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Large-scale Cosmological Magnetic Fields

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Abstract

We suggest a new mechanism for generation of large-scale magnetic field in the hot plasma of early universe which is based on the parity violation in weak interactions and depends neither on helicity of matter turbulence resulting in the standard α-effect nor on general rotation. The mechanism can result in a self-excitation of an (almost) uniform cosmological magnetic field.

1 Introduction

Magnetic fields of galaxies are thought to be originated in galactic dynamo action driven by differential rotation and mean helicity of turbulent motions. Mean helicity is presented in magnetic field governing equations as α-effect and is supported by Coriolis force connected with galactic rotation and density stratification. Dynamo needs some seed magnetic field which can be produced by various battery effects, say, in protogalaxy and then amplified by turbulent small-scale dynamo (Beck et al. 1996).

Particle processes related to phase transitions in the early Universe produce magnetic field which the strength sufficient to be seed for galactic dynamo. This option does not contradict to the galactic dynamo concept and is very attractive from the viewpoint of galactic physics because it gives an additional degree of freedom for models of galactic magnetic field generation. The point is however that the spatial scale of magnetic field generated by particle process is usually related to the particle scale. Such small-scale magnetic fields hardly can survive just after recombination when the Universe is already cool enough and galactic turbulence still can not support dynamo action.

A way to resolve this contradiction was suggested by Zeldovich as early as in 1965 (Zeldovich 1965). He pointed out that an almost homogeneous cosmological magnetic field could survive from the epoch just after the Big Bang up to the epoch of the galaxy formation. Cosmology provides a moderate limitations on such cosmological magnetic field. More stronger upper limit, about $10^{-10} - 10^{-11}\,G$, is provided by the analysis of rotation measures of extragalactic radio sources. The uniform magnetic field of about $10^{-15}\,G$ is still sufficiently strong to be seed for galactic dynamo (Beck et al. 1996). This possibility was analyzed in various papers (see for review Kulsrud, 1999). The problem is however that the concept of a uniform cosmological magnetic field prescribed as an initial condition at the Big Bang is somehow not coherent with modern trends in cosmology which explains formation of all kinds of matter in phase transitions in early Universe.

In our recent paper (Semikoz and Sokoloff 2004) we presented a way to embed the concept of cosmological large-scale magnetic field in the context of modern cosmology.

2 α-effect driven by collective neutrino-plasma interaction

Let us consider hot plasma of early universe after electroweak phase transition, $T \ll T_{EW} \simeq 10^5$ MeV and a weak random magnetic field of a small scale comparing with the horizon. Obviously, this does not violate the isotropy of universe as a whole with many randomly oriented domains.

Within a domain with an uniform magnetic field obeying the WKB limit $\mid e \mid B \ll T^2$ the single quantum (spin) effect remains for electrons and positrons which populate the main Landau level only and contribute to the lepton gas magnetization. The magnetization $M_j^{(\sigma)}$ changes sign for electrons and positrons, sign $\sigma = \pm 1$, effectively due to the opposite spin projections on the magnetic field at the main Landau levels.

In magnetized plasma the pseudovector $M_j^{(\sigma)}$ enters weak interaction of the charged σ-fluid component with neutrinos (antineutrinos) through the axial part of the point-like current $\times$ current interaction Hamiltonian,

$$V_\sigma^{(A)} = G_F M_j^{(\sigma)} \cdot \delta j_j^{(\nu)} / \mu_B,$$

where G_F is the Fermi constant, $\delta \mathbf{j}^{(\nu)} = \mathbf{j}_\nu - \mathbf{j}_{\bar{\nu}}$ is the neutrino current density asymmetry.

Such interaction provides a force $\mathbf{F}_\sigma^{\rm weak}$ that is additive to the Lorentz force $q_\sigma(\mathbf{E}+\mathbf{V}_\sigma \times \mathbf{B})$ acting in MHD plasma on charged particles of the kind σ and obviously depends on gradients of the interaction potential, $(F_\sigma^{\rm weak})_i \sim -\partial_i V_\sigma^{(A)}$, or for an uniform magnetization within a domain ($M_j =$ constant) on derivatives of the neutrino current density asymmetry, $\partial_i \delta j_j^{(\nu)}$.

The electric field $\mathbf{E}$ being common for all charged particles is obtained multiplying the motion equations for each charged components by the corresponding electric charge q_σ with the following summation over components that leads to $\sum_\sigma q_\sigma^2 \mathbf{E}$ in the Lorentz force and the remarkable addition of $n_{0\sigma}$ in the weak electromotive force term for electron-positron components, $E_j^{\rm weak} = \alpha B_j \sim (n_{0+} + n_{0-})$, due to the independence of the product $q_\sigma \partial_i V_\sigma^{(A)} \sim q_\sigma G_F M_j^{(\sigma)} \cdot \partial_i \delta j_j^{(\nu)} / \mu_B$ on the sign of the electric charge since $M_j^{(\sigma)} \sim$ sign σ. Such term violates parity and provides a new particle physics origin of α-effect for magnetic field generation.

The pair motion equation in the one-component MHD is derived after the summation of Euler equations for comoving electrons and positrons for which the standard (polar vector) electric field cancels since $q_\sigma = \pm \mid e \mid$. In contrast, the standard Lorentz force $\mid e \mid (\mathbf{V}_+ - \mathbf{V}_-) \times \mathbf{B} = {\rm rot}\mathbf{B} \times \mathbf{B}/4\pi {\rm n_e}$ arises while the weak force term $\sum_\sigma \partial_i V_\sigma^{(A)}$ depends in hot lepton plasma on the negligible difference of densities $(n_{0+} - n_{0-})$ as well as for the neutrino axial vector potential $V^{(A)}$ describing a probe neutrino in the electron-positron plasma when $\delta j_j^{(\nu)} \to k_j$ and the sum over σ leads to $V^{(A)} = G_F \sqrt{2} (n_{0+} - n_{0-}) \mathbf{B} \cdot \mathbf{k}/Bk$.

We estimate the α-effect originated in early universe by particle effects to yield

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \alpha \mathbf{B} + \eta \nabla^2 \mathbf{B} \ , \tag{1}$$

with

$$\alpha \simeq \frac{\ln 2}{4\sqrt{2}\pi^2} \left(\frac{10^{-5} T}{m_p^2 \lambda_{\rm fluid}^{(\nu)}} \right) \left(\frac{\delta n_\nu}{n_\nu} \right) \ , \tag{2}$$

where we assume a scale of neutrino fluid inhomogeneity $t \sim \lambda_{\rm fluid}^{(\nu)}$, that is small comparing with a large Λ-scale of the mean magnetic field $\mathbf{B}$, $\lambda_{\rm fluid}^{(\nu)} \ll \Lambda$. The diffusion coefficient

$\eta \approx (4\pi \times 137\ T\ )^{-1}$ is given by the relativistic plasma conductivity. We do not present in Eq. (1) standard terms like differential rotation etc which seems to be not very important in the problem under consideration.

We stress that the Eq. (1) is the usual equation for mean magnetic field evolution with α-effect based on particle effects rather on the averaging of turbulent pulsations. It is well-known that Eq. (1) describes a self-excitation of a magnetic field with the spatial scale $\Lambda \approx \eta/\alpha$ and the growth rate $\alpha^2/4\eta$.

3 Estimates for α-effect

For a small neutrino chemical potential μ_ν, $\xi_{\nu_a}(T) = \mu_{\nu_a}(T)/T \ll 1$, the neutrino asymmetry in the r.h.s. of Eq. (2) is the algebraic sum following the sign of the axial coupling, $c^{(A)}_{e\nu_a} = \pm 0.5$, $\xi_{\nu_\mu}(T) + \xi_{\nu_\tau}(T) - \xi_{\nu_e}(T) \approx -2\xi_{\nu_e}(T)$ because different chemical potentials almost compensate each other for high temperatures, i.e. $\xi_{\nu_e}(T) + \xi_{\nu_\mu}(T) + \xi_{\nu_\tau}(T) \approx 0$. As a result, we arrive to the estimate $\alpha = 2.8 \times 10^{-34}(T/\mathrm{MeV})^6(\mathrm{l_\nu(T)}/\lambda^{(\nu)}_{\mathrm{fluid}}) \mid \xi_{\nu_e} \mid$,, where the scale $\lambda^{(\nu)}_{\mathrm{fluid}}$ is normalized on the neutrino mean free path $l_\nu(T) = \Gamma_W^{-1}$ given by the weak rate $\Gamma_W = 5.54 \times 10^{-22}(T/\mathrm{MeV})^5$ MeV.

Substituting α into $\Lambda = \eta/\alpha$ we arrive now to

$$\frac{\Lambda}{l_H} = 1.6 \times 10^9 \left(\frac{T}{\mathrm{MeV}}\right)^{-5} \left(\frac{\lambda^{(\nu)}_{\mathrm{fluid}}}{l_\nu(T)}\right) (\mid \xi_{\nu_e}(T) \mid)^{-1} , \tag{3}$$

where $l_H(T) = (2H)^{-1}$ and H is the Hubble parameter.

If the neutrino fluid inhomogeneity scale $\lambda^{(\nu)}_{\mathrm{fluid}}$ is of the order $l_\nu(T_0) \sim 4$ cm $\ll l_H(T_0) \sim 10^6$ cm, we have $\Lambda/l_H \geq 1$ at the beginning of the lepton era ($T = T_0 \sim 10^2$ MeV, redshift z$\sim 3\times 10^{11}$). If this neutrino parameter would be much smaller at high temperatures T_0, $\mid \xi_{\nu_e}(T_0) \mid \ll 0.07$, one can choose another free neutrino parameter $\lambda^{(\nu)}_{\mathrm{fluid}} \ll l_H(T_0)$ in such a way that the ratio $\lambda^{(\nu)}_{\mathrm{fluid}}/(l_\nu(T_0) \mid \xi_{\nu_e}(T_0) \mid)$ remains invariant and our conclusion about the tendency to a global uniform field is still valid. Note that for the neutrino gas the macroscopic parameter $\lambda^{(\nu)}_{\mathrm{fluid}}$ varies in a wide region $T^{-1} \ll \lambda^{(\nu)}_{\mathrm{fluid}} \leq l_\nu(T)$.

Then $B(t) = B_{\max}\exp(\int_{t_{\max}}^t \alpha^2(t')/4\eta(t')dt')$, where $B_{\max}$ is some seed value at the instant $T_{\max} \ll T_{EW} \sim 100$ GeV. For $\lambda^{(\nu)}_{\mathrm{fluid}}(T) \sim l_\nu(T)$ we can estimate the index in the exponent substituting $t(T) = 3.84 \times 10^{21}(T/\mathrm{MeV})^{-2}\mathrm{MeV}^{-1}/\sqrt{\mathrm{g}^*}$ with the effective number of degrees of freedom $g^* \sim 100$ at the temperatures $T \gtrsim 1$ GeV. Then using the above values of $\alpha(T)$ and $\eta(T)$ with the change of the variable $x = T/2 \cdot 10^4$ MeV one finds the fast growth of the mean field in hot plasma ($x \leq 1$) with a conservative estimate,

$$B(x) = B_{\max}\exp\left(25\int_x^1 \left(\frac{\xi_{\nu_e}(x')}{0.07}\right)^2 {x'}^{10}dx'\right), \tag{4}$$

given by the upper limit $x_{\max} = 1$, $T_{\max} = 20$ GeV.

4 Symmetry properties of cosmological α-effect

Note that our cosmological α-effect is connected neither with any peculiar motions nor with a general rotation with the Universe. To illuminate the physical nature of corresponding dynamo action, let us stress that the conventional α-coefficient is a pseudo-scalar (because $\alpha \sim \tau < \mathbf{v}\,\mathrm{rot}\,\mathbf{v} >$, where $\mathbf{v}$ is turbulent velocity, τ is its memory time and $< ... >$ means the ensemble averaging) while α-coefficient given by Eq. (2) is a *scalar* quantity. Correspondingly, the field $\mathbf{B}$ must contain a usual pseudo-vector part $\mathbf{H}$ as well as a pure vector part $\mathcal{B}$. Then we consider $\mathbf{B}$ as a two-component vector with first component $\mathbf{H}$ and the second component $\mathcal{B}$ and rewrite the Eq. (1) in the form which presents its symmetry properties in an explicit way:

$$\frac{\partial \binom{\mathbf{H}}{\mathcal{B}}}{\partial t} = \nabla \times \begin{pmatrix} 0 & \alpha \\ \alpha & 0 \end{pmatrix} \begin{pmatrix} \mathbf{H} \\ \mathcal{B} \end{pmatrix} + \eta \nabla^2 \begin{pmatrix} \mathbf{H} \\ \mathcal{B} \end{pmatrix}, \tag{5}$$

or

$$\frac{\partial \mathbf{H}}{\partial t} = \nabla \times \alpha \mathcal{B} + \eta \nabla^2 \mathbf{H}\,, \tag{6}$$

$$\frac{\partial \mathcal{B}}{\partial t} = \nabla \times \alpha \mathbf{H} + \eta \nabla^2 \mathcal{B}\,. \tag{7}$$

It means that our dynamo action is based on the transformation of $\mathbf{H}$ into $\mathcal{B}$ and of $\mathcal{B}$ into $\mathbf{H}$ due to the parity violation in weak interactions.

The eigenfunctions for Eqs. (6, 7) for a given eigenvalue γ have the form

$$\mathbf{B} = \mathbf{H}(\mathbf{r}) \begin{pmatrix} 1 \\ \pm 1 \end{pmatrix} \exp \gamma t\,. \tag{8}$$

The vector field $\mathcal{B}$ can be considered as a macroscopic manifestation of Z-boson responsible for the weak interaction in the similar way as the field $\mathcal{H}$ can be considered as a macroscopic manifestation of photons with zero frequency, responsible for electromagnetic interaction. We see from Eq. (8) that the field $\mathcal{B}$ gives a substantial contribution into the cosmological magnetic field. This illuminates the fact that the generation occurs due to a substantial exchange between electromagnetic and weak fields.

Astrophysical role of the field $\mathcal{B}$ should be addressed in following investigations. Here we note only the following. According to the symmetry properties, both fields, $\mathbf{H}$ and $\mathcal{B}$, can affect moving electrons and produce synchrotron radiation, while the Faraday rotation can be associated with the pseudo-vectorial component $\mathbf{H}$ only. An observation of a body with substantial synchrotron radiation and too low Faraday rotation could be an indication that the field $\mathcal{B}$ is presented there.

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