10^{-9} gauss and an ion temperature for HII regions $T_i \sim 10^4$K is $\sim 10^{-7}$ pc). This would lead to an azimuthal current distribution determined essentially by the ion gravity drift $V_{gi} >> V_{ge}$, as well as by the diamagnetic drift. This, would, in turn lead to a zero order equilibrium polodial magnetic field.

In what follows we first discuss the equilibrium of the plasma disk in terms of the appropriate MHD equations. It is then perturbed with density, electromagnetic, and fluid velocity field perturbations. The eigenmodes of the disk are then identified with the galactic field morphology.

Basic equations

As mentioned above, we consider the dynamics of the plasma under the action of the gravitational field of the bulge and an external (intergalactic) magnetic field normal to the plane of the disk. The governing MHD equations are :

$$\frac{\delta\sigma}{\delta t} + \nabla.(\sigma\vec{v}) = 0 \qquad (1)$$

$$\sigma\frac{d\vec{v}}{dt} = -\nabla\hat{p} - \frac{GM}{r^2}\sigma\vec{e_r} + \frac{1}{2\pi}(B_rB_z\vec{e_r} - B_\phi B_z\vec{e_f}) \qquad (2)$$

$$\frac{\delta\vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) \qquad (3)$$

$$2B_r = \frac{4\pi}{c}I_\phi, \qquad 2B_\phi = -\frac{4\pi}{c}I_r \qquad (4)$$

$$\nabla.\vec{B} = 0 \qquad (5)$$

$$\hat{p} = C^2\sigma. \qquad (6)$$

These equations have been obtained for a thin plasma disk by integrating the usual volume equations across the disk so that we have surface current densities I_ϕ and I_r rather than the volume current densities. The Ampere's law takes the form of Eq. (4) and the $\vec{j} \times \vec{B}$ force takes the form of the last term in Eq. (2). σ and $\hat{p}$ are respectively the surface density and pressure, M is the mass of the galactic bulge, and the collisional drag on the MHD fluid by the neutrals is neglected. Equation (3) follows from the Faraday law of induction by using the infinite conductivity Ohm's law, $E + \vec{v} \times \vec{B}/c = 0$, which is justified for the large scales of galactic plasma.

Equilibirium

In equilibrium, $\partial/\partial t \equiv 0$, the axisymmetry yields for the velocity field $\vec{v}$ and the surface current density $\vec{I}$

$$\vec{v} = (0, v_{0\phi}, 0) \tag{7a}$$

$$\vec{I} = (0, I_{0\phi}, 0) \tag{7b}$$

with $v_{0\phi}$ and $I_{0\phi}$ as arbitrary functions of r. For a thin disk, the induction equation in steady state gives :

$$\frac{\partial}{\partial r}(B_r v_{0\phi}) + \frac{\partial}{\partial z}(B_z v_{0\phi}) = 0 \tag{8}$$

while $\nabla.\vec{B} = 0$, with axisymmetry yields

$$\frac{I}{r}\frac{\partial}{\partial r}(rB_r) + \frac{\partial B_z}{\partial z} = 0 \tag{9}$$

Or, using the fact that the vorticity is solely directed along z, so that

$$\frac{\partial v_{0\phi}}{\partial z} = 0 \tag{10}$$

one gets from (3.9), (3.10) and (3.11)

$$B_r \frac{\partial v_{0\phi}}{\partial r} - \frac{B_r}{r} v_{0\phi} = 0, \tag{11}$$

This gives the solution,

$$v_{0\phi} = \Omega_0 \tag{12}$$

that is, a rigid rotation with a constant angular velocity Ω_0. This is the only solution consistent with the infinite conductivity Ohm's law for a thin disk and is in agreement with the Ferraro's law of isorotation. The rigidly rotating disk may appear to be contrary to the differentially rotating disk of the kinematic dynamo. But as we shall see our mechanizm does not require any differential rotation.

The equilibrium momentum balance equation is obtained from (2) using the fact that Bf = 0 in equilibrium

$$\sigma_0 \left(\frac{GM}{r^2} \Omega_0^2 r \right) = - \frac{dp_0}{dr} + \frac{1}{2\pi} B_{0r} B_{0z}. \tag{13}$$

Given a certain current distribution and using the equation of state (3.6), we determine the surface density distribution as

$$\sigma_0 = \frac{c}{8\pi C^2} \exp\left[\frac{GM}{C^2 r} + \frac{(\Omega_0 r)2}{2C^2} \right] \int_0^r dr' \exp\left[- \left(\frac{GM}{r} + \frac{1}{2} (\Omega r)^2 \right) / C^2 \right] B_{0r} B_{0z}. \tag{14}$$

A current distribution of the following form is assumed

$$I_{0\phi}(r) = I_0 J_1 (kr),\ r \le R_{disk} \tag{15}$$

$$= 0,\ r > R_{disk}$$

The corresponding B_{0r} and B_{0z} are given by

$$B_{0r} = \frac{2\pi}{c} I_0 J_1 (kr)$$

$$B_{0z} = \frac{2\pi}{c} I_0 J_0 (kr). \tag{16}$$

Using these expressions for B_{0r} and B_{0z}, σ_0 can be determined from Eq. (14), which must be positive to be physical. The density distribution σ_0 is plotted in figure 3 while the B_{0r} and B_{0z}, for the currrent distribution (15) is plotted in figure 4. All are plotted as functions of the radius non-dimensionalized with respect to the disk radius, R. The density distribution is non-dimensionalized with respect to the surface density $M / 2\pi R^2$.

Stability analysis

We now linearize the Eqns. (1) – (6) around the equilibrium defined above assuming all perturbation quantities to vary as

$$\tilde{Q} \sim \exp\left[-i(\omega t - m\phi)\right]; \tag{17}$$

we obtain after eliminating all other quantities in favour of υ_r the differential equation

$$\frac{d^2\upsilon_r}{dr^2} + \frac{1}{r}\frac{d\upsilon_r}{dr}\left[1 + \frac{\pi \nu m}{\Omega B_r B_z} \left(C^2 \frac{d\sigma_0}{dr} + \frac{B_r B_z}{2\pi} \right) \right] + \upsilon_r \left\{ - \frac{1}{r^2} \left(1 + \frac{2\pi m^2 C^2}{B_r B_z} \frac{d\sigma_0}{dr} \right) \right.$$

$$\left. \frac{\pi \nu m \sigma_0}{\Omega B_r B_z r} \left[\nu^2 - 4\Omega^2 + C^2 \frac{d}{dr} \left(\frac{1}{\sigma_0} \frac{d\sigma_0}{dr} \right) - \frac{1}{2\pi} \frac{d}{dr} \left(\frac{B_r B_z}{\sigma} \right) \right] \right\} = 0 \tag{18}$$

where $\nu = \omega - m\omega_0$.

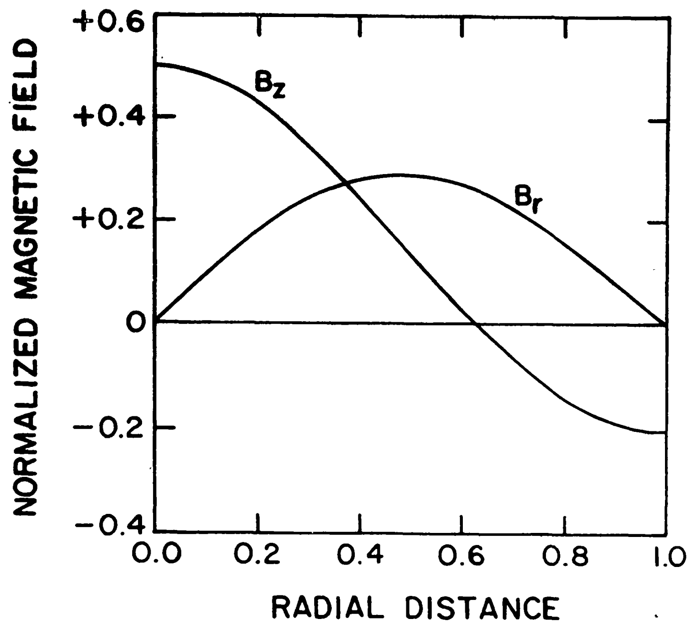

Figure 3. Radial plasma density distribution in the plasma disk in equillibrium Eq. (15) for the current distribution (16).

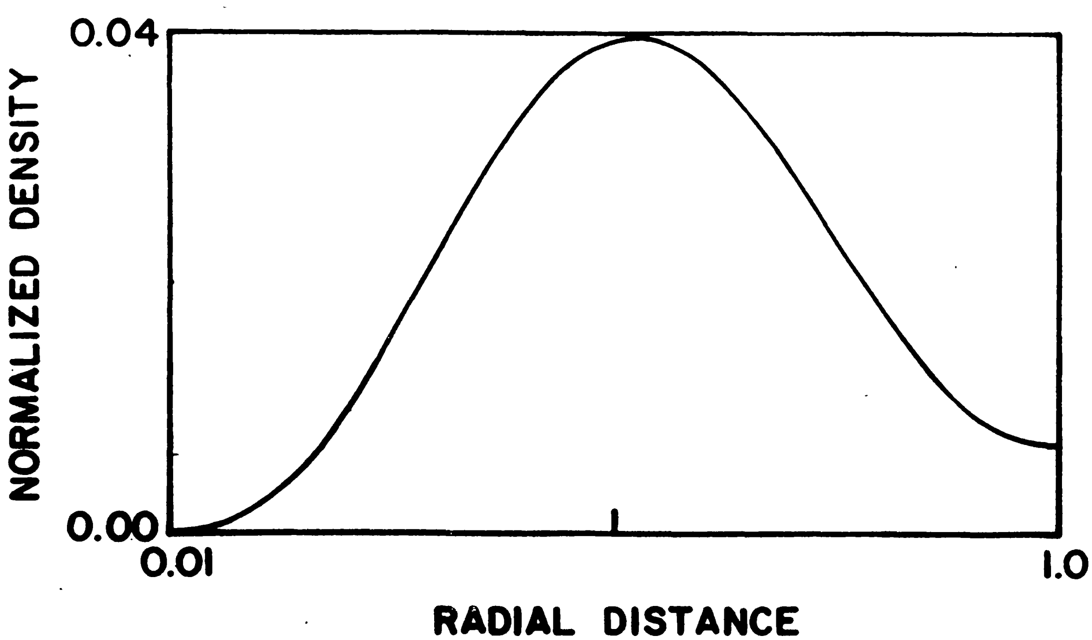

Figure 4. The magnetic field distribution (B_r and B_z) in the disk for the current distribution (16).

If, for simplicity, one assumes the density scale length to be small compared to the radial wave length of the perturbation then neglecting the first two terms of Eq. (18), we get the approximate dispersion relation

$$\left[v^2 - 4\Omega^2 + C^2 \frac{d}{dr}\left(\frac{1}{\sigma_0}\frac{d\sigma_0}{dr}\right) - \frac{1}{2\pi}\frac{d}{dr}\left(\frac{B_r B_z}{\sigma}\right)\right] = 0, \tag{19}$$

where we have also neglected terms of order $\Omega B_r B_z / r\sigma_0$ compared to v^3. The first assumption is justified as the density scale length in the inverted density region is ~ 2 – 3kpc while for the open spirals the radial perturbation may have a scale length ~ 7 - 8kpc, while the second is valid if the rigid rotation frequency Ω_0 is much less than v. Simplifying we obtain,

$$v \approx \pm \left[4\Omega^2 + \frac{d}{dr}\left(\frac{B_r B_z}{\sigma}\right)\right], \tag{20}$$

where we have assumed that $(d\sigma/dr)^2 / \sigma^2 \sim (d^2\sigma / dr^2) / \sigma$, so that these two terms roughly cancel each other. We thus get the condition for the instability as

$$4\Omega^2 + \frac{1}{2\pi}\frac{d(B_r B_z/\sigma)}{dr} < 0. \tag{21}$$

Now writing $d(B_r B_z/\sigma)dr \sim \kappa(B_r B_z/\sigma)$ where κ represents the wave number corresponding to the scale of variation of $B_r B_z/\sigma$, then the criterion for the instability becomes

$$\kappa < 0, \text{ and } \frac{|\kappa| B_r B_z}{2\pi\sigma_0} > 4\Omega^2. \tag{22}$$

Now using the density variation as given in figure 3 and the expressions (16) for B_r and B_z, we obtain the variation $B_r B_z/\sigma$ as a function of r which is shown in figure 5. Clearly, it exhibits a sharp negative gradient close to the center of the disk and up to about 0.2 disk radius though still negative and not so sharp beyond that radius. This, of course, implies $\kappa < 0$ in this region and the necessary condition for the instability is satisfied.

Next consider the expression $B_r B_z/2\pi\sigma_0$ itself. The magnetic fields B_r and B_z are generated by azimuthal current which is comprised dominantly of the ion gravity drift (since the electron gravity drift is smaller by the mass ratio) in the field B_z normal to the disk. Thus the azimuthal surface current is given by,

$$I_{0\phi} = \frac{\sigma_0 c}{m_i}\upsilon_{gi} = \frac{\sigma_0 c}{m_i}\frac{g}{\omega_{ci}} = \frac{c\sigma_0 g}{B_z}$$

where g is a gravity and m_i is the ion mass and ω_{ci} is the ion gyrofrequency.

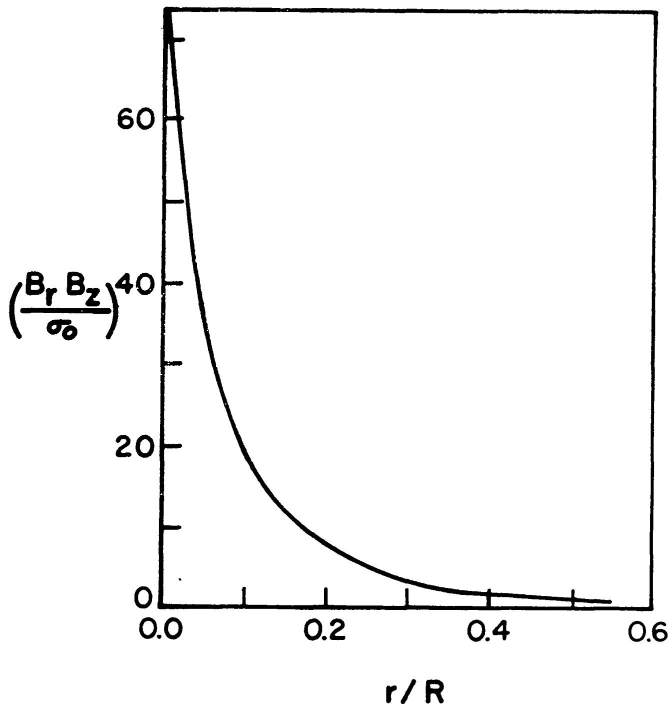

Figure 5. Plot of $B_rB_z/\sigma)$ as a function of the radial distance (normalised with respect to disk radius).

Now, from Eq. (4) B_r is given by $2\pi I_\phi/c$. Hence, we obtain,

$$B_r = \frac{2\pi}{c} I_\phi = \frac{2\pi\sigma_0 g}{B_z}$$

so that,

$$\frac{B_r B_z}{2\pi\sigma_0} = g = \frac{GM}{r^2}$$

The instability criterion thus takes the form,

$$|\kappa|\, g \equiv \frac{|\kappa| GM}{r^2} > 4\Omega^2$$

which has the Rayleigh-Taylor form in the presence of the rotation, and the growth rate is

$$\gamma = (|\kappa|\, g - 4\Omega^2)^{1/2}.$$

Now taking $M \approx 10^{11} M_\odot \approx 3 \times 10^{44}$ gms and $k \approx 1/r \approx 0.5(\text{kpc})^{-1}$, we get

$$\gamma^2 \approx \frac{GM}{r^3} \approx 4 \times 10^{-30} \text{sec}^{-2}$$

whence $\gamma \approx 6 \times 10^{-8}$/y and the growth time $\tau \approx 1.6 \times 10^7$ yrs.

We thus obtain the right order of magnitude for the growth times to explain the generation and maintenance of the large scale magnetic field. In fact, we get smaller growth times compared to those of the kinematic dynamo. To obtain a more precise result for the various modes we must solve the complete eigenvalue problem. Either, one then solves the differential equation (18) for the eigenvalues and the eigenfunctions with appropriate boundary conditions, or solves the infinite set of matrix equations incorporating the appropriate boundary conditions. The latter procedure has been adopted in the present case. The detailed results of these calculations will be published elsewhere. Figure (6) gives a typical form of the eigenfunction for the m = 1 case. As can be seen we do get the form of the bisymmetric magnetic field spirals.

One may, of course ask the question as to what is the origin of the intergalactic magnetic field ~ 10^{-9}g assumed to be present initially. This question pertains to the more general question of the origin of the cosmic magnetic fields and is not attempted to be answered here.

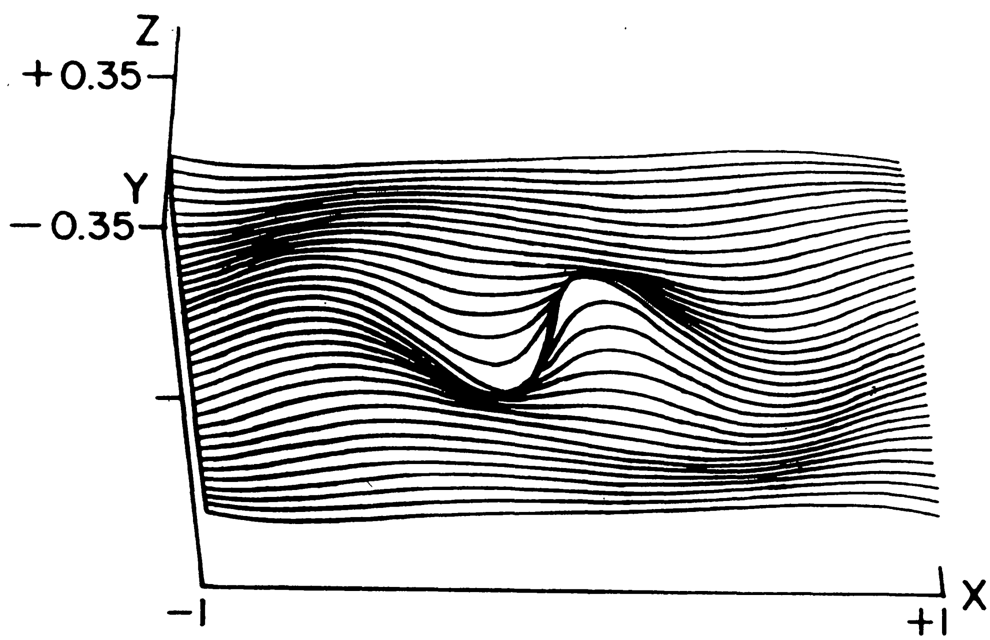

Figure 6. Eigen-pattern for the m = 1 mode showing bisymmetric magnetic field structure.

However, it may be mentioned that the mechanism outlined here would work even if the magnetic field were to be weaker as the drift approximation would still be satisfied, provided of course one has an inverted plasma density distribution available for the instability to grow.

Conclusion

As was mentioned already in the text, this mechanism may have a limitation in that it depends on the HII density distribution as it is observed "today". And it is not clear whether the observed magnetic field was generated even before the "present" HII distribution was established or it is indeed a consequence of the latter as the theory given here implies.

In particular, one can ask the question whether this mechanism can be applied to galaxies in the early stages of their evolution. This requires that one should establish observationally that an inverted plasma distribution exists even in the early stages of galaxy evolution.

It is worth looking in this connection, at the cases of M83 and NGC 6946.

Both of these galaxies belong to the "zero" case, showing high degree of polarization, but, low rotation measures. M83 shows high degree of granularity in the magnetic field structure (Sukumar 8 Allen 1989).

On the other hand, if one looks at the HII region distribution of NGC 6946 then it appears to be rather flat. (See figure 7). It would appear that it may not induce large enough Rayleigh-Taylor growth rates and the large scale magnetic field structure may not be well defined.

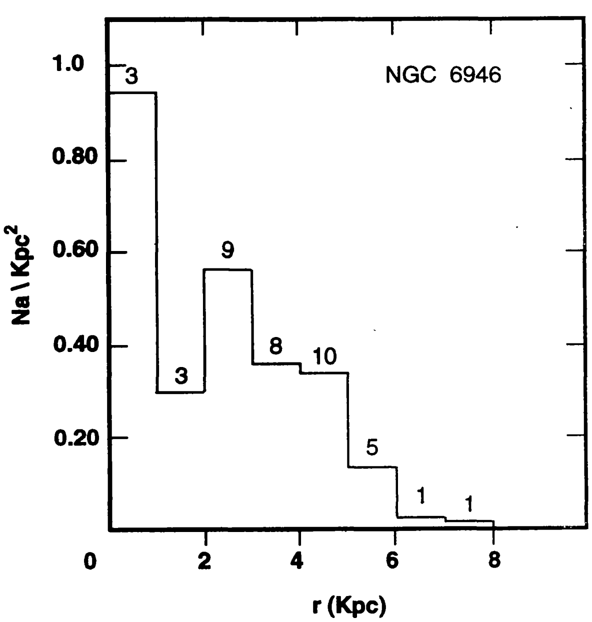

Figure 7. The radial distribution of the number of HII regions for NGC 6946. (Figure adapted from Ref. 18 P.W. Hodge).

Should the 'zero' case of NGC 6949 be due to this circumstance, then the same should hold also for the case of M83 which also belongs to the 'zero' case. In other words M83, should also exhibit a rather flat HII region distribution.

Since HII region distribution of M83 is not available to the authors, this cannot be checked. However, should that not be available in the literature, an observation should be made to see what that distribution looks like.

By the same token, since the M51 exhibits a very clean and well formed bisymmetric spiral pattern, one should also check the HII distribution pattern for the M51 galaxy to see if it is well peaked.

As a matter of fact, one should carry out an HII distribution survey for at least all those galaxies for which large scale magnetic fields have been mapped. This would enable one to find correlaion, if any, between the HII region distribution and magnetic field structure.

References

Beck R., 1982, A&A, 106, 121.

Beck R., Gräve R., 1987, Interstellar Magnetic Fields, Springer, Berlin.

Beck R., *et al.*, 1990, Galactic and Intergalactic Magnetic Fields, ed. R. Beck, P.P. Krönberg and R. Weilebinski, Kluwer, Dordrecht, p. 213.

Hodge P.W., ApJ, 1969, 155, 417.

Horellon C., *et al.*, 1990, Galactic and Intergalactic Magnetic Fields, ed. R. Beck, P.P. Krönberg and R. Weilebinski, Kluwer, Dordrecht, p. 211.

Krause M., *et al.*, 1989a, A&A, 217, 4.

Krause M., *et al.*, 1989b, A&A, 217, 17.

Kulsrud R.M., Anderson S.W., 1992, ApJ., 396, 606.

Kulsrud R.M., Anderson S.W., 1993, in Theory of Solar and Planetary Dynamos, eds. M.R.E. Proctor, D.C. Mathews and A.M. Rucklidge, Cambridge Univ. Press, p. 1.

Kulsrud R.M., Anderson S.W., ibid, p. 198.

Kulsrud R.M., in Plasma Astrophysics, Joint Varenna-Abastuman Int. School and Workshop, Sukhumi USSR.

Pandey B.P., Varma R.K., 1996, (in preparation).

Parker E.N., 1979, Cosmical Magnetic Fields, Pergamon Press, Oxford.

Ruzmaikin A.A., Shukurov A.M., Sokoloff D.D., 1988, in Magnetic Fields of Galaxies, Kluwer, Dordrecht.

Sawa T., Fujimoto M., 1980, PASJ, 32, 551.

Sofue Y., Fujimoto M., Weibelinski R., 1986, ARA&A, 24, 459.

Sukumar S., Allen R.J., 1989, Nature, 340, 537.

Zeldovich Y.B., Ruzmaikin A.A., Sokoloff D.D., 1983, in Magnetic Fields in Astrophysics, Gordon and Breach, New York.