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Seed fields for galactic dynamos

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We demonstrate that a uniform cosmological seed field is a much less suitable seed field for a galactic dynamo than has often been expected. The age of the Universe is insufficient for a conventional galactic dynamo to generate a contemporary galactic magnetic field starting from such a seed, accepting conventional estimates for physical quantities. We discuss modifications to the scenario for the evolution of galactic magnetic fields implied by this result.

Keywords: Magnetic fields; Galaxies

1 Introduction

Magnetic fields are thought to be a result of dynamo action driven by galactic differential rotation and mirror asymmetric interstellar turbulence. A dynamo needs however a seed from which to generate the mature field. Two options are apparent. A very weak magnetic field can be created in a protogalaxy by a battery effect, and then excited by turbulent motions (the small scale dynamo), to produce a small-scale field of strength up to approximate equipartition with the turbulent motions. This then serves as a seed for a mean-field galactic dynamo (e.g. [1, 2]). This scenario appears uncontroversial given our present understanding of the physics of galaxies.

However there is also the possibility that a magnetic field can survive from a very early stage of the Universe's evolution, and serve then as a seed for a galactic dynamo (see for example the review [3]). This scenario also looks also attractive, in the context of recent claims concerning the presence of a significant magnetic field in the intergalactic medium [4], and has been discussed earlier in various other contexts (see e.g. [5]). A problem to be solved in the framework of this scenario is how then to excite a substantial magnetic field with a scale suitable for seeding a mean-field galactic dynamo, and then to maintain it against Ohmic losses between the epochs of recombination and galaxy formation. A straightforward possibility here is to consider a strictly homogeneous magnetic field which exists from the epoch of the Big Bang [6]. It has been widely accepted that a galactic mean-field dynamo can, without any

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obvious problems, use this field (provided it is sufficiently strong) as a seed from which to produce contemporary galactic magnetic fields. This idea has been accepted as obvious in many reviews (e.g. [1]).

An obvious way to attempt to distinguish between the above scenarios is to formulate observable predictions from each of them, and to propose them for confrontation with future observations with forthcoming telescopes such as LOFAR and SKA. Some predictions for the first of these possibilities were suggested in [7].

Our original intention when starting this work was to suggest some observational tests for the second scenario. In the spirit of this intention we performed numerical simulations of a galactic dynamo model with a homogeneous seed. Contrary to the usual expectations, we arrived at the conclusion that a homogeneous seed is not as suitable as has been widely thought for generation of a contemporary galactic magnetic field. The aim of this paper is to present and elaborate this finding.

2 The code

We use a thin disc galaxy code that employs the "no-z" formulation (e.g. [8, 9] and subsequent papers), taking the $\alpha\omega$ approximation, and including the correction factors for the vertical diffusion described in [10]. This code solves explicitly for the field components parallel to the disc plane with the implicit understanding that the component perpendicular to this plane is given by the condition $\nabla \cdot \mathbf{B} = 0$. The only novel feature is that the code is now written in cartesian coordinates x, y, z, with z-axis parallel to the rotation axis. The key parameters are the aspect ratio $\lambda = h/R$, where h is the disc semi-thickness and R its radius, and the dynamo numbers $R_\alpha = \alpha_0 R/\eta, R_\omega = \Omega_0 R^2/\eta$. η is the turbulent diffusivity, assumed uniform, and α_0, Ω_0 are typical values of the α-coefficient and angular velocity respectively. Of course, in principle in the $\alpha\omega$ approximation the parameters R_α, R_ω can be combined into a single dynamo number $D = R_\alpha R_\omega$, but for reasons of convenience and clarity of interpretation we choose to keep them separate. A naive α-quenching nonlinearity is assumed.

For the rotation curve we take

$$r\frac{d\Omega}{dr} = -\frac{1}{rR}\tanh\left(\frac{rR}{0.3}\right) + \frac{1}{0.3\cosh^2(rR/0.3)}. \tag{1}$$

$\alpha = \alpha_0$ is assumed to be uniform.

In order to implement boundary conditions that $\mathbf{B} \to \mathbf{0}$ at the disc boundary (as used in earlier versions of the code written in polar coordinates), the disc region $x^2 + y^2 \le 1$ was embedded in a larger computational region $|x| \le x_\mathrm{b}, |y| \le y_\mathrm{b}$, where $x_\mathrm{b} = y_\mathrm{b} \approx 1.35$ (x and y are measured in units of R). In the region $x^2 + y^2 > 1$ outside of the disc the field satisfies the diffusion equation without dynamo terms. This was found to give solutions that were small at the disc boundary, and rapidly became negligible outside of the disc. The standard implementation used a uniform grid of 115×115 points over $-1 \le x, y \le +1$, with appropriate additional points in the surrounding "buffer zone". With a nominal galaxy radius of 10 kpc, this gives a resolution of about 175 pc.

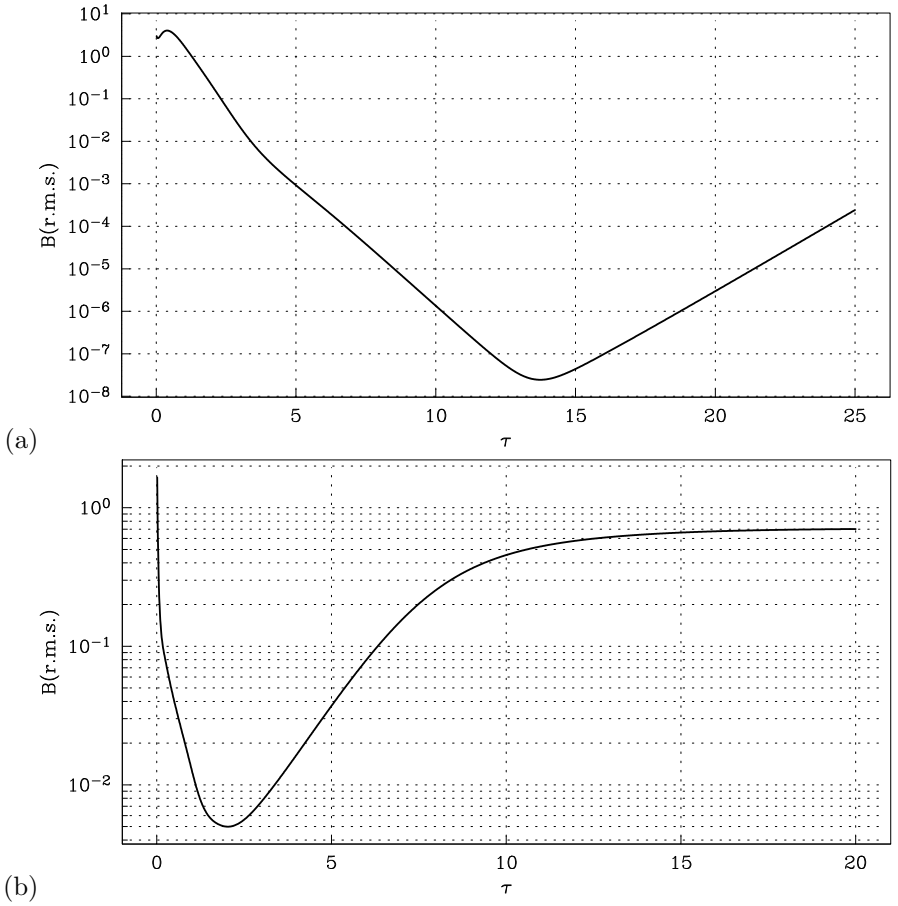


Figure 1 The evolution of the magnetic field for $R_\alpha = 0.8, R_\omega = 8$: (a) uniform seed field, (b) random seed field

3 Computational results

Length, time and magnetic field are nondimensionalized in units of R, h^2/η and the equipartition field strength $B_{\rm eq}$ respectively. Taking typical galactic values, we can estimate $R_\alpha = O(1)$, $R_\omega = O(10)$ (i.e. $D \approx 10$) with, however, a considerable degree of uncertainty. Of course these estimates apply to conditions in contemporary spiral galaxies, and may need revision for very young objects – we will return to this later. With $R = 10$ kpc, $h = 500$ pc gives $\lambda = 0.05$, and the unit of time is then approximately 0.75 Gyr.

From experiments with an arbitrary seed field, the marginal values are $R_\alpha \approx 0.6$ with $R_\omega = 8$, so the above estimates correspond to a slightly supercritical dynamo.

We first took a homogeneous seed field, $B_x = 1, B_y = 0$, with the slightly supercritical values $R_\alpha = 0.8, R_\omega = 8$. The field is wound up by the differential rotation in the anticipated manner, but its strength decays until time $\tau > 14$, i.e. of order the

age of the universe – see the evolution of the field strength with time shown in Fig. 1a. Only when the dynamo numbers are increased to something like $R_\alpha = 0.8, R_\omega = 20$ is there unambiguous growth after an initial relaxation phase.

In contrast to this very ordered seed field, we then took a field that was random in B_x, B_y on the scale of the grid, with r.m.s. value of unity. Now, with $R_\alpha = 0.8, R_\omega = 8$ growth is seen after a short initial relaxation – see Fig 1b.

The explanation for these contrasting behaviours is clear and straightforward. The uniform seed field has a Fourier component $m = 1$ only. In contrast, the random seed field contains all Fourier modes m. It is much harder to excite an $m = 1$ field than $m = 0$ – a well known result (e.g. [11]). In the second example the $m = 0$ part of the seed is selected and amplified, while in the linear regime at least, the other components decay. In Fig. 1a the eventual growth of the homogeneous seed when $\tau \gtrsim 14$ is from the amplification of numerical noise. (When this case is rerun with a code written in polar coordinates, this growth appears at a somewhat later time: the polar code preserves the Fourier structure of the field rather better than the cartesian.)

These conclusions were verified by simulations with several other large-scale seed fields: those with no $m = 0$ component behaved much as shown in Fig. 1a, whereas the behaviour of those with a $m = 0$ part resembled more closely that of Fig. 1b, with the initial fall in B(r.m.s.) being smaller for larger dynamo numbers or a larger proportion of the energy in the $m = 0$ component.

4 Discussion and conclusions

Note again that we have arrived at a quite unexpected conclusion: a uniform cosmological magnetic field is a "bad" seed for mean-field galactic dynamos.

Of course, this conclusion holds for the conventional estimate for the intensity of dynamo action, as measured by the dynamo number D, and estimated using knowledge of contemporary galaxies. It is possible that this estimate should be reconsidered for very young galaxies. However, the situation is unclear, and galactic dynamos can anyway work without any cosmological seed field.

The other point is that a uniform field, being affected by, say, small-scale turbulence or rotation of an asymmetric galactic disc, will acquire all modes including $m = 0$. Then a mean-field dynamo can take as a seed the $m = 0$ component so generated, and amplify it up to the currently observed field strengths and configurations. Thus our result does not exclude in principle the role of cosmological seed fields. The point however is that the growth of the initial field component $m = 0$ is then determined by a particular distortion that creates it, rather than being present in the cosmological field itself. Numerous such distortions will occur during early galactic evolution, and so the real difference between two scenarios seems to be much less important than is usually assumed.

Note that contemporary dynamo theory considers much more detailed dynamo models than the simple mean-field dynamo model that we have used. Detailed models, based on direct numerical simulations of the induction equation rather than on mean-field dynamo equations, include however both the galactic dynamo action and distortion of the uniform field by small-scale motions simultaneously, and demonstrate the joint action of both effects. In contrast, we are interested in separating them.

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