КОСМИЧЕСКАЯ ФИЗИКА

КИНЕМАТИКА И ФИЗИКА НЕБЕСНЫХ ТЕЛ том 24 № 1 2008

UDC 523.165

B. A. Shakhov[1], M. Stehlik[2]

[1]Main Astronomical Observatory, National Academy of Sciences of Ukraine
27 Akademika Zabolotnoho St., 03680 Kiev
[2]Institute of Experimental Physics SAS
04353 Kosice, Slovakia

The α-effect and proton acceleration in the solar wind

The quantum field model is used to study the correlation functions of velocity and magnetic fluctuations in helical developed MHD turbulence of solar wind which is generated by random forces with mixed noise correlators. The exponential increase of the magnetic fluctuations is stabilized by spontaneous symmetry breaking mechanism, which leads to the creation of homogeneous magnetic field $\langle \mathbf{E} \rangle$*, and consequently, gives rise to the* α*-effect. The maximum value of the* α*-effect is determined in the Kolmogorov universal regime and its contribution to the proton acceleration is estimated. The contribution of the* α*-effect to ~100 MeV-proton acceleration is discussed and compared with the 2nd Fermi acceleration mechanism.*

α-ЭФФЕКТ И УСКОРЕНИЕ ПРОТОНОВ В СОЛНЕЧНОМ ВЕТРЕ, ШАХОВ Б. А., СТЕГЛИК М. — Используется квантовополевая модель для исследования корреляционных функций скорости и магнитных флуктуаций в развитой спиральной МГД-турбулентности солнечного ветра, которая возбуждается случайными силами со смешанными корреляторами шума. Экспоненциальное возрастание магнитных флуктуаций стабилизируется механизмом спонтанного нарушения симметрии. Это приводит к появлению однородного магнитного поля $\langle \mathbf{E} \rangle$ *и к возникновению* α*-эффекта. Определена его максимальная величина для универсального колмогоровского режима, и оценен его вклад в ускорение протонов. Обсуждается вклад в ускорение с энергией порядка 100 МэВ протонов и проводится сравнение с механизмом ускорения Ферми второго рода.*

α-ЕФЕКТ І ПРИСКОРЕННЯ ПРОТОНІВ У СОНЯЧНОМУ ВІТРІ, ШАХОВ Б. О., СТЕГЛІК М. — Використовується квантовопольова модель для дослідження кореляційних функцій швидкості і магнітних флуктуацій у розвиненій спіральній МГД-турбулентності сонячного вітру, яка збуджується випадковими силами зі змішаними кореляторами шуму. Експоненційне зростання магнітних флуктуацій стабілізується механізмом спонтанного порушення симетрії, що призводить до появи однорідного магнітного поля $\langle \mathbf{E} \rangle$ *і до виникнення* α*-ефекту. Визначено його максимальну величину для універсального колмогорівського режиму, і оцінено*

його внесок у прискорення протонів. Обговорюється внесок у прискорення з енергією порядку 100 МеВ протонів, проводиться порівняння з механізмом прискорення Фермі другого роду.

1. INTRODUCTION

The astrophysical turbulent dynamo theory still arouses great interest. As it is well known, instabilities occuring in astrophysical conductive turbulent medium lead to the growth of magnetic fluctuations and to the creation of large-scale (mean) magnetic field. Presently existing models describing the stationary and/or nonstationary turbulent dynamo are mostly based on linearized magnetohydrodynamic (MHD) equations [14, 15]. The α-effect is a very important mechanism aligned with the mean magnetic field generation, which appears in the reflective non-invariant, i.e., helical or gyrotropic MHD with non-zero helicity density. In fact, the origin of the α-effect is connected with the creation of mean electromotive force **E** parallel with the mean magnetic field $\langle \mathbf{B} \rangle$. The coefficient alpha is designed as a coefficient of proportionality, $\mathrm{E} = \alpha\langle \mathbf{B} \rangle$.

The α-effect is of great importance in kinetics of high-energy particles in the astrophysical plasma. In fact, the occurrence of E along $\langle \mathbf{B} \rangle$ causes effective acceleration of charged particles [5, 12]. Known various estimations of α-coefficient were usually made in terms of the magnetic field correlation tensor [14] or in terms of the HD velocity field tensor [11], and its magnitude is expressed by the nonsymmetric part of correlation tensors using some linearization procedure.

Here an alternative and more close view on the astrophysical HD as well as MHD turbulence is used which is provided by the quantum field (QF) formalism. It is suitable to describe the *final stationary turbulent regime* (see [1] and references therein). The stationary turbulent dynamo was explained by the spontaneous symmetry breaking mechanism widely used in quantum theory [2, 9]. In the present paper the magnitude of α-coefficient is calculated in this formulation [9], therefore, its value holds for the steady state of fully developed MHD turbulence. The next section gives a brief description of the QF model.

2. THE STOCHASTIC MODEL

The interaction of electrically neutral conductive turbulent incompressible astrophysical plasma is driven by the stochastic MHD equations. In the following, the magnetic induction **B** will be measured in Alfvén velocity units, $\mathrm{B} = \sqrt{4\pi m}\,(\mathbf{B}_0 + \mathrm{b})$, where m is the mass density, $\mathbf{B}_0$ and **b** are the mean and fluctuating parts of magnetic field in Alfvén velocity units, respectively. Then the MHD equations may be read as:

$$\hat{L}^{\mathrm{u}} + \mathbf{f}^{\mathrm{u}} = 0, \qquad \hat{L}^{\mathrm{b}} + \mathbf{f}^{\mathrm{b}} = 0, \tag{1}$$

where

$$\hat{L}^{\mathrm{u}} \equiv -\nabla_\tau \mathbf{u} + \nu\Delta\mathbf{u} - (\mathbf{b}\partial)\mathbf{b} - \nabla p + \mathbf{F}^{\mathrm{u}}[\mathbf{u}, \mathbf{b}], \tag{2}$$

$$\hat{L}^{\mathrm{u}} \equiv -\nabla_\tau \mathbf{b} + \nu\Delta\mathbf{b} - (\mathbf{b}\partial)\mathbf{u} + \mathbf{F}^{\mathrm{b}}[\mathbf{u}, \mathbf{b}].$$

Here $\nabla_\tau = \partial_t + (\mathrm{u}\partial)$ is a covariant derivative. The magnetic diffusivity ν' is connected with the coefficient of molecular viscosity ν by the relation $\nu' = \tilde{u}\nu$ with dimensionless magnetic Prandtl number $\tilde{u}^{-1}$. Additional terms $\mathbf{F}^{\mathrm{u}}$ and $\mathbf{F}^{\mathrm{b}}$

will be specified later. The external random forces $\mathbf{f}^{b}$ and $\mathbf{f}^{b}$ simulate the stochasticity of the interaction of the fields fluctuations with mean flows, and they are assumed to have a Gaussian distribution with a given matrix of the noise correlators $D = \langle \mathrm{ff} \rangle$, with the following matrix elements: the hydrodynamic D^{uu} noise, magnetic D^{bb}, and mixed D^{ub} ones. Their choice depends on the model of an energy injection into the turbulent medium to compensate the dissipation losses and usually are chosen in the standard power form [1]:

$$\begin{aligned} D^{uu}_{js} &= g\nu^3 k^{1-2\varepsilon} P^1_{js}, \\ D^{uu}_{js} &= g'\nu^3 k^{1-2a\varepsilon} P^2_{js}, \\ D^{ub}_{js} &= g''\nu^3 k^{1-(1+a)\varepsilon} P^3_{js}. \end{aligned} \tag{3}$$

In helical MHD the tensor structure of the noises is represented by linear combination of both tensor and pseudotensor parts. Therefore, $P^3_{js} = P_{js} + i\rho_r \varepsilon_{jsl} k_l / k$, where $P_{js} = (\delta_{js} - k_j k_s / k^2)$ stands for transversal projector and ε_{jsl} is the Levi — Civita pseudotensor. Dimensionless real parameters $\rho = \{\rho_1, \rho_2, \rho_3\}$ satisfy the conditions $|\rho| \le 1$, $\rho_3^2 \le |\rho_1 \rho_2|$. The parameters g, g', g'' play the role of the bare coupling constants, and a, ε are free parameters of the theory (the value $\varepsilon = 2$ corresponds to the Kolmogorov energy pumping from infra-red region of small k [6]). The QF renormalization group approach makes possible to construct ε-expansion of correlation functions with respect to ε close to zero.

In the QF formulation problem (1) is described by the action of fields, **u**, **b** and some "auxiliar" transversal fields **u**$'$, **b**$'$:

$$S = \frac{1}{2}(\mathrm{u}' D^{uu} \mathrm{u}' + 2\mathrm{u}' D^{ub} \mathrm{b}' + \mathrm{b}' D^{bb} \mathrm{b}') + \mathrm{u}' [\hat{L}^{u}] + \mathrm{b}' [\hat{L}^{b}]. \tag{4}$$

The integration over the space-time variables and the trace over the vector indexes were implied. All the correlation and response functions (Green functions) are usual functional averages of corresponding fields with the weight exp$S$, i.e.,

$$\langle \Phi \ldots \Phi \rangle \equiv \int \Phi \ldots \Phi \exp S D\mathrm{u} D\mathrm{b} D\mathrm{u}' D\mathrm{b}',$$

where $\Phi = \{\mathbf{u}, \mathbf{b}, \mathbf{u}', \mathbf{b}'\}$. These functions (or $\langle v_i b_j \rangle$ in our case) may be calculated through the usual Feynman diagram procedure.

The central problem in the QF theory is to eliminate the singularities which appear in diagrams of the perturbation theory for Green functions. The problem has been solved for the reflective symmetric magnetoturbulence [7] as well as for the helical magnetoturbulence [10]. In the latter case, the additional divergences appear but they can be eliminated by the appropriate counterterms into the action S. For this reason it is necessary to consider the extended theory with the additional cross dissipative terms:

$$\mathbf{F}^{u} = \tilde{v}\nu \Delta \mathbf{B},$$
$$\mathbf{F}^{b} = \tilde{w}\nu \Delta \mathbf{u}$$

with new helical magnetic Prandtl numbers $\tilde{v}^{-1}$, $\tilde{w}^{-1}$. All the inverse Prandtl numbers $\tilde{u}$, $\tilde{v}$, $\tilde{w}$ and the coupling constants g_i have definite values in stable scaling regime [10].

Moreover, in helical MHD an additional singularity appears that causes exponential increase of the magnetic response function $\langle \mathrm{bb}' \rangle \equiv \Delta^{bb}$ in time for the small wave numbers k. Thus the system becomes unstable, because the magnetic response function must be retarded and at the same time it must ensure the damping of all the perturbations. This problem can be solved with elegance by the mechanism of spontaneous symmetry breaking.

3. THE SPONTANEOUS SYMMETRY BREAKING MECHANISM

The QF perturbation theory generates the so-called rotor term (rotb) which should be added to the magnetohydrodynamic equations and this leads to the instability [16]. The instability problem may be solved on the basis of the spontaneous symmetry breaking mechanism. Briefly, the "normal state" of the turbulent helical conductive fluid with zero mean value of the magnetic field is unstable being stabilized by the spontaneous appearance of the space-uniform mean magnetic field $\mathbf{B}_0 \equiv \langle \mathrm{b} \rangle \neq 0$ [2, 9]. The value of the field appeared is determined by the system stability condition but unlike the case of standart models this condition is not reduced to a simple requirement, i.e., to the minimum free energy. The assumption $\mathbf{B}_0 \neq 0$ is fixed directly in action (4) by the replacing $\mathbf{b} \to \mathbf{b} + \mathbf{B}_0$ which leads to new perturbation diagrams for correlation functions. The stability condition is equivalent to the requirement that the unstable rotor term in magnetic response function would be removed. It turned out to be possible with proper choice of the $\mathbf{B}_0$ value. The direction of $\mathbf{B}_0$ is not fixed in this case and its absolute value is [9]:

$$|\mathbf{B}_0| = \frac{8\nu k_d}{3\pi} \sqrt{\frac{(\tilde{u}+1)^2(\tilde{u}-\widetilde{vw})}{(\tilde{u}+1)^2-(\tilde{v}-\tilde{w})^2}} \tag{5}$$

in the Alfvén units. Here k_d is the parameter of ultraviolet cutoff ($k_d^{-1} \equiv r_d$ has the meaning of the turbulent dissipative length, an inner scale of turbulence). Consequently, set (1) has to be completed by terms of $\mathbf{B}_0$ and action (4) takes the form [9]:

$$\overline{S} = S + \mathbf{u}'(\mathbf{B}_0\nabla)\mathbf{b} + \mathbf{b}(\mathbf{B}_0\nabla)\mathbf{u}. \tag{6}$$

Action (6) creates Feynman diagrams with non-zero free propagators (pair Green functions in the lowest order) $\langle \Phi\Phi \rangle \equiv \Delta^{\Phi\Phi}$. They can be directly found by extracting the quadratic part $\Phi K \Phi$ from the action $\overline{S}$ and by calculating the elements of the inverse matrix $K^{-1} = \Delta$. For our purpose it is sufficient to calculate only propagator $\Delta_{is}^{\mathbf{ub}}(\mathbf{k}, \omega$ given (in the Fourier components) by the formula:

$$\Delta^{\mathbf{ub}} = \frac{-D^{\mathbf{uu}}\mu\sigma^+ + D^{\mathbf{ub}}(\mu\lambda^+ + \theta\sigma^+) - D^{\mathbf{bb}}\theta\lambda^+}{(\lambda^+\mu^+ - \sigma^+\theta^+)(\lambda\mu - \sigma\theta)}, \tag{7}$$

were $\lambda = -i\omega + \nu k^2$, $\mu = -i\omega + \nu\tilde{u}k^2$, $\theta = -i\gamma + \nu\tilde{v}k^2$, $\sigma = -i\gamma + \nu\tilde{w}k^2$ and λ^+ denotes the Hermitian conjugation to λ, etc. All these are proportional to the transverse projector $P_{js}(\mathbf{k})$ and $\gamma = (\mathbf{k}\cdot\mathbf{B}_0)$.

4. CALCULATION OF THE α-COEFFICIENT

The α-coefficient is defined by the relation $\mathbf{E} = \alpha\mathbf{B}_0$, and the electromotive force $\mathbf{E} = \sqrt{4\pi m}\langle \mathbf{u} \times \mathbf{b} \rangle$. So, one can write:

$$E_j = \sqrt{4\pi m}\, \varepsilon_{isj}\langle u_i b_s \rangle \equiv \sqrt{4\pi m}\, \varepsilon_{isj}\Delta_{is}^{\mathbf{ub}}, \tag{8}$$

where m is the mass density. Note that the magnetic field is measured in the Alfvén units and that $E_j(\mathbf{x}, t) = E_j(x) = G(x, x)$ is treated as the full one-point

Green function, so, past the tensor summation in (8) using (7) one obtains:

$$E_j = \frac{\sqrt{4\pi m}}{(2\pi)^4} \int dk^3 d\omega G_j(\mathbf{k}, \omega) \tag{9}$$

Propagator (7) has two pairs of poles in the complex plane. Performing contour integration in positive semiplane of ω one gets:

$$E_j = \frac{2\sqrt{\pi m}\, \nu^3}{(2\pi)^3} A \int dk^3 \frac{(\mathbf{B}_0 \cdot \mathbf{k})k}{\beta_1 \nu^2 k^4 + \beta_2 (\mathbf{B}_0 \cdot \mathbf{k})^2}, \tag{10}$$

where

$$\beta_1 = (\tilde{u} + 1)^2(\tilde{u} - \widetilde{vw}),$$

$$\beta_2 = (\tilde{u} + 1)^2 - (\tilde{v} - \tilde{w})^2,$$

$$A = g\rho_1 [\tilde{u}(\tilde{u} + 1) - \tilde{w}(\tilde{v} + \tilde{w})] + g'\rho_2 [\tilde{v}(\tilde{v} + \tilde{w}) - (\tilde{u} + 1)] + 2g''\rho_3(\tilde{w} - \widetilde{uv}).$$

The integral in (10) can be handled to the form:

$$\frac{4\pi}{\beta_2} \frac{B_{0j}}{B_0^2} \int_0^{k_d} \left[k^2 - \frac{8k^3 k_d}{3\pi} \arctan\left(\frac{3\pi}{8k_d k}\right) \right].$$

Using the linear relation between B_0 and k_d (see (5)) one can ascertain that this integral possesses the linear ultraviolet divergence which has to be removed by cutting off the dissipation region $k > k_d$. Putting the integral into (10) one obtain the result:

$$\alpha = \frac{0.0659A}{\beta_1} \nu \sqrt{m}\, k_d. \tag{11}$$

The authors of [10] report $\tilde{u} = \tilde{u}_* = 1.393$ and $g = \tilde{g}_* = \frac{32}{5}\pi^2 \tilde{u}(\tilde{u} + 1)$ in the Kolmogorov regime. Others coupling constant as well as the inverse Prandtl numbers are zero in this stable regime. Note however, that existence of another regime can modify the resulting α, but its numerical value remains very close. Consequently, because $|\rho_i| \le 1$, the maximal value of α is $\alpha_{max} = 5.80\nu k_d \sqrt{m}$.

Note that unlike classical quasilinear approximations for the construction of $\mathbf{E}$ dependence on $\mathbf{B}_0$ the quantum field approach together with spontaneous symmetry breaking mechanism directly yields the linear dependence of $\mathbf{E}$ on $\mathbf{B}_0$, and α is simply the proportionality coefficient.

5. THE PARTICLE ACCELERATION

The effectivity of charged particle acceleration by α-effect in helical turbulent media can be easily compared with another mechanism, the well-known statistical Fermi acceleration mechanism. Following [5], the non-zero α leads to additional particle flux $J_p = -\kappa_p \partial_p N$ in the modulus space with the diffusion coefficient

$$\kappa_p = \frac{p^2}{3v\Lambda_{II}} (U^2 + \tilde{D}(p)). \tag{12}$$

Here Λ_{II} is the transport path along $\mathbf{B}_0$ for particles with the momentum p and velocity v, $N(p)$ is the particle density,

$$U = \alpha \frac{\Lambda_{II}}{R_b}$$

is the effective convective velocity along $\mathbf{B}_0$, R_b is the particle gyroradius in the random field $\sqrt{\langle b^2 \rangle}$. The coefficient $D(p)$ is aligned to statistical particle acceleration; it consists of several parts and depends on concrete peculiarities of medium. For simplicity two extreme situations are considered [5].

The first situation: the component b is weak, $b^2 \ll B_0^2$, then:

$$\widetilde{D}(p) = \frac{B_0^2}{\langle b^2 \rangle} \left(1 - \frac{\langle \mathbf{u} \cdot \mathbf{b} \rangle^2}{\langle u^2 \rangle \langle b^2 \rangle} \right) \langle u^2 \rangle$$

and a strong cross-correlation $\langle \mathbf{u} \cdot \mathbf{b} \rangle$ causes a decrease in the rate of the Fermi acceleration, so, the α-effect can play principal role. Note that a linear theory gives $\langle \mathbf{u} \cdot \mathbf{b} \rangle = 0$ for an isotropic random field, while the non-linear interactions asymptotically lead to the state of maximal correlation $\langle \mathbf{u} \cdot \mathbf{b} \rangle$ [8].

The second situation corresponds to the inequality of $B_0^2 \ll b^2$ when the main contribution is given by estimation of:

$$\widetilde{D}(p) = \alpha_1 \langle u^2 \rangle$$

and it is connected with the second order Fermi acceleration [6] in randomly moving magnetic field inhomogeneities (in non-helical magnetoturbulence). Here $\alpha_1 \approx 0.53$ (the Kolmogorov spectrum of magnetic field) up to $\alpha_1 \approx 1$ (when the correlation length of u exceeds Λ_{II}) [5].

6. DISCUSSION

Numerical estimations of α are nowadays poorly known therefore we restrict ourselves only to simple estimations. The coefficient $\alpha_{\max}$ would reach a large value in the astrophysical objects if the *full developed magnetoturbulence* is realized. In the solar wind near the Sun the rough estimation of viscosity [18] is $\nu = 10^9 T^{5/2}/n \approx 1.6\times10^{19}$ cm^2/s, for the temperature $T \approx 4\times10^4$ K and for the proton concentration $n \approx 20$ cm^{-3} $n \sim 20$ cm^{-3}. The maximal value $\alpha_{\max} \approx 5\times10^8$ cm/s is obtained for $k_d \approx 1$ cm^{-1}. The real value of $\widetilde{u}$ is approximately three orders less than $\widetilde{u}_*$; in this case $\alpha \approx 10^5$ cm/s. It is necessary to remark that the *fully developed hydrodynamic turbulence* has tendency to reaching a limit value of ρ ($\rho \approx 1$) [3]. The question remains if this happens in the *fully developed magnetohydrodynamic turbulence* as well.

In [17] a rotating system (with the angular velocity Ω and the density scale height H) was discussed. Their estimation $\alpha = L_{cor}^2 \Omega / H \leq 10^5$ cm/s in the galactic wind seems to be realistic. An estimation $\alpha = 10^5$ cm/s was obtained in [4] as well. Note that the estimation of turbulent diffusivity is known for a very large interval (from 10^{15} cm^2/s in the solar convection zone [19, 20] up to 10^{21} cm^2/s in the interstellar medium of the Galaxy [13]).

The value of α which is sufficient for a higher effectivity of particle acceleration by α-effect in helical turbulent media compared with the well-known Fermi acceleration mechanism can be easily estimated using (12). In the solar wind, for example, $(\lambda_{II}/R_b)^2 \approx 10^4$, (or 10^3—10^5), for protons with the kinetic energy $E_k \approx 100$ MeV and $\sqrt{\langle u^2 \rangle} \approx 10^5$ cm/s. The relative effectiveness of the acceleration by the α-effect is determined by the parameter

$$\eta^2 = U^2 / \widetilde{D}(p),$$

for which inequality $\eta^2 \gg 1$ holds if $\alpha^2 > 10^8$ cm/s.

Consequently the realistic value $\alpha = 10^5$ cm/s ensures high effectivity of the considered particle acceleration (with energy of 10 up to 10^3 MeV) in the gyrotropic turbulent medium [4] compared to the well-known Fermi acceleration mechanism.

Acknowledgments. M. Stehlik gratefully acknowledges the hospitality of the staff of the Main Astronomical Observatory of NASU (Kyiv). This work was supported in part by Science and Technology Assistance Agency under the contract N APVT-51-027904, and by SAS, projects N 2/6193 and N 2/7063/27.

1. *Adzhemyan L. Ts., Antonov V. N., Vasiliev A. N.* The field theoretic renormalization group in fully developed turbulence. — Gordon and Breach Sci. Publ., 1999.—202 p.
2. *Adzhemyan L. Ts., Vasiliev A. N., Hnatich M.* Turbulent dynamo as spontaneous symmetry breaking // Teoreticheskaya i Matematicheskaya Fizika.—1987.—72.—P. 369—383.
3. *Adzhemyan L. Ts., Hnatic M., Stehlik M.* Theory of developed turbulence: Principle of maximal randomless and spontaneous parity violation // J. Phys. II France.—1995.—5.—P. 1077—1092.
4. *Chiba M., Tosa M.* Structure of magnetic fields in spiral galaxies — Global properties of the turbulent dynamo // Mon. Notic. Roy. Astron. Soc.—1989.—238.—P. 621—648.
5. *Fedorov Yu. I., Katz M. E., Kichatinov L. L., Stehlik M.* Cosmic ray kinetics in a random anisotropic reflective non-invariant magnetic field // Astron. and Astrophys.—1992.—260, N 1-2.—P. 499—509.
6. *Fermi E.* On the origin of the cosmic radiation // Phys. Rev.—1949.—75.—P. 1169—1174.
7. *Fournier J. D., Sulem P. L., Pouquet A.* Infrared properties of forced magnetohydrodynamic turbulence // J. Phys. A: Math. and Gen.—1982.—15.—P. 1393—1420.
8. *Grappin R., Frisch U., Pouquet A., L'eorat J.* Alfvenic fluctuations as asymptotic states of MHD turbulence // Astron. and Astrophys.—1982.—105.—P. 6—14.
9. *Hnatich M., Jurcisin M., Stehlik M.* Dynamo in helical MHD turbulence // Magnitnaya Gidrodinamika.—2001.—37.—P. 80—86.
10. *Hnatich M., Stehlik M.* Renormalization group in gyrotropic magnetic hydrodynamics // Renormalization Group '91 / Eds D. V. Shirkov, V. B. Priezzev. — Singapore: World Sci. Pub., 1992.—P. 204—218.
11. *Keinigs R. K.* A new interpretation of the alpha effect // Phys. Fluids.—1983.—26.—P. 2558—2560.
12. *Kichatinov L.* Novyi mekhanizm uskoreniya kosmicheskikh chastic pri nalichii otrazhatel'noi neinvariantnoi turbulentnosti // Pis'ma Zh. Eksp. Teor. Fiz.—1983.—37.—P. 43—45.
13. *Ko M., Parker E. N.* Intermittent behaviour of galactic dynamo activities // Astrophys. J.—1989.—341.—P. 828—831.
14. *Krause F., Roedler K. H.* Mean-field magnetohydrodynamics and dynamo theory. — Berlin: Akademie-Verlag, 1980.—271 p.
15. *Moffat H. K.* Magnetic field generation in electrically conducting fluids. — Cambridge: Univ. Press, 1978.—343 p.
16. *Pouquet A., Frisch U., L'eorat J.* Strong MHD helical turbulence and the nonlinear dynamo effect // J. Fluid Mech.—1976.—77.—P. 321—354.
17. *Ruediger G.* The alpha-effect in galaxies is highly anisotropic // Geophys. and Astrophys. Fluid Dynamics.—1990.—50.—P. 53—61.
18. *Spitzer L.* Physics of fully ionized gases. — New York: Wiley, 1962.—217 p.
19. *Spruit H. C.* A model of the solar convection zone // Solar Phys.—1974.—34.—P. 277—290.
20. *Vainstein S. I., Kichatinov L. L.* The macroscopic magnetohydrodynamics of inhomogeneously turbulent cosmic plasmas // Geophys. and Astrophys. Fluid Dynamics.—1983.—24.—P. 273—298.

Received 28 March 2007