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Symmetry and direction of seed magnetic fields in galaxies

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Abstract. Radio observations of large-scale magnetic fields in spiral galaxies suggest that these fields show in many cases a dominating S0 symmetry, i.e. even symmetry to the central plane and axisymmetry with respect to the rotational axis. In addition, detailed evaluation of Faraday rotation measures in five nearby galaxies reveals that in four cases the magnetic field lines are directed toward the centre of these galaxies. Dynamo theory, successful in explaining the existence of such fields, does not contain any statement concerning the sign of the field which depends on the initial conditions. Hence we investigate whether there is a mechanism which produces seed fields with a definitely determined field direction. Neither pre-galactic seed fields, nor galactic battery seed fields, nor ionization fronts are able to imprint such a dominating direction.

Key words: magnetic fields – galaxies: formation – galaxies: magnetic fields – early Universe – radio continuum: galaxies

1. Introduction

Large-scale magnetic fields have been observed in a number of spiral galaxies. Probably these fields have been built up by dynamo processes from seed fields (see e.g. Wielebinski & Krause 1993, Beck et al. 1996). Detailed maps of the large-scale magnetic fields exist for a number of nearby galaxies. In the disk of a galaxy these fields show a spiral structure. This appearance is in accordance with the results of dynamo theory. However, four out of five galaxies observed so far show spiral fields which are directed towards the centre of these galaxies (Sect. 2). This point is remarkable, since dynamo theory does not contain any statement concerning the sign of the excited field.

Although four galaxies do not yet represent an adequate statistical ensemble, we will analyse the question for this (possible) preference of one field direction. These investigations lead us beyond dynamo theory and need a closer consideration of the candidates for seed fields, whether or not they show preference of inward-directed, large-scale components.

The existence of seed fields in the Universe before and at the beginning of the formation of galaxies is far from being understood: Have there been magnetic seed fields at all? Were these fields sufficiently strong? These questions have to be discussed in the context of the ages of galaxies, the dynamo growth rates, and the observed field strengths in galaxies of some 10^{-6} G.

Furthermore, the dynamo provides exponential growth only of the large-scale part of the seed field. Thus we have to specify the problem and ask whether the seed field has a sufficiently strong large-scale part which makes the excitation to the presently observed magnitude probable.

Several mechanisms for seed fields have been considered in the past. The results indicate that there have been, indeed, sufficiently strong fields (e.g. Rees 1987, 1994, Lesch & Chiba 1995). However, the considered mechanisms produce almost randomly distributed magnetic fields which show length scales that are small compared to the scale of a galaxy. Certainly, this set of small-scale seed fields will have a non-vanishing large-scale part, but not with a systematically preferred direction.

In this paper we will concentrate on large-scale seed magnetic fields in a pregalactic cloud which are produced by the "Biermann battery", a mechanism for magnetic field generation in a plasma due to electromotive forces proportional to the acceleration (Biermann 1950, 1952). Biermann discussed this process in the context of field generation in the sun by differential rotation and, in our Galaxy, by irregular motions of the interstellar medium. Thus, Biermann presented an early explanation for the existence of magnetic fields in our Galaxy which remained plausible until the discovery of large-scale magnetic fields in the seventies.

We investigate here whether in a pregalactic cloud evidence can be found for a preferred field symmetry and a preferred direction of large-scale seed magnetic fields which are produced by the Biermann battery effect due to internal motions, such as differential rotation of this cloud and irregular small-scale motions under the influence of the overall rotation. We further discuss symmetry and field direction of seed magnetic fields caused by a mechanism invoking ionization fronts as proposed by Subramanian et al. (1994).

2. Observations of large-scale fields

2.1. Symmetries

There are two basic symmetry types of large-scale regular magnetic fields in a galactic disk, fields of the one type (denoted by

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S) are symmetric with respect to the central plane, the others antisymmetric (denoted by A). The azimuthal mode is classified by the number m : $m = 0$ is an axisymmetric field, $m = 1$ a bisymmetric one, etc. The S0 field consists of an axisymmetric quadrupole-like poloidal field combined with one toroidal ring field arranged about the central plane (Krause & Wielebinski 1991, Wielebinski & Krause 1993), whereas the A0 field of a dipole-like poloidal field is combined with two toroidal ring fields below and above the central plane, but with opposite directions.

In symmetric (S-type) fields of any mode, the radial field direction is preserved above and below the central plane of the galaxy. In the antisymmetric (A-) case, the radial component changes its sign at the central plane. Fields of predominantly S0 mode (with admixtures of higher even modes S2, S4, ...) are directed either inwards or outwards everywhere in a galaxy, while fields of predominantly $m > 0$ modes change their direction within the galaxy. An inward-directed spiral means an inward-directed radial component of the magnetic field. The classification of dynamo-excited fields does not distinguish between inward- and outward-directed fields.

Radio polarization observations at high frequencies yield *no directions*, only *orientations* of magnetic field lines which are ambiguous by multiples of $180°$. Regular magnetic fields in normal galaxies generally reveal spiral shapes, but with the strongest regular fields generally located *between* the optical spiral arms (Krause et al. 1989, Beck & Hoernes 1996, Beck et al. 1996), with the exception of M51 where the field is compressed by strong density waves (Neininger & Horellou 1996). Due to the angle ambiguity, polarization data at one single frequency are insufficient to determine field directions.

Faraday rotation between several frequencies allows to determine the *direction* of the regular field along the line of sight. The variation of Faraday rotation measures (RM) along the azimuthal angle reveals the type of azimuthal symmetry in the central plane if it is inclined against the plane of the sky (Krause 1990). Present-day data indicate that both axisymmetric $(m = 0)$, bisymmetric $(m = 1)$ and mixed modes are present in galaxies (Beck et al. 1996). Dominating $m = 0$ modes (with a weaker $m = 1$ mode superimposed) were found in M31, IC 342 and NGC 253, while M81 and possibly M33 and NGC 2276 host a dominating $m = 1$ mode. In M51 the $m = 0$ and $m = 1$ modes are mixed with about equal weights (Berkhuijsen et al. 1997). A candidate for a $m = 2$ mode mixed with a $m = 0$ mode is NGC 6946 (Beck & Hoernes 1996; see Fig. 2). For all other galaxies observed so far the results are not yet conclusive. Modes higher than $m = 2$ may also exist but are difficult to detect with the present-day accuracy of radio observations.

The type of symmetry with respect to the central plane (S or A) is hard to determine in mildly inclined galaxies because the observable RM average along the line of sight differs only by a factor of two. The analysis of disk dynamos near the dynamo instability indicates that a S0-mode is generally excited preferentially (Elstner et al. 1992) and the regular magnetic fields are strongest in the region of strong differential rotation. In special conditions, however, an A0-mode may also be excited.

Edge-on galaxies, on the other hand, have small regular field components along the line of sight and thus low RM values. Observations of NGC 4631 (Golla & Hummel 1994) were inconclusive, and the data for NGC 253 (Beck et al. 1994) gave only weak evidence for the even field symmetry S0.

The best way to investigate the field symmetry is the distribution of pulsar RMs in our own Galaxy. Han et al. (1997) discussed a possible A0-component in the local Galactic magnetic field, but more data are needed for a reliable result.

If all S-type fields in external galaxies with a predominantly $m = 0$ mode had the same direction (either inwards or outwards), there is a simple method to detect any dominance of S- or A-type fields:

In the S0-case the radial component is determined by the quadrupolar field which either enters the disk at the edge and leaves it at the central regions or, vice versa, enters the disk at the central region and leaves it at the edge. Consequently, observations of arbitrarily in space orientated galaxies will show a preferred direction of the magnetic field.

In A0-type fields, i.e. those which change sign at the central plane, one would observe a rotation measure that is smaller by a factor of two because the polarization vectors of the emission from the far-side toroidal field are rotated in the far-side field, but re-rotated in the near-side field. The sign of the observable RM average is determined by the near-side field. Thus one would observe an inward (outward) field direction if looking from the one side, but an outward (inward) field direction if looking from the other side. Consequently, the average over an ensemble of galaxies with even A0-fields orientated arbitrarily in space will not reveal any preferred direction. If the observation of a preferred field direction were to be generally confirmed, this would be an indirect evidence for the excitation of predominantly S0-fields in galaxies.

2.2. Radial directions

Faraday rotation tells us the sign of the line-of-sight component of the regular field. The radial component of a dominating axisymmetric ($m = 0$) mode can be detected in inclined disks of galaxies by observing the azimuthal variation of RM. Any non-zero phase of this variation indicates radial fields, e.g. due to the pitch angle of a spiral field (Krause 1990). As RM near the minor axis of the galactic disk is small, it is sufficient to determine the direction of radial field components from RM near the major axis, or, in case of edge-on galaxies in the outer disk regions.

Deciding whether the radial field in a galaxy with a predominantly S0 mode points inwards or outwards needs knowledge about the near and far side of the galaxy. As spiral arms are generally trailing, the near and far sides follow from the observed velocity field. Comparing the signs of the radial velocity and RM yields the radial direction, again assuming trailing spiral arms. If both quantities have the same sign, the radial field points outwards, while opposite signs indicate inward direction (Fig. 1). In M31 (Beck 1982), IC 342 (Gräve & Beck 1988,

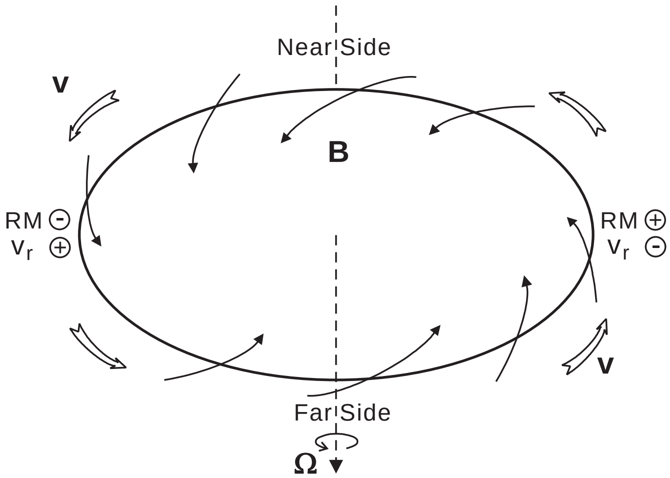

Fig. 1. Signs of the radial component of rotational velocity $v_{\rm r}$ and of the Faraday rotation measure RM in an inclined galactic disk with trailing spiral arms and with a predominantly S0 field

Krause et al. 1989) and NGC 253 (Beck et al. 1994) the signs are opposite, indicative of the *inward* direction.

The case of NGC 6946 is of special interest. Early RM analysis indicated a RM distribution resembling S0 fields, but with a "wrong phase" of its azimuthal variation (Ehle & Beck 1993). More recent high-resolution observations showed that the regular magnetic fields are concentrated in two "magnetic arms" so that the distribution is far from being axisymmetric (Beck & Hoernes 1996). A superposition of $m = 0$ and $m = 2$ modes may explain the data. For a mixture of these even azimuthal modes with equal weights, there is still a general direction of the radial field component. In NGC 6946, the high-resolution RM distribution shows positive on the northern (near) side and negative values an the southern (far) side (Fig. 2), again opposite signs compared with the velocity field.

The only exception among the spiral galaxies observed so far is M51: The distribution of RM at four wavelengths indicates that the $m = 0$ part of its disk field points outwards, while the halo field (where $m = 0$ dominates) points inwards, with a similar pitch angle as the disk field (Berkhuijsen et al. 1997). Hence the magnetic field morphology of M51 is quite unusual, probably a result of the interaction with its companion galaxy.

Statistics tells us that the by-chance probability of four "inward" fields in a sample of four cases is $1/2^4 = 6.25\%$. Taking M51 as a full member of the sample, the by-chance probability increases to $5/2^5 = 15.625\%$. Already two more "inward" cases would decrease the by-chance probability to 5%. This will be possible to test by observations in the near future.[1]

Pursuing the reason of the preferred inward field direction we have to search for properly directed seed fields.

[1] After this paper had been accepted, Shoutenkov & Beck discovered another case of an inward-directed $m = 0$ field in the barred galaxy NGC 1097.

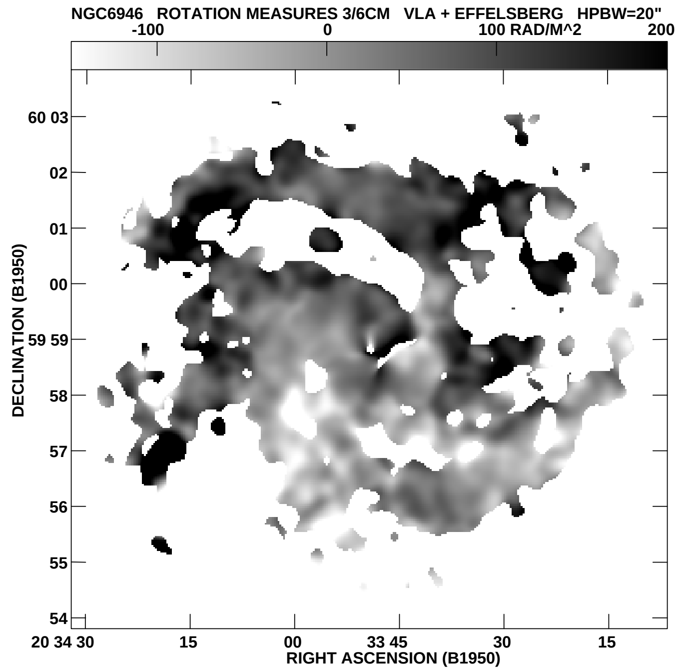

Fig. 2. Distribution of Faraday rotation measures (in $\rm rad/m^2$) between 6 cm and 3 cm wavelengths in the spiral galaxy NGC 6946 at $20''$ angular resolution. Both polarization maps are results of merging the observations from the VLA and Effelsberg radio telescopes (Beck et al., in prep.).

3. Large-scale magnetic fields in a pregalactic cosmos

Let us consider a Universe without any structure, i.e. homogeneously filled with matter which is in irregular motion. These motions we assume to be of random character, described by a homogeneous isotropic and, apart from the general expansion, steady turbulence. The matter is assumed to be electrically conducting. Here we rely on the consequences of the absence of Lyα absorption troughs in the spectra of even the highest redshift $(z \geq 4)$ QSOs, which indicate that the intergalactic matter is highly ionized below redshifts below $z \sim 5$ (Gunn & Peterson 1965).

The Biermann-battery mechanism describes an impressed electromotive force $\mathbf{E}_{\rm imp}$ proportional to $\frac{{\rm d}\mathbf{u}}{{\rm d}t}$,

$$\mathbf{E}_{\rm imp} = \gamma \, \frac{{\rm d}\mathbf{u}}{{\rm d}t} = \gamma \left\{ \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot {\rm grad})\mathbf{u} \right\} , \qquad (1)$$

where $\mathbf{u}$ represents the velocity field and γ a certain constant. The formation of a magnetic field is described by the inhomogeneous induction equation

$$\frac{\partial \mathbf{B}}{\partial t} - {\rm curl}\,(\mathbf{u} \times \mathbf{B}) - \eta \triangle \mathbf{B} = \, {\rm curl}\, \mathbf{E}_{\rm imp} \, , \qquad (2)$$

where $\mathbf{B}$ denotes the magnetic field and η the magnetic diffusivity.

We are interested in the large-scale magnetic fields. In particular we will investigate whether there are concerted actions of the fluctuating small-scale fields which provide these large-scale fields.

We define

$$\mathbf{u} = \overline{\mathbf{u}} + \mathbf{u}', \ \mathbf{B} = \overline{\mathbf{B}} + \mathbf{B}', \ \mathbf{E}_{\rm imp} = \overline{\mathbf{E}_{\rm imp}} + \mathbf{E}'_{\rm imp} \,, \tag{3}$$

where the bar indicates the average and the dash the fluctuations. Since

$$\begin{aligned} \overline{\frac{\mathrm{d}\mathbf{u}}{\mathrm{d}t}} &= \overline{\frac{\partial \mathbf{u}}{\partial t}} + \overline{(\mathbf{u}\cdot \mathrm{grad})\mathbf{u}} \\ &= \frac{\partial \overline{\mathbf{u}}}{\partial t} + (\overline{\mathbf{u}}\cdot \mathrm{grad})\overline{\mathbf{u}} + \overline{(\mathbf{u}'\cdot \mathrm{grad})\mathbf{u}'} \,, \end{aligned} \tag{4}$$

we find from Eqs. (1) and (2)

$$\begin{aligned} \frac{\partial \overline{\mathbf{B}}}{\partial t} \ - \ \mathrm{curl}\,(\overline{\mathbf{u}}\times\overline{\mathbf{B}}) - \eta \bigtriangleup \overline{\mathbf{B}} = \mathrm{curl}\Bigg(& \overline{\mathbf{u}'\times\mathbf{B}'} \\ & +\gamma \left\{ \frac{\partial \overline{\mathbf{u}}}{\partial t} + (\overline{\mathbf{u}}\cdot \mathrm{grad})\overline{\mathbf{u}} + \overline{(\mathbf{u}'\cdot \mathrm{grad})\mathbf{u}'} \right\} \Bigg) \ . \end{aligned} \tag{5}$$

It is obvious that a mean magnetic field may be formed from temporal changes of the vorticity of a mean velocity field, the Reynolds stresses of the mean velocity field and the Reynolds stresses of the fluctuations, in case the latter two have a non-vanishing curl.

Consider the case of a structureless Universe, i.e. there are no mean motions, and averages of the fluctuations, if unequal zero, do not depend on the spatial coordinates. We thus see that no mean magnetic field will be generated. However, fluctuating magnetic fields will be formed, as we can see from Eq. (2). This question for the effects of the fluctuations is still unanswered and needs further treatment.

By subtracting Eq. (5) from (2) we find with (3)

$$\begin{aligned} \frac{\partial \mathbf{B}'}{\partial t} \ = \ & \mathrm{curl}\left(\mathbf{u}'\times\overline{\mathbf{B}} + \overline{\mathbf{u}}\times\mathbf{B}' + \mathbf{u}'\times\mathbf{B}' \right. \\ & \left. - \overline{\mathbf{u}'\times\mathbf{B}'} + \mathbf{E}'_{\rm imp}\right) - \eta \bigtriangleup \mathbf{B}' \,. \end{aligned} \tag{6}$$

With

$$\overline{\mathbf{E}_{\rm imp}} = \gamma \left\{ \frac{\partial \overline{\mathbf{u}}}{\partial t} + (\overline{\mathbf{u}}\cdot\nabla)\overline{\mathbf{u}} \ + \ \overline{(\mathbf{u}'\cdot\nabla)\mathbf{u}'} \right\} \,, \tag{7}$$

we find

$$\begin{aligned} \mathbf{E}'_{\rm imp} \ &= \ \mathbf{E}_{\rm imp} - \overline{\mathbf{E}_{\rm imp}} \\ &= \ \frac{\partial \mathbf{u}'}{\partial t} + (\overline{\mathbf{u}}\cdot\nabla)\mathbf{u}' \ + \ (\mathbf{u}'\cdot\nabla)\overline{\mathbf{u}} \\ &\quad + (\mathbf{u}'\cdot\nabla)\mathbf{u}' \ - \ \overline{(\mathbf{u}'\cdot\nabla)\mathbf{u}'} \,. \end{aligned} \tag{8}$$

Under the conditions of vanishing mean flow and homogeneity of the fluctuating fields this equation can be reduced to

$$\frac{\partial \mathbf{B}'}{\partial t} - \mathrm{curl}\,(\mathbf{u}'\times\mathbf{B}') - \eta \bigtriangleup \mathbf{B}' = \mathrm{curl}\,\mathbf{E}'_{\rm imp} \,, \tag{9}$$

and, taking into account Eq. (8), we obtain

$$\begin{aligned} \frac{\partial \mathbf{B}'}{\partial t} \ &- \ \mathrm{curl}\,(\mathbf{u}'\times\mathbf{B}') - \eta \bigtriangleup \mathbf{B}' \\ &= \ \gamma\,\mathrm{curl}\left(\frac{\partial \mathbf{u}'}{\partial t} + (\mathbf{u}'\cdot\nabla)\mathbf{u}' \right) \ . \end{aligned} \tag{10}$$

Magnetic fields are generated in two ways: First, there is a source term (the battery) on the right-hand side, which causes currents to flow and magnetic fields to appear. Further, the velocity field interacts with the magnetic fields and, by stretching and folding, the field strength will be increased up to the equipartition value. This is the old idea of Biermann (1950, 1952) and Schlüter & Biermann (1950) for explaining the existence of a Galactic magnetic field. They analysed the strength of the magnetic field which is produced by the battery if the involved motions are identified with the motions of the interstellar gas. Their estimate led to a field strength of about 10^{-16} G.

In order to analyze the first step we omit the second term of the left-hand side of Eq. (10) in the following. Furthermore, we neglect the time derivative of the velocity field on the right-hand side. Hence we consider the equation

$$\frac{\partial \mathbf{B}'}{\partial t} - \eta \bigtriangleup \mathbf{B}' = \ \gamma\,\mathrm{curl}\,((\mathbf{u}'\cdot\nabla)\mathbf{u}') \ , \tag{11}$$

which may be integrated by

$$\begin{aligned} B'_h(\mathbf{x},t) \ = \ \gamma \int_{t_0}^{t} \int & G(\mathbf{x}-\xi, t-\tau)\gamma\epsilon_{hij} \\ & \frac{\partial}{\partial \xi_i}\left(u'_k(\xi,\tau)\frac{\partial u'_j(\xi,\tau)}{\partial \xi_k}\right) \mathrm{d}\xi\,\mathrm{d}\tau \,. \end{aligned} \tag{12}$$

Here we introduced the Green's function

$$G(\mathbf{x},t) = \left(\frac{1}{4\pi\eta t}\right)^{3/2} \exp\left\{\frac{-x^2}{4\eta t}\right\} \,, \tag{13}$$

where $x = \mid \mathbf{x} \mid$.

We now introduce the vector

$$\mathcal{R}(\mathbf{x},t) = \mathrm{curl}\ \left[\left(\mathbf{u}'(\mathbf{x},t)\cdot\nabla\right)\mathbf{u}'(\mathbf{x},t)\right] \,, \tag{14}$$

with the components

$$\mathcal{R}_h = \epsilon_{hij}\,\frac{\partial}{\partial x_i}\left(u'_l\,\frac{\partial u'_j}{\partial x_l}\right) \ . \tag{15}$$

If we assume that the fluctuations of the velocity field are represented by a homogeneous, isotropic and steady random field, the vector field $\mathcal{R}$ will also be a random field of this type, i.e. the tensor

$$\mathcal{R}_{hk}(\mathbf{x},\xi,t,\tau) \ = \ \overline{\mathcal{R}_h(\mathbf{x},t)\mathcal{R}_k(\mathbf{x}+\xi,t+\tau)} \tag{16}$$

does especially not depend on **x** and t.

We are interested in the mean square of the fluctuations. With the notation introduced before we have

$$\begin{aligned} \overline{\mathbf{B}'^2(\mathbf{x},t)} \ = \ \gamma^2 \int_{t_0}^{t}\int\int_{t_0}^{t}\int & G(\mathbf{x}-\xi,t-\tau)\,G(\mathbf{x}-\eta,t-\sigma) \\ & \mathcal{R}_{hh}(\xi-\eta,\tau-\sigma)\,\mathrm{d}\xi\,\mathrm{d}\tau\,\mathrm{d}\eta\,\mathrm{d}\sigma \,, \end{aligned} \tag{17}$$

where $\mathcal{R}_{hh}$, with respect to the spatial coordinates, depends on the magnitude $\mid \xi - \eta \mid$ only because of isotropy. With the relation

$$\int G(\xi,\tau)\,G(\mathbf{x}-\xi,t-\tau)\,\mathrm{d}\xi \ = \ G(\mathbf{x},t) \tag{18}$$

we find

$$\overline{\mathbf{B}'^2(\mathbf{x},t)} = \gamma^2 \int_{t_0}^{t} \int G(\zeta,\omega)\mathcal{R}_{hh}(\zeta,\omega)\,\mathrm{d}\zeta\,\mathrm{d}\omega\ . \tag{19}$$

Let $\mathbf{u}'$ be an irrotational field, i.e. it can be represented by $\mathbf{u}' = \nabla\Phi$. Then we have

$$\begin{aligned}\mathcal{R}_h &= \epsilon_{hij}\,\frac{\partial}{\partial x_i}\left(u'_l\,\frac{\partial u'_j}{\partial x_l}\right) = \epsilon_{hij}\,\frac{\partial}{\partial x_i}\left(\frac{\partial\Phi}{\partial x_l}\,\frac{\partial^2\Phi}{\partial x_j\partial x_l}\right)\\ &= \epsilon_{hij}\left\{\frac{\partial\Phi}{\partial x_l}\,\frac{\partial^3\Phi}{\partial x_l\partial x_i\partial x_j} + \frac{\partial^2\Phi}{\partial x_i\partial x_l}\,\frac{\partial^2\Phi}{\partial x_j\partial x_l}\right\}\\ &= 0\ .\end{aligned} \tag{20}$$

We learn here that $\mathcal{R} = 0$, i.e. an irrotational field, does not provide magnetic fields. In so far the idea that such battery effect could provide magnetic fields in the early Universe "has lost favour, because whirls decay during the cosmic expansion, whereas irrotational density perturbations (arising from initial curvature fluctuations) would grow" (Rees 1987).

If we consider density fluctuations causing the turbulence of the intergalactic (pregalactic) medium, they will be of no interest for the generation of magnetic fields unless nonlinear interactions appear (e.g. shocks).

In a pregalactic medium magnetic fields may be generated by the Biermann-battery effect in the case where there is turbulence with non-zero vorticity. The magnetic fields will have the scales of the turbulence, and no large-scale field pervading the cosmos will be formed. However, there are indications from numerical simulations that the scales of the turbulent magnetic fields will grow in the course of time (Brandenburg et al. 1996, Kulsrud et al. 1997).

It should, however, be noted that even in the case of a large-scale magnetic field in the Universe, no seed field with a preferred direction will be formed in a pregalactic disk. Such fields will enter the pregalactic disk on one side and leave it on the other one. The component of this field parallel to the central plane dies out because of the skin-effect due to the differential rotation (Wielebinski & Krause 1993). The vertical component provides a seed field of A0-symmetry. Thus no field directed towards the centre will be formed.

4. Magnetic seed fields in a rotating disk formed by the Biermann-battery effect

A flat region which is filled with ionized, i.e. electrically conducting, matter will represent our model of a galaxy in the following. Let ρ be the density of the matter. The galaxy shows an overall rotation, denoted by $\overline{\mathbf{u}}$, combined with internal small-scale, turbulent motions, denoted by $\mathbf{u}'$. Let the region itself and all quantities show symmetry with respect to a certain axis, the axis of rotation, and with respect to a certain plane, the central plane. Let the mean quantities derived from fluctuating ones also show these symmetries. Further, let us assume that all these quantities do not depend on time.

Under these conditions we find from Eq. (5) for the mean magnetic field the equation

$$\begin{aligned}\frac{\partial\overline{\mathbf{B}}}{\partial t} \;-\; \mathrm{curl}\,(\overline{\mathbf{u}}\times\overline{\mathbf{B}}+\mathcal{E}) \;-\;\eta\,\triangle\,\overline{\mathbf{B}}\\ = \gamma\,\mathrm{curl}\left((\overline{\mathbf{u}}\cdot\mathrm{grad})\overline{\mathbf{u}} + \overline{(\mathbf{u}'\cdot\mathrm{grad})\mathbf{u}'}\right)\ ,\end{aligned} \tag{21}$$

where $\mathcal{E}$ denotes the turbulent emf

$$\mathcal{E} = \overline{\mathbf{u}'\times\mathbf{B}'}\ . \tag{22}$$

We will introduce a cartesian coordinate system $\mathbf{x} = (x, y, z)$ with the z-axis as axis of rotation, and $\mathbf{e}_\mathrm{r} = r^{-1}(x, y, 0)$ with $r = \sqrt{x^2+y^2}$ the radial unit vector in the planes orthogonal to the axis of rotation. We also will use the corresponding system of cylinder coordinates (r, ϕ, z).

Let the rotational motion $\overline{\mathbf{u}}$ be represented by

$$\overline{\mathbf{u}} = \mathbf{\Omega}\times\mathbf{x}\ , \tag{23}$$

$\mathbf{\Omega} = (0, 0, \Omega(r, z))$ denotes the angular velocity. Due to the symmetries assumed above, $\Omega(r, z)$ is an even function of z, i.e. $\Omega(r, z) = \Omega(r, -z)$. The same also holds for the density: $\rho(r, z) = \rho(r, -z)$.

According to the right-hand side of Eq. (21), large-scale magnetic seed fields are produced by the impressed electromotive forces due to both the differential rotation and the concerted action of the turbulent motions. Let these electromotive forces be denoted by $\mathbf{E}^{(1)}_\mathrm{imp}$ and $\mathbf{E}^{(2)}_\mathrm{imp}$, respectively. The produced seed fields undergo dynamo excitation by the concerted action of the turbulent motions, represented by the turbulent electromotive force $\mathcal{E}$ at the left-hand side of Eq. (21), and amplification by the differential rotation, represented by $\overline{\mathbf{u}}\times\overline{\mathbf{B}}$.

4.1. Magnetic seed fields due to differential rotation

From Eq. (23) we find

$$\mathbf{E}^{(1)}_\mathrm{imp} = \gamma(\overline{\mathbf{u}}\cdot\nabla)\overline{\mathbf{u}} = -\gamma\,\Omega^2 r\,\mathbf{e}_\mathrm{r}\ , \tag{24}$$

Currents will flow and magnetic fields will be formed in case $\mathbf{E}^{(1)}_\mathrm{imp}$ has a non-vanishing curl. We find

$$\mathrm{curl}\,\mathbf{E}^{(1)}_\mathrm{imp} = \mathrm{curl}\,(-\gamma\,\Omega^2 r\,\mathbf{e}_\mathrm{r}) = -\,\gamma\,\frac{\partial\Omega^2 r}{\partial z}\,\mathbf{e}_\phi\ . \tag{25}$$

It is thus obvious that the *radial* dependence of the angular velocity has no influence on the formation of the magnetic field. Only the dependence of Ω on z provides a magnetic field, which will be formed in the course of time. This field is toroidal and Schlüter & Biermann (1950) estimated an order of magnitude 10^{-17} to 10^{-15} G.

Since the angular velocity Ω is an even function of z, the toroidal field $\mathrm{curl}\,\mathbf{E}^{(1)}_\mathrm{imp}$ is of odd parity, it consists of two field belts, arranged symmetrically to the central plane but with opposite field directions.

By the dynamo processes, especially by the α-effect involved in the turbulent emf $\mathcal{E}$ on the left-hand side of Eq. (21), also a dipolar poloidal field part will be formed. Finally an odd-parity field, of type A0, grows exponentially with time.

The Biermann-battery effect due to the differential rotation does indeed provide a large-scale magnetic seed field, however, this field is of symmetry A0. The field generated from this seed field by the dynamo process will have the same symmetry. A preferred inward direction of the magnetic field cannot be explained in this way.

To further investigate the above question we consider the concerted action of small-scale motions which undergo the influence of the overall differential rotation.

4.2. *Large-scale magnetic seed fields due to small-scale motions*

The impressed emf $\mathbf{E}^{(2)}_{\rm imp}$, is given by

$$\mathbf{E}^{(2)}_{\rm imp} = \gamma\overline{(\mathbf{u'}\cdot\mathrm{grad})\mathbf{u'}}\,. \tag{26}$$

The detailed evaluation of this expression is clearly a complicated problem of turbulence theory. However, as is shown in the following, we can arrive at the desired results on the basis of some general arguments, which are widely used in the theory of the turbulent dynamo (cf. Krause & Rädler 1980).

The expression $\mathrm{curl}\,\mathbf{E}^{(2)}_{\rm imp}$ is an axial vector, derived by average processes from the turbulent motions of the interstellar gas in a galaxy. In case it is calculated in detail, it can only be a proper combination of the physical quantities which determine the dynamics of the interstellar gas, that are in our context
(i) the angular velocity $\mathbf{\Omega}$,
(ii) the density ρ,
(iii) the magnitude of the angular velocity Ω^2.

The angular velocity itself is an axial vector, thus suitable as a constituent of $\mathrm{curl}\,\mathbf{E}^{(2)}_{\rm imp}$. It is of dipolar type A0, of odd parity. According to our model the scalars ρ and Ω^2 are symmetric to the central plane, i.e. of even parity. We may derive further axial vectors by multiplying $\mathbf{\Omega}$ with one of the scalars ρ or Ω^2. All these vectors are of odd parity, and no axial vector of even parity will appear.

We can now construct further quantities by applying the differential operators $\frac{\partial}{\partial x_j}$ and $\epsilon_{ijk}\frac{\partial}{\partial x_j}$. The latter operator changes a quantity from an axial one into a polar one or vice versa. We arrive at the polar vectors $\mathrm{grad}\,\rho$, $\mathrm{grad}\,\Omega^2$ and $\mathrm{curl}\,\mathbf{\Omega}$, and the pseudo-scalars $\mathrm{div}\,\mathbf{\Omega}$ and $\mathbf{\Omega}\cdot\mathrm{grad}\,\rho$, $\mathbf{\Omega}\cdot\mathrm{grad}\,\Omega^2$.

The three polar vectors are of even parity, the pseudo-scalars of odd parity. Possible axial vectors we may derive by multiplying the three polar vectors $\mathrm{grad}\,\rho$, $\mathrm{grad}\,\Omega^2$, $\mathrm{curl}\,\mathbf{\Omega}$ with one of the pseudo-scalars $\mathrm{div}\,\mathbf{\Omega}$, $\mathbf{\Omega}\cdot\mathrm{grad}\,\rho$, $\mathbf{\Omega}\cdot\mathrm{grad}\,\Omega^2$. Further we find the cross product $\mathrm{grad}\,\rho\times\mathrm{grad}\,\Omega^2$. All vectors are of odd parity, of symmetry type A0.

We can now proceed further in the same way. However, with the operations mentioned above, which are the only possible ones, we will in any case arrive at axial vectors of odd parity only. Hence, also the concerted action of the small-scale turbulent motions cannot provide seed fields of type S0. In all cases the fields are of type A0, antisymmetric with respect to the central plane.

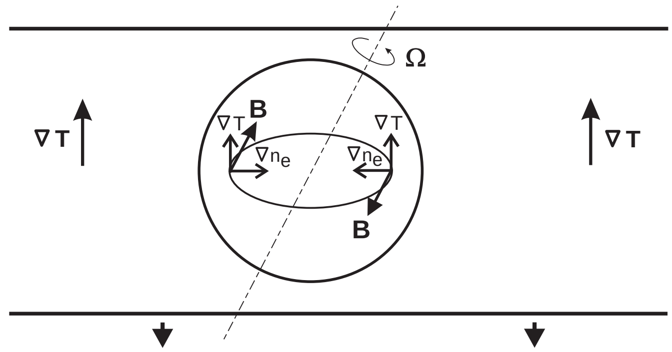

Fig. 3. A magnetic field will be formed if a ionization front crosses a protogalactic cloud. This field $\mathbf{B}$ is parallel to the cross product of the gradient of the temperature T of the intergalactic medium and the gradient of the electron density $n_{\rm e}$ in the cloud. Ω denotes the angular velocity of the overall rotation of the cloud.

5. Ionization fronts crossing density fluctuations

We saw in the foregoing chapter that it is impossible to find an axial vector of even parity in a system with the symmetries assumed there, where we have scalars of even symmetry only. The conditions will be significantly different in case we have a scalar of odd symmetry. A physical situation of that kind, which may appear in the pregalactic cosmos, was described by Subramanian et al. (1994).

The authors considered the case of an ionization front crossing a density fluctuation. In addition to the scalars characterizing the (say, for simplicity, spherical) density fluctuation we have a scalar characterizing the ionization front, the temperature of the intergalactic medium. Assuming plane geometry of the ionization front, the gradient of this temperature is a polar vector which, with respect to the symmetries of the spherical fluctuation, shows odd parity (Fig. 3). Thus we have the possibility to construct an axial vector of even parity.

The following model may illustrate the situation: Across an ionization front an impressed emf $\mathbf{E}^{(if)}_{\rm imp}$ arises which is given by

$$\mathbf{E}^{(if)}_{\rm imp} = -\frac{\mathrm{grad}\,p_{\rm e}}{e n_{\rm e}}\,. \tag{27}$$

e denotes the charge of an electron, $n_{\rm e}$ the electron density and $p_{\rm e}$ the electron pressure, which is given by $p_{\rm e} = n_{\rm e}kT$. T denotes the temperature. If we insert this emf into Eq. (2) we arrive at

$$\frac{\partial\mathbf{B}}{\partial t} - \mathrm{curl}\,(\mathbf{u}\times\mathbf{B}) - \eta\triangle\mathbf{B} = -\frac{k}{e n_{\rm e}}(\mathrm{grad}\,n_{e}\times\mathrm{grad}\,T)\,. \tag{28}$$

Let us define an "axis" of the sphere which is normal to the ionization front and with respect to this axis is an "equatorial plane". Then the axial vector at the right-hand side of Eq. (28) represents a toroidal vector field encircling this axis. At the entrance into the sphere $\mathrm{grad}\,n_{\rm e}$ and $\mathrm{grad}\,T$ will be parallel, and the cross product in Eq. (28) is zero. When the front has crossed half of the sphere, i.e. arriving at the "equatorial plane", $\mathrm{grad}\, n_\mathrm{e} \times \mathrm{grad}\, T$ will be at maximum, and will go again to zero when the front leaves the sphere. The magnetic field produced in the course of time will also show the same shape. With respect to the axis normal to the ionization front this magnetic field will be toroidal, and, on the assumption of weak attenuation of the ionization front when crossing the sphere, it will show symmetry with respect to the "equatorial plane" and will be strongest there.

The geometry of the dynamo working in this protogalactic cloud is related to the axis of rotation. Hereby the fastest growing mode is represented by a toroidal field belt around the equatorial plane, and this field coincides with that described above only if the normal of the ionization front is parallel to the axis of rotation. In this case the produced magnetic field is, indeed, a proper seed field for a S0-dynamo mode. In case the normal to the ionization front and the axis of rotation are inclined at a certain angle, the projection of the induced magnetic field in the equatorial plane may also serve as such a seed field.

Let us come back to the point whether these seed fields may show a preferred direction, inwards to the centre of the pregalactic cloud.

First we have to note that the inward direction is coupled to the poloidal field with the radial component B_r. Since the considered seed field is purely (mainly) toroidal, a radial component will not appear unless dynamo action starts. It is the common view that an $\alpha\Omega$-dynamo is responsible for the built-up of a large-scale field in a galaxy. Hereby the poloidal field is formed from the toroidal field by the α-effect. It will change its sign if α changes its sign. The α-effect is caused by rotation and, especially, is an odd function of the angular velocity. Consequently, for a fixed direction of the toroidal field, the poloidal field changes its sign if the angular velocity Ω changes its sign.

Let us consider the ionization front crossing the density fluctuation. Then the cross-product of both the gradients in Eq. (28) provide a toroidal field with a definite direction. Let the density fluctuation rotate about a certain axis. Now the dynamo is working and produces a poloidal field. However, the cloud can rotate in either sense. Therefore α can have either sign, and the induced poloidal field can be either directed inwards or outwards. No preferred direction can be explained in this way.

6. Discussions and conclusions

The investigations of disk dynamos lead to the result that in the most reasonable models there is a (at least slight) preference of S0-type fields in competition with those of A0-type (Stix 1975, Brandenburg et al. 1990, Elstner et al. 1992). Hence, from a background of small magnetic seed fields, the dynamo will preferentially excite that of symmetry type S0.

Likewise, observations suggest that a significant (possibly dominant) fraction of the large-scale fields in galaxies show S0 symmetry and, in addition, are directed inwards (Sect. 2). If this is not an effect of insufficient statistics, what could be the origin of S0-type seed fields?

We first considered in detail the generation of large-scale seed fields in a protogalactic cloud by the Biermann effect due to different motions. Assuming the natural symmetries in such a cloud we found seed fields of A0-symmetry only. However, in reality a galaxy is never as symmetric as we assumed in our consideration. Deviations from symmetry with respect to the central plane will be the cause that the produced magnetic seed fields will not be of genuine A0-type, but there will be also a S0-part. Since the dynamo excites this part with preference, it will also dominate after some time.

Seed fields may also be generated locally, e.g. from a contamination of the interstellar space by magnetic fields from early stars, from supernova explosions, from AGNs and radio galaxies (Rees 1994). Fields on the scale of a galaxy can only be formed by random superposition of these more local fields. Hence, no preference of one or the other field type is given here, and the magnitude of the large-scale field component may be significantly smaller than the magnitude estimated for the small-scale component.

As we have shown, the ionization-front mechanism proposed by Subramanian et al. (1994) provides a seed field of the desired symmetry type S0. The dynamo will preferentially excite the projection of the seed field in the geometry set by the rotational motion, and the resulting field will be of type S0. However, we have not found an answer to the question of the preferred inward direction: The cloud can rotate about a fixed axis in one or the other sense, hence the poloidal field produced by the dynamo can be either directed inwards or outwards.

There is a scenario where a preferred inward direction of the magnetic fields in a group of nearby galaxies may appear. Assume a group of galaxies originating from a larger protogalactic cloud by fragmentation. The protogalactic cloud should show a certain angular momentum which by the process of fragmentation is distributed among the individual fragments. Hence these galaxies will possess rotation axes which are more or less aligned. If these galaxies are crossed by the same extended ionization front, the generated seed fields will show the same direction, and so will the dynamo-excited fields.

If the direction of the rotation axes of a group of galaxies is the same in space, the observed inclination with respect to the sky plane would be of opposite sign in opposite regions of the sky, and the sense of rotation would also be opposite. At small angular distances on sky, the sense of rotation should be the same, but the inclination should vary with distance along the minor axis of the ellipse of the projected galaxy plane.

The four galaxies of symmetry type S0 or S0+S2 (M31, IC 342, NGC 253 and NGC 6946) are located within 7 Mpc distance and could originate from the same protogalactic cloud. They have similar position angles of their rotation axes (between -40° and -53°) and the signs of inclination are the same (the northwestern half inclined towards us). This allows an immediate check whether the directions of their rotation axes are similar in space.

M31 and IC 342 have the same sense of rotation, and the difference of their inclinations of $\simeq 50^\circ$ is of the same order as their angular separation on the sky ($\simeq 30°$). Thus their rotation axes are indeed roughly aligned in space.

M31 and NGC 253, on the other hand, have an opposite sense of rotation although their angular distance is only $\simeq 65°$. Furthermore, their small inclination difference is not consistent with this angular separation. Finally, NGC 6946 is located at $\simeq 50°$ from M31, but also rotates in the opposite sense.

We have to conclude that in the case of the four galaxies under consideration there seems not to be a parallelism of their rotation axes. The results of our consideration provide no argument in favour of a preferred direction of the large-scale magnetic fields in a group of galaxies.

We cannot exclude that the observational results discussed in Sect. 2 are due to the small sample. We await with interest the results from a larger observational sample.

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