

## Magnetic Fields in Young Galaxies

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**Abstract.** We have studied the fate of initial magnetic fields in the hot halo gas out of which the visible parts of galaxies form, using three-dimensional numerical MHD-experiments. The halo gas undergoes compression by several orders of magnitude in the subsonic cooling flow that forms the cold disk. The magnetic field is carried along and is amplified considerably in the process, reaching  $\mu\text{G}$  levels for reasonable values of the initial ratio of magnetic to thermal energy density.

### 1. Introduction

The origin of large scale magnetic fields in disk galaxies is an unsettled issue. Proposed solutions to this problem fall in two categories. On the one hand, *in situ* dynamo action has been invoked to amplify exponentially an initially weak, small scale, seed field (for recent reviews, see Beck et al. 1996; Kulsrud 1999). On the other hand, large scale pre-galactic fields in the halos of forming galaxies might be compressed and stretched sufficiently during the formation and evolution of galactic disks to explain the observed large scale fields (see e.g. Howard & Kulsrud 1997).

Observations of  $\mu\text{G}$  level large scale fields in slowly rotating irregular galaxies (Chyží et al. 2000), high redshift objects (e.g. Perry et al. 1993), and in the intracluster medium (Eilek 1999; Colgate & Li 2000), pose fundamental problems for the classical  $\alpha - \Omega$  galactic dynamo as a cornerstone for creating magnetic fields on galactic (and larger) scales. In addition, it seems difficult to attribute the strong vertical field found in the central molecular zone of our Galaxy to a Galactic dynamo, which may be suggestive of a primordial origin for this component of the Galactic magnetic field (Sofue & Fujimoto 1987; Chandran, Cowley, & Morris 2000).

The observational evidence for magnetic fields in cluster halos and the association between these fields and outflows from AGNs suggests that similar processes may seed protogalactic halos with large scale magnetic fields. The compression and stretching of the field during the galaxy formation process further amplifies the halo field and could possibly account for the observed fields in present day disk galaxies. The conventional criticism that these kinds of scenarios will result in an incorrect parity with respect to the galactic plane may be shown to result from overly simplified assumptions about the initial field. Only in the case of a field that is both weakly inclined and initially located near the center of the potential well does it follow that the wound-up field is predominantly of odd parity.

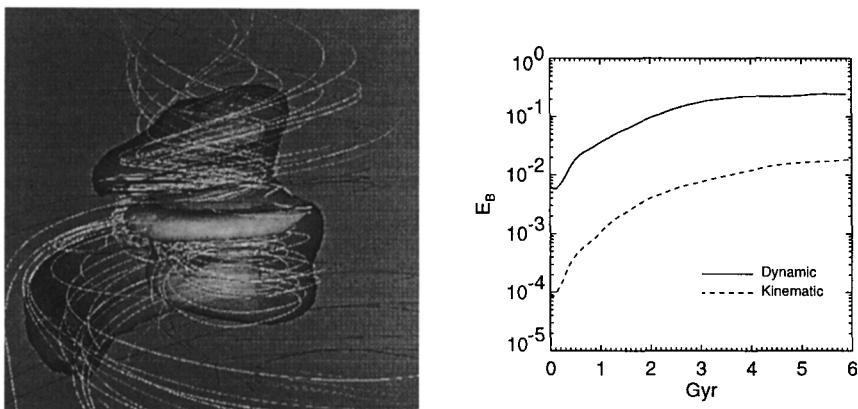


Figure 1. (a) The magnetic energy isosurface (dark gray) shows the asymmetry of the field as it gets dragged into the cold disk (light gray) with the cooling flow (for 3-D color renderings see [www.astro.ku.dk/~aake/talks/IAU2000](http://www.astro.ku.dk/~aake/talks/IAU2000)). Field lines show that the polarity of the field changes in the halo, above the plane of the disk. (b) The growth of the average magnetic energy in a volume enclosing the cold disk and the halo gas immediately above and below the disk. The initial magnetic pressure in the “dynamic” experiment is 1% of the thermal pressure, while the kinematic case starts off with 0.01%.

This has prompted us to study the compression and wind-up of initial halo fields during the build-up of a disk galaxy in a cooling flow. By adopting a smooth background potential and by using sufficient numerical resolution (enhanced by grid stretching) we achieve that the disk forming at the bottom of the potential well has the characteristic size, mass, and specific angular momentum of a typical disk galaxy (the initial spin parameter  $\lambda = JE^{1/2}/GM^{5/2}$  is equal to 0.056). The hot halo gas is threaded by a random magnetic field with approximately constant  $P_{\text{mag}}/P_{\text{gas}}$ , plus a large scale component of similar energy content that has a non-zero inclination and offset from the rotation axis.

## 2. Results and Discussion

If the initial field has a significant inclination and offset from the center, the resulting wound-up field has a reversal that is offset into the halo (see Fig. 1a). When observed face-on, in optically thin radio frequencies, the magnetic field would appear to be uni-directional, as is normally observed, because one of the winding directions dominates over the other. The reversal in the halo could be revealed by analyzing observations in different radio frequencies, as has indeed been done for M51 (Berkhuijsen et al. 1997). Note that, in the model presented here, there is no creation of “new” magnetic flux—the growth of magnetic energy (Fig. 1b) is purely a result of compression and winding of an (approximately conserved) amount of magnetic flux, initially threading the disk plane over a range of radii. With sufficient numerical resolution of the disk dynamics, there would

of course be additional fine scale structure and enhancement of the magnetic energy, associated with turbulence in the disk.

The other common point of criticism against galactic magnetic fields originating from large scale, pre-galactic fields is the issue of pitch angle. Here it should be remarked that conventional mean field dynamos invoke a large amount of magnetic diffusion, particularly in spiral arms, together with a rapid regeneration of the radial magnetic field component, to maintain the pitch angle. The magnetic diffusion is assumed to arise, for example, from turbulence driven by star formation. If such a mechanism were allowed for in the current experiments, it would be equally effective in maintaining the pitch angle. Regeneration of the radial field component is not necessary; apart from vertical transport effects, its magnitude is determined by the (conserved) amount of wound-up magnetic flux and the pitch angle. It has also been argued that galactic winds, caused by the same SNe that drive the turbulence, could be a significant source of loss of magnetic field from galactic disks. However, as has been demonstrated by Gudiksen (1999), the hot wind emanates from the disc in "chimneys", which are intermixed with much denser regions that are able to hold on to the magnetic field. Loss of magnetic flux is also counteracted by the incoming cooling flow.

In summary, the scenario adopted here is consistent both with current ideas about early AGNs as the origin of the observed, large scale magnetic fields in clusters, and with observed properties of galactic magnetic fields. Since the results were obtained by simply tracing the magnetic field evolution in a cooling flow that results in a disk galaxy which is in other respect consistent with observations, one may even turn the argument around and conclude that the initial  $P_{\text{mag}}/P_{\text{gas}}$  of the halo gas would have to be much smaller than the  $P_{\text{mag}}/P_{\text{gas}}$  typical of large scale cluster magnetic fields, in order not to give rise to galactic magnetic fields similar to the observed ones.

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