# Galaxy dynamo in inhomogeneous interstellar medium

E. A. Mikhailov[1] *, D. A. Grachev[1]

[1] *M.V.Lomonosov Moscow State University, Russia*

* *E-mail: ea.mikhajlov@physics.msu.ru*

**Abstract**

In some galaxies there are magnetic fields of several microgauss. Their evolution is connected with dynamo mechanism which is based on joint action of alpha-effect and differential rotation. The equations of the dynamo theory usually include some averaged kinematic characteristics of the interstellar turbulence. This approach is quite suitable for galaxies with "calm" interstellar medium. As for the galaxies with intensive star formation or supernovae explosions it will not give proper results. For this case the HII regions are quite small, exist for small-time and their localization can be assumed random. So it is useful to take the dynamo equations with random coefficients, which take one of two values (the first one is connected with HI regions, and the second one – with HII). We have studied the magnetic field evolution in the stochastic dynamo model for some typical cases. From the mathematical point of view, the results show some special effects. Firstly, the magnetic field evolution demonstrates the intermittency effect: higher statistical moments of the field grow faster than the lower ones. Moreover, the magnetic field in this model can have large fluctuations, so we have also described the correlation function of the field.

***Keywords:*** *galaxies - magnetic fields – dynamo – intermittency – correlation function.*

## 1. Introduction

Nowadays it is no doubt that some of the galaxies have large-scale magnetic fields of order of microgauss (Beck et al. 1996). From the observational point of view, they are studied by the measurements of Faraday rotation of polarization plane of radiowaves on modern radio telescopes, such as VLA, LOFAR and SKA (in future). Also their existence is proved by synchrotron emission spectra. It is thought that the magnetic field has two different components: the first one (small-scale) is fully random and it has the typical


DOI: 10.52526/25792776-2018.2.2-346

lengthscale of 50–100 pc, and the second one has the lengthscale comparable with the whole galaxy. It can be obtained as a result of averaging the full magnetic field, and it is called regular, or large-scale magnetic field.

As for theoretical description, the galactic magnetic fields evolution is usually connected with the dynamo theory (Arshakian et al. 2009). As for the large-scale field, the dynamo mechanism is based on joint action of alpha-effect and differential rotation. Alpha-effect is connected with vorticity of the interstellar turbulent motions (it makes the radial component of the magnetic field from the angular one). The second effect characterizes non-solid rotation of the galaxy, and it transforms the radial magnetic field to the angular one. They compete with the turbulent diffusion, which makes the field decay. If the joint intensity of the alpha-effect and differential rotation is higher than the dissipative processes, the magnetic field grow, else it decays. So the dynamo mechanism is threshold: the field evolution is characterized by so-called dynamo number, and the field enlarges only for some of its values.

The evolution of the regular magnetic field is described by the Steenbeck – Krause – Rädler equation, which is quite difficult to be solved both analytically and numerically. So the equations are usually solved using different simplified models for the field. One of the most important approaches is connected with so-called no-$z$ approximation. It takes into account that the galaxy disc is quite thin, so some of the derivatives can be changed by the algebraic expressions. The equations of the no-$z$ approximation include coefficients constructed of averaged characteristics of the interstellar turbulence (Moss 1995; Phillips 2001).

This method is quite well for modelling the magnetic field in "calm" galaxies, where the parameters of the interstellar motions are well described by averaged one. However, there are a lot of galaxies where there are such intensive processes as star formation, supernovae explosions, outflows from stars etc. The interstellar turbulence can differ very much from the effective characteristics. There are two different ways of modelling the magnetic fields in such objects. On the one hand, we can parameterize the velocity of the interstellar motions, typical lengthscale of turbulence and another values (Mikhailov et al. 2012). On the other hand, the star formation (and other active processes) are quite rapid and they are localized in some small regions. Roughly it can be said that the localization of these regions is random. So it would be useful to describe the magnetic field evolution taking the model with random coefficients. The estimates of the magnetic field evolution have been made in some previous works (Mikhailov & Modyaev 2015; Mikhailov & Pushkarev 2018). It is also interesting to study the correlation function for the magnetic field, which can connect the values of the field at different times. In this work we give the results for the magnetic field evolution for the model with random coefficients and for the correlation function.

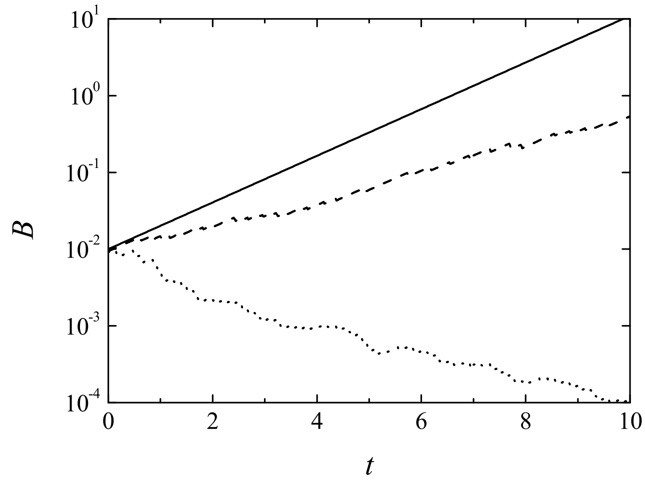


**Figure 1:** Evolution of the magnetic field. Solid line shows $p = 0.00$, dashed line – $p = 0.05$, dotted line – $p = 0.20$.

## 2. Basic equations

The galactic magnetic field **H** contain two main parts:

$$\mathbf{H} = \mathbf{B} + \mathbf{b},$$

where **b** is the small scale magnetic field, which has the same lengthscale as the turbulent motions, and **B** is the large-scale component of the field. The evolution of this component is described by Steenbeck – Krause – Rädler equation (Steenbeck et al. 1966):

$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{curl}[\mathbf{V}, \mathbf{B}] + \mathrm{curl}(\alpha \mathbf{B}) + \eta \Delta \mathbf{B};$$

where **V** is the large-scale velocity of the interstellar medium (usually it is connected with rotation of the galaxy), $\alpha$ characterizes the vorticity of the turbulent motions, $\eta$ is the turbulent diffusivity.

In the no-$z$ approximation it is assumed that the magnetic field nearly lies in the equatorial plane, and for the field components we have:

$$B_{r,\varphi}(r, \varphi, z, t) = B_{r,\varphi}(r, \varphi, 0, t) \cos\left(\frac{\pi z}{2h}\right),$$

where $h$ is the half-thickness of the galaxy disc. So the $z$-derivatives of the field will be the following:

$$\frac{\partial^2 B_{r,\varphi}}{\partial z^2} = -\frac{\pi^2 B_{r,\varphi}}{4h^2}.$$

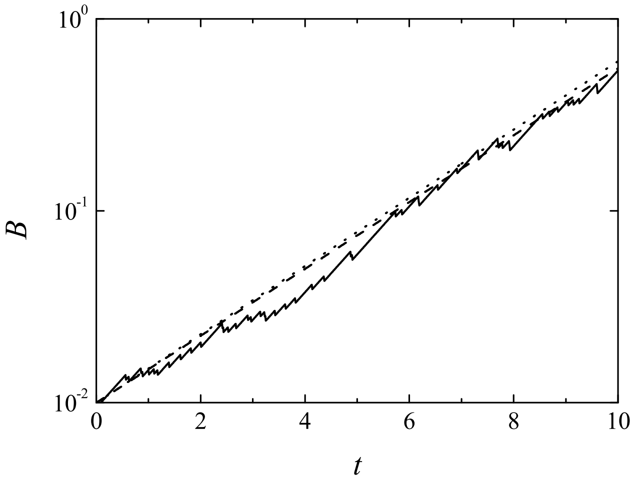


**Figure 2:** Momentums of the magnetic field. Solid line shows the typical field, dashed line – mean field, dotted line – mean square field.

As for the alpha-effect, it is often used that $\alpha = \alpha_0 \frac{z}{h}$, where $\alpha_0 = \frac{\Omega l^2}{h}$. Usually it is convenient to use the dimensionless time measured in units of $h^2/\eta$. If we neglect the dissipation in the disc plane, for the magnetic field we have the equations (Moss 1995; Phillips 2001; Mikhailov & Modyaev 2015):

$$\frac{\partial B_r}{\partial t} = -R_\alpha B_\varphi - \frac{\pi^2 k B_r}{4};$$

$$\frac{\partial B_\varphi}{\partial t} = -R_\omega B_r - \frac{\pi^2 k B_\varphi}{4},$$

where $R_\alpha$ characterizes alpha-effect, $R_\omega$ – differential rotation. The coefficient $k$ depends on the velocity of the turbulent motions. The values of $k = 1$ can characterize "calm" galaxies, and $k \approx 3$ is connected with regions of star formation.

## 3. Model with random coefficients

If we solve the eigenvalue problem for no-$z$ approximation equations, we obtain that the field can grow with velocity of

$$\gamma = -\frac{\pi^2 k}{4} + \sqrt{D},$$

where $D = R_\alpha R_\omega$ is the dynamo-number which described the possibility of the field generation. Usually for such galaxies as Milky Way or M31 $D \approx 10$,

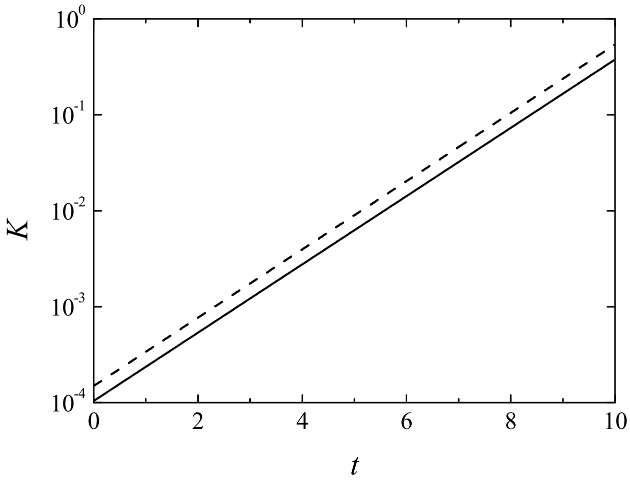


**Figure 3:** Correlation function for the field. Solid line shows $T = 0.1$, dashed line – $T = 1.0$.

so if the star formation is weak ($k = 1$), the field can grow. If we have more intensive turbulent diffusivity, the field will decay.

To model the magnetic field, we use the equations with random coefficient $k$. It is constant during time intervals $[0, \Delta t)$, $[\Delta t, 2\Delta t)$, ..., $[(n-1)\Delta t, n\Delta t)$, ... and it takes random values:

$$k = \begin{cases} k_1 \text{ with probability } p; \\ k_2 \text{ with probability } (1-p) \end{cases}$$

We take $k_1 = 3.5$ (for HII regions) and $k_2 = 1.0$ (for HI). The probability $p$ can be connected with star formation rate $\Sigma$ (Mikhailov 2014):

$$p \approx 12\Sigma,$$

where $\Sigma$ is measured in $M_{\odot}\text{kpc}^{-2}\text{yr}^{-1}$. The field evolution is shown on Figure 1. We can see that the magnetic field can grow if $p < 0.12$, else large-scale structures decay. It is connected with intensive turbulent dissipation processes, which destroy regular structures of the field.

It is also interesting to study the statistical momentums of the solution, which characterize the field evolution (Figure 2). We can see the intermittency effect: mean square field grows faster than the mean one. This is connected with rare, but very large solutions of the equations (Zeldovich et al. 1987).

Such effects can be studied better using the correlation function of the field, which connects its values for different time momentums:

$$K(t, T) = < B(t), B(t+T) > .$$

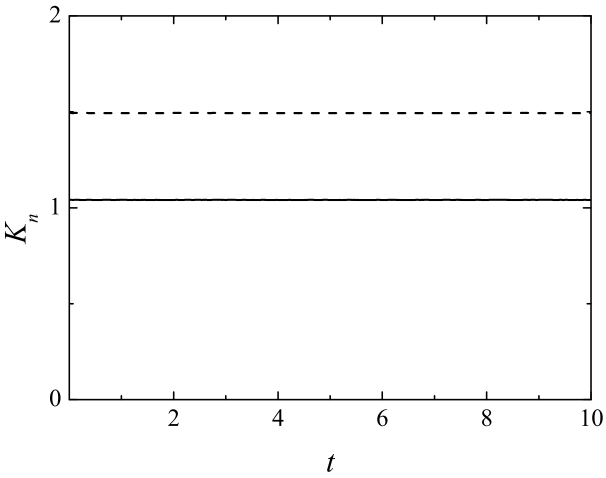


**Figure 4:** Normalized correlation function for the field. Solid line shows $T = 0.1$, dashed line – $T = 1.0$.

The typical results are shown on Figure 3. The main part of the correlation function is connected with the exponential growth. To study the connection between the field for different times, it is much better to use the normalized correlation function:

$$K_n(t, T) = \frac{K(t, T)}{K(t, 0)}.$$

It is shown on Figure 4.

## 4. Conclusions

We have studied the magnetic field evolution in the galaxies with inhomogeneous interstellar medium, using the model with random coefficients. We have shown that for intensive star formation the large-scale structures of the field can be destroyed. This effect can be supported by the observations of the magnetic field in NGC 6946: the field in this galaxy is concentrated *between* the spiral arms, where there is quite intensive star formation (Beck & Hoernes 1996).

The magnetic field also demonstrates the intermittency effect in this model: the higher momentums grow faster than lower ones. We have studied the correlation function for the field, too. It shows that in our model the values of the field for different momentums are quite close.

It would be interesting to study another random effects in the dynamo model. For example, we can study the fluctuations of another governing parameters, or injections of the magnetic field (Moss et al. 2014).

### Acknowledgements

This work was supported by Russian Foundation for Basic Research under grant 18-32-00124. Authors thank the organizers of the International Conference Dedicated to Victor Ambartsumian's 110th Anniversary "Instability Phenomena and Evolution of the Universe" for the opportunity to present this work.

## References

Arshakian, T.; Beck, R.; Krause, M.; Sokoloff, D. 2009, A&A 494, 21
Beck, R.; Brandenburg, A.; Moss, D. et al. 1996, ARA&A 34, 155
Beck, R.; Hoernes, P. 1996, Nature, 379, 47
Mikhailov, E. 2014, Ast. Lett., 40, 398
Mikhailov, E.; Modyaev I. 2015, Balt. Astron. 24, 194
Mikhailov, E.; Pushkarev, V. 2018, A&AT, 30, 343
Mikhailov, E.; Sokoloff, D.; Yefremov Yu.N. 2012, Astron. Lett. 38, 543
Moss, D. 1995, MNRAS 275, 191
Moss, D.; Sokoloff, D.; Beck, R.; Krause, M. 2014, A&A, 566, A40
Phillips, A. 2001, Geophys. Astrophys. Fluid Dyn. 94, 135
Steenbeck, M.; Krause, F.; Rädler K.-H. 1966, Z. Natusforsch., 369 (in German)
Zeldovich, Ya.B.; Molchanov, S.A.; Ruzmaikin, A.A; Sokoloff, D.D. 1987, Sov.Phys., 30, 353