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OCCURENCE OF "PRIMING" MAGNETIC FIELDS DURING THE FORMATION OF PROTOGALAXIES

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It is shown that weak magnetic fields may arise during the post-recombination stage of evolution of the Universe. Field generation occurs in the presence of protogalaxy rotation with respect to the homogeneous background of the residual radiation.

THE most attractive possibility for explaining galactic magnetic fields is the generation of these fields during the process of formation and evoluation of the galaxies by a self-excitation mechanism of the "dynamo" type[1,2]. As is well known, such mechanisms can operate only in the presence of weak "priming" magnetic fields. The "priming" magnetic fields should apparently occur during the initial stage of galaxy formation. The problem of galaxy formation is presently under intense study. There are two alternative points of view on the evolution of galaxy formation. The first is based on the theory of gravitational instability[3,4], and the second, developed in[5], presupposes the presence of strong vortical motions already in the initial stage of expansion of the Universe. Within the framework of the vortex theory, Harrison[6] proposed the mechanism of generation of "priming" magnetic fields in the pre-recombination plasma. In the present article we investigate the possible occurrence of weak magnetic fields during the period after the recombination of the residual plasma.

During this period, the expanding Universe consists mainly of neutral hydrogen and helium atoms with density n_H, and of free electrons and protons with densities $n_e = n_p = xn_H$ (where $x \approx 3 \times 10^{-4}$–$3 \times 10^{-5}$ is the residual degree of ionization[7]), and also residual radiation with density ρ_γ. Practically immediately after the instant of recombination t_r, matter becomes transparent to radiation on a protogalactic scale[8] and the motions of the gas do not drag the radiation, so that these motions can be regarded as occurring against a homogeneous radiation background.

Let us assume that for some reason the neutral matter of the protogalaxy, participating in the Hubble expansion, rotates with a specified angular velocity $\omega(t)$ about the radiation background. Within the framework of gravitational instability, as shown by Peebles[9], the inhomogeneities of the density can acquire an angular momentum via tidal interaction even if they did not possess one initially. The corresponding law governing the variation of ω in the steady state is[1)]

$$\omega(t) \sim t^{1/3}. \tag{1}$$

In the vortex theory, the rotation of the protogalaxies can be the consequence of initially existing vortical perturbations of the velocity. Assuming the angular momentum of the protogalaxy to be conserved, we obtain for this case

$$\omega(t) \sim a^{-2} \sim t^{-4/3}, \tag{2}$$

where a = a(t) is a scale factor. Formulas (1) and (2) are valid only up to the instant that the protogalaxies become separated from the Hubble background. All the subsequent reasoning will pertain to a arbitrary $\omega(t)$ law, and expressions (1) and (2) will be used only for concrete estimates.

We shall show that rotation of the protogalaxy is accompanied by electron motion relative to the protons and by generation of a magnetic field. In fact, the collisions of the protons with the neutral atoms, the density of which greatly exceeds the proton density, causes the protons to rotate at the same angular velocity as the neutral matter. The protons practically do not interact with the radiation, whereas the electrons interact with

[1)]We assume that the protoobject acquiring the angular momentum also acquires an angular velocity, although motion with nonzero angular momentum but without a vortex actually occurs first, and only subsequently does the motion approach the rigid-body rotation with angular velocity equal to the angular momentum divided by the moment of inertia.

the radiation much more effectively than with the neutral atoms. The radiation slows down the rotation of the electrons, producing a difference between the angular velocities of the electrons and protons, i.e., an electric current, and consequently a magnetic field. The electrons and protons are coupled by the induced electric field, which balances the radiation-friction force. Electroneutrality equalizes the radial velocities of the electrons and protons. Their direct Coulomb collisions, as will be shown below, are negligible.

The described scheme for the generation of the magnetic field can be analyzed easily by means of an approximate analytic calculation. Let $\tau_{e\gamma}$, τ_{ep}, and τ_{pH} be the characteristic times of momentum exchange between the particles of the corresponding types:

$$\frac{1}{\tau_{e\gamma}}=\frac{4\sigma_T\rho_\gamma c}{3m_e},\quad \frac{1}{\tau_{ep}}\approx 1.2\ln\Lambda\cdot n_e\left(\frac{e^2}{kT_m}\right)^2\left(\frac{kT_m}{m_e}\right)^{1/2},$$

$$\frac{1}{\tau_{pH}}\approx 2.2\sigma_0 n_H\left(\frac{kT_m}{m_p}\right)^{1/2}, \tag{3}$$

where $\sigma_T \approx 6.65\times 10^{-25}$ cm^2 is the Thomson scattering cross section, $\sigma_0 \approx 10^{-15}$ cm^{-2} is the cross section of interaction between the protons and the neutral atoms, $\ln\Lambda \approx 30$ is the Coulomb logarithm, and $T_m \sim a^{-2}$ is the temperature of the matter. The equation of electron motion is

$$0=-\alpha\{c\mathbf{E}+[\mathbf{V}_e\mathbf{B}]\}-\frac{1}{\tau_{e\gamma}}\mathbf{V}_e+\frac{1}{\tau_{ep}}(\mathbf{V}_p-\mathbf{V}_e) \tag{4}$$*

Here $\alpha = e/m_e c$, $\mathbf{V}_e$ and $\mathbf{V}_p$ are the velocities of the electrons and the protons, and $\mathbf{E}$ and $\mathbf{B}$ are the induced electric and magnetic fields. We neglect the gradient of the gravitational potential, the inertial force acting on the electrons, and also the force of friction between the electrons and the neutral matter. As follows from a more detailed calculation, allowance for these factors introduces an inessential contribution.

Application of the curl operator to Eq. (4) with allowance for Maxwell's equations and the Hubble expansion leads in first approximation to the equation

$$\frac{1}{a^2}\frac{d}{dt}a^2\alpha\mathbf{B}=\frac{1}{\tau_{e\gamma}}\zeta_p, \tag{5}$$

where we have discarded the term

$$\frac{1}{\tau_{ep}}(\zeta_p-\zeta_e)=-\frac{m_e c^2}{4\pi n_e e^2\tau_{ep}}\nabla^2\alpha\mathbf{B};\quad \zeta_{e,p}=\operatorname{rot}\mathbf{V}_{e,p},$$

describing the dissipation of the magnetic field as a result of the Coulomb collisions of e and p, which is negligible at scales encompassing a mass $M > 10^4 z^{9/2}$; z is the red shift. This also justifies the replacement of ζ_e by ζ_p (it is recognized that $\tau_{ep}/\tau_{e\gamma} \ll 1$). Obviously, $\zeta_p \approx 2\omega$, since τ_{ph} is much smaller than $\tau_{e\gamma}$, τ_{ep}, or t. For the induced magnetic field we thus obtain the expression

$$\mathbf{B}(t)=\frac{1}{\alpha a^2}\left\{\int_{t_r}^{t}\frac{2a^2\omega}{\tau_{e\gamma}}dt+(a^2\alpha\mathbf{B})|_{t=t_r}\right\}. \tag{6}$$

The final estimates are best expressed in terms of the red shift z, which is connected with t by the formula

$$H_0 dt=-\frac{dz}{(1+z)^2(1+\Omega z)^{1/2}}\approx-\Omega^{-1/2}\frac{dz}{z^{5/2}},$$

where $H_0 \approx 10^{-10}$ yr^{-1} is the Hubble constant, $\Omega = \rho_m/\rho_c$, $\rho_c = 2\times 10^{-29}$ g/cm^3 is the critical density, and ρ_m is the present-day average density of matter.

Using formula (1) for $\omega(t)$ and introducing the initial condition B = 0 at $t = t_r$, we obtain from (7) the following expression for the magnetic field:

$$B(z)\approx 3{,}3\cdot 10^{-28}\Omega^{1/6}z^2 z^{*5/2}\ln(z_r/z),\qquad z^*\leqslant z<z_r, \tag{7}$$

where z* is the red shift corresponding to the instant of separation, $z_r = 1500$ is the instant of recombination. The numerical coefficient here and in formula (9) below has been calculated under the assumptions that the angular momentum of the protogalaxy is conserved after the separation and that the contemporary values of the angular velocity and of the average density of the galaxy are respectively 10^{-15} sec^{-1} and 10^{-24} g/cm^3.

To obtain the field in the vortex model, we use formula (2) and the initial condition $B(z_r) - B_0$:

$$\mathbf{B}(z)\approx 1{,}2\left(\frac{z}{z_r}\right)^2\omega(z_r)\left[\frac{t}{\tau_{e\gamma}}\bigg|_{z=z_r}-\frac{t}{\tau_{e\gamma}}\right]+\left(\frac{z}{z_r}\right)^2\mathbf{B}_0,\quad \frac{t}{\tau_{e\gamma}}\sim z^{5/2}. \tag{8}$$

The second term in the right-hand side of this formula describes the change of the initial field in accordance with the frozen-in condition. If we take for the initial field the value $B_0 = -2m_p c e^{-1}\omega(z_r)$, calculated by Harrison[6] for the pre-recombination period, then we see that the field produced after the instant z_r has the opposite direction and greatly exceeds it in magnitude:

$$B(z)\approx 1{,}2\cdot 10^{-10}\Omega^{1/6}\omega(z_r)z^2 z_r^{1/2}\approx 6\cdot 10^{-21}z^2,\quad z^*\leqslant z\ll z_r. \tag{9}$$

It is easy to understand the physical meaning of such a result. Up to the instant z_r, the photon liquid, with which the electrons were coupled, rotated much more rapidly than the proton liquid ($\omega_\gamma \sim a^{-1}$, $\omega_p \sim a^{-2}$, at the initial instant $\omega_\gamma = \omega_p$), and this indeed produced the current. After the detachment of the radiation from the matter, the protons continue to rotate together with the neutral atoms at an angular velocity $\omega \sim a^{-2}$, and the electrons lag them, since they are now decelerated by the homogeneous background of radiation, the relative velocity of the electrons and protons reverses sign, and this leads to a change in the sign of the field.

We note that the magnetic flux Bz^{-2} corresponding to the field (7) increases like ln z when $z < z_r$, whereas in the vortex model (9) we have

$$Bz^{-2}\sim(z_r^{5/2}-z^{5/2}),$$

i.e., it is approximately constant. The values of the magnetic field at the moment $z \sim z^* \sim 100$ are respectively 10^{-18} and 6×10^{-17} G from formulas (7) and (9).

Thus, if for some reason the protoobject has an angular velocity in the post-recombination period of the hot model, then generation of priming magnetic fields on a galactic scale is possible.

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*$[\mathbf{V}_e\mathbf{B}] = \mathbf{V}_e\times\mathbf{B}$.

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