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LARGE SCALE MAGNETOGENESIS THROUGH RADIATION PRESSURE

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ABSTRACT

We present a new model for the generation of magnetic fields on large scales occurring at the end of cosmological reionisation. The inhomogeneous radiation provided by luminous sources and the fluctuations in the matter density field are the major ingredients of the model. More specifically, differential radiation pressure acting on ions and electrons gives rise to electric currents which induce magnetic fields on large scales. We show that on protogalactic scales, this process is highly efficient, leading to magnetic field amplitudes of the order of 10^{-11} Gauss. While remaining of negligible dynamical impact, those amplitudes are million times higher than those obtained in usual astrophysical magnetogenesis models. Finally, we derive the relation between the power spectrum of the generated field and the one of the matter density fluctuations. We show in particular that magnetic fields are preferably created on large (galactic or cluster) scales. Small scale magnetic fields are strongly disfavoured, which further makes the process we propose an ideal candidate to explain the origin of magnetic fields in large scale structures.

Key words : cosmology: large scale structure – magnetic fields

I. INTRODUCTION

Magnetic fields are found everywhere in the Universe. Synchrotron emission and Faraday rotation measurements allow us to detect their presence in galaxies (Beck *et al.*, 1996), in galaxy clusters (Carilli & Taylor, 2002; Clarke, these proceedings) and even on larger scales (Kronberg, 2001, and these proceedings) with amplitudes from ~ 0.1 μG to a few 10 μG.

The origin of magnetic fields on cosmological scales remains unknown. However, the possible impact of any dynamically important field on structure formation makes it clear that the fields must have been first created as weak seeds that have subsequently been amplified, probably through some dynamo mechanism. Various processes have been proposed for the generation of such seeds. The mechanisms of the first kind operate basically before matter-radiation decoupling and rely upon high energy physics such as inflation (*e.g.* Ratra, 1992) or phase transitions (*e.g.* Grasso & Riotto, 1998). For a review, consult for instance Giovannini (2004). Unfortunately, these models are not very predictive since the seeds can be as weak as 10^{-65} G and as strong as 10^{-9} G, depending strongly on the assumptions of the underlying model. In addition, extremely tight constraints on pre-BBN magnetic fields from gravity wave production have been recently derived (Caprini & Durrer, 2002), possibly ruling out a majority of the proposed models.
The mechanisms of the second kind produce magnetic seeds after decoupling. Apparently less constrained, they rely essentially on charge separation, provided by variants of the battery mechanism (Biermann, 1950) adapted to cosmological contexts (*e.g.* Pudritz & Silk, 1989; Lesch & Chiba, 1995). The amplitude of the induced seeds is usually found roughly of the order of 10^{-19} G.

Whatever the mechanism invoked, the fields produced are generally weak and need to be amplified by some powerful process. The dynamo mechanism, sustained by turbulence and differential rotation in protogalaxies, has long been considered suitable for that purpose. However, it remains controversial in some aspects. One major difficulty is due to small scale fields. Amplified faster than fields on large scale, they may inhibit, in back reaction, the dynamo process itself (*e.g.* Kulsrud *et al.*, 1997). This happens long before large scale fields can reach the observed equipartition values. A possible way out of this problem resides in the magnetic helicity escape process . Significant progress has been made recently (*e.g.* Brandenburg & Sandin, 2004; Vishniac, these proceedings), but further development is needed to ascertain the applicability of this to real galaxies.
The second problem for the dynamo comes from microgauss fields detected at high redshifts (up to $z \sim 2$, Athreya *et al.*, 1998). Starting with 10^{-19} Gauss seed fields at the time of galaxy formation, there is simply not enough time for galaxies to rotate sufficiently and amplify the seeds efficiently (*e.g.* Widrow, 2002).

The mechanism we propose appears to be relatively free of the problems mentioned above, which makes it a good candidate to explain the origin of magnetic fields on large scales. Similarly to the battery effect, it relies

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on charge separation provided, in our case, by radiation pressure.

II. OUR MODEL

(a) Description

The mechanism we present here belongs to the second of the classes of models described in the introduction. It operates after matter-radiation decoupling, in the context of cosmological reionisation, and the driving mechanism for charge separation is the radiation pressure provided by the first luminous sources. The strong dependence of the Thomson cross-section on the charged particle mass provides a powerfull acceleration of electrons with respect to ions. The matter density fluctuations present in the medium leave an imprint in the radiation flux which thus becomes inhomogeneous. The flux inhomogeneities are responsible for the creation of electric currents which in turn induce magnetic fields on the scale of the density inhomogeneities.

We investigated the effects of that mechanism in the late stages of reionisation, when the Universe is essentially ionised, at a redshift $z \sim 6-7$ as indicated by quasar absorption lines (Becker *et al.*, 2001). Further details are available in Langer, Puget & Aghanim (2003).

(b) Formalism

Combining the momentum conservation equation for charged species (electrons and protons for simplicity), in the limit $m_e \ll m_p$, we obtain the generalised Ohm's law,

$$\frac{d\vec{j}}{dt} = \frac{\omega_p^2}{4\pi}\left(\vec{E} + \frac{\vec{u}\times\vec{B}}{c}\right) + \frac{q_e}{m_e c}\vec{j}\times\vec{B} - \nu_c\vec{j} + \nu_{\rm phot}\vec{I}, \quad (1)$$

where the electric current is $\vec{j} = n_e q_e(\vec{v}_e - \vec{v}_p)$, and ω_p is the electron plasma frequency. The source term due to radiation pressure is

$$\nu_{\rm phot}\vec{I} \equiv q_e n_e c \frac{h\nu}{m_e c^2}\sigma_{\rm T}\vec{\phi}. \quad (2)$$

The region of study is assumed to be at some distance from the dominating source of radiation, such that the radiation flux is considered anisotropic and defines a preferred axis, $\vec{\phi} \parallel (Oz)$. Furthermore, the flux is inhomogeneous, due to the matter density fluctuation in the ambient plasma, and we assume the inhomogeneities small as compared to the mean value of the radiation flux, i.e. $\vec{\phi} = (1+f)\,\vec{\phi}_0$ with $f(\vec{r}) \ll 1$.

Along the line of radiation propagation (Oz), the density fluctuations imprinted inhomogeneities into the radiation flux, in the region of study where the properties of the medium are supposed not to vary significantly along (Oz). Provided this assumption, the spatial variations of f are confined to the plane orthogonal to (Oz), and derivatives with respect to z can thus be taken equal to zero. Finally, in this first approach, we consider the stationary regime and take therefore $\partial_t = 0$ as well.

III. RESULTS

Combining Ohm's law and Maxwell equations, we obtain the following equation for the magnetic field,

$$\vec{\nabla}^2\vec{B} = 4\pi\sigma_{\rm T}\frac{h\nu}{m_e c^2}\vec{\nabla}\times\left(\frac{e n_e}{\nu_e}\vec{\phi}\right) \quad (3)$$

which can be inverted to get the analytical form of the field, provided well defined boundary conditions. In the absence of such conditions, we nevertheless can still obtain crucial information on the magnitude of the magnetic field and on its power spectrum from the above equation.

(a) Order of Magnitude

We rewrite the ionising flux as

$$h\nu\phi_0 = \frac{L}{4\pi D^2} \quad (4)$$

where L is the luminosity of the typical source and D the distance to it. Then, Eq. (3) gives

$$B \sim 3.1\,10^{-2} f^{1/3} B_s^{2/3}\left(\frac{T}{10^4\,\rm K}\right)^{1/2} \times\left(\frac{R}{100\,\rm kpc}\frac{LD^{-2}}{10^{-8}\,\rm W.m^{-2}}\right)^{1/3} \quad (5)$$

where we took into account that the electrical conductivity $\sigma_0 = q_e^2 n_e/(m_e\nu_c)$ is modified and becomes $\sigma \sim \sigma_0(\nu_c/\omega_e)^2$ for magnetic fields above the "saturation" value $B_s = 2\pi\nu_c m_e c/q_e$ (for physical conditions at $z \sim 7$, $B_s \sim 7.1\,10^{-15}$ Gauss). The term LD^{-2} can be estimated by calculating the number of photons necessary for the reionisation of the Universe (see Langer, Puget & Aghanim, 2003). This gives

$$\frac{LD^{-2}}{10^{-8}\rm W.m^{-2}} \approx 6.4\,10^{-3}\,(1+z)^3\left(\frac{L}{10^{12}L_\odot}\right)^{1/3}. \quad (6)$$

Taking $z \sim 7$ for the reionisation redshift, for a dominant $L \sim 10^{12}L_\odot$ source (quasar) and on protogalactic scale fluctuations, $R \sim 100$ kpc, the order of magnitude obtained is

$$B \sim 10^{-11}\,\rm Gauss \quad (7)$$

assuming an inhomogeneity level of $f \sim 10\%$. If the magnetic field is frozen into the plasma, considering a subsequent amplification by adiabatic collapse we end up with a galactic seed field of

$$B_{\rm gal} \sim \delta_c^{2/3} B \sim 3\,10^{-10}\,\rm Gauss \quad (8)$$

with $\delta_c = \rho_{\rm gal}/\bar{\rho} \sim 200$. This result is very promising and indicates that our mechanism could actually account for magnetic fields in high redshift objects as dynamo amplification would need much less time than in usual battery models to bring that value to the microgauss level.

(b) Power Spectrum

From Eq. (3), we deduce that the power spectrum of the generated seed is $P_{\rm B}(k) \propto |f_k|^2/k^2$, where $|f_k|^2$ is the power spectrum of the flux inhomogeneities. The latter are related in a simple way to the fluctuations in the optical depth, since we can express f as

$$f = \exp(-\tau_l) - 1 \tag{9}$$

where

$$\tau_l \propto \int_0^l \delta(\vec{r}) dz \tag{10}$$

with $\delta(\vec{r})$ being the matter density contrast. Following Bartelmann & Schneider (2001) in their derivation of Limber's formula in Fourier space, we obtain the following relation between the magnetic field power spectrum and the spectrum $|\delta_{k'}|^2$ of the density fluctuations:

$$P_B(|\vec{k}_\perp|) \propto \frac{l^2}{k_\perp^2} \int d^2\vec{k}'_\perp \delta_{\rm D}(\vec{k}_\perp - \vec{k}'_\perp) \int dk'_\parallel |\delta_{k'}|^2 \left[\frac{2}{k'_\parallel l} \sin\left(\frac{k'_\parallel l}{2}\right)\right]^2 . \tag{11}$$

Figure (1) shows the shape of the power spectrum calculated in the non-saturated regime assuming an integration depth $l \sim 10$ Mpc. We considered an initial Harrison-Zel'dovich matter density power spectrum, $|\delta_k|^2 \propto k$. Use has also been made of the BBKS (Bardeen *et al.*, 1986; Sugiyama, 1995) fit to the transfer function $T_{\vec{k}}$ as obtained for a flat universe with $\Omega_{\rm CDM} = 0.27$, $\Omega_{\rm b} = 0.044$ and $h = 0.71$ (Bennett *et al.*, 2003).

The contribution to the optical depth fluctuations of density inhomogeneities on scales larger than l is scale independent. Therefore, $|f_k|^2$ does not depend on the scale, and $P_B(k) \propto k^{-2}$ for $k < l^{-1}$. This part of the spectrum, however, is not relevant for our study since it involves fluctuations on scales larger than l. These scales are of the order of the mean distance between the sources of radiation, and at those scales the assumption of anisotropy breaks down.

On the relevant scales, as one can see, the magnetic field is generated preferentially on large scales, and is substantially suppressed on smaller scales. Moreover, the slope of the power spectrum is steeper and steeper on smaller and smaller scales. On cluster scales for instance, it goes roughly like k^{-4} whereas on galactic scales, its slope is ~ -4.7. This result confers a very favorable property to our magnetogenesis model

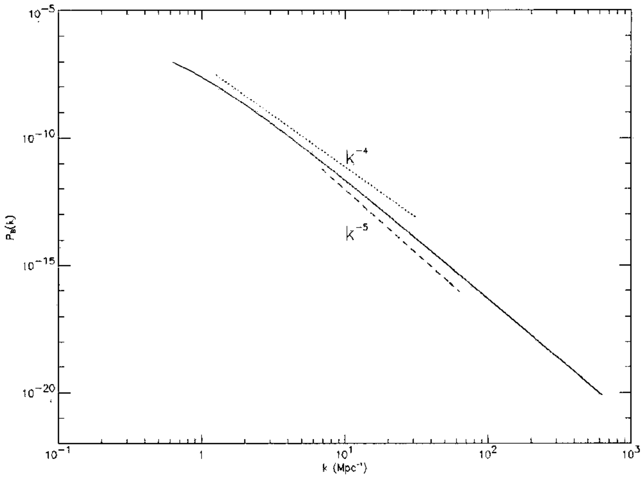

Fig. 1.— Power spectrum of the generated magnetic field in the non-saturated regime. A Harrison-Zel'dovich $|\delta_k|^2 \propto k$ power spectrum has been assumed for the initial density fluctuations. The integration depth is $l \sim 10$ Mpc. Normalisation is arbitrary.

with respect to possible subsequent amplification by dynamo action. With the seeds created by our mechanism, the dynamo quenching problem may be delayed as small scale magnetic fields are initially much weaker than seed fields on large scales.

IV. CONCLUSION AND PROSPECTS

We presented a new model for the generation of magnetic fields on cosmological scales. The driving mechanism is the force exerted on electrons by radiation pressure. Two essential ingredients are required: the anisotropy (for charge separation) and the inhomogeneity (for electric current generation) of the radiation flux. Such properties are reunited in the situation that we explored here, namely during the late stages of the cosmological reionisation.

The magnetic seed fields generated by our mechanism possess two essential properties. First, the seed fields we found are quite higher, as much as by eight orders of magnitude, on large (protogalactic) scales than in usual thermal battery models. This suggests that our model is suitable to account for the microgauss amplitudes of magnetic fields detected in high redshift objects.

Second, the magnetic field appears to be generated mainly on large scales, fields on smaller scales being strongly damped. With this property provided by our model, the apparition of the problem in dynamo theories of early quenching due to precocious small scale field amplification can be delayed.

To further develop our model and demonstrate its applicability to realictic conditions, we are now relaxing some of our assumptions. In particular, we will present elsewhere the study of the transient regime of the magnetic field generation process driven by radiation pressure. Finally, we will perform numerical simulations in order to account correctly for the distribution of luminous sources. This approach will also enable us to address the question of the dependence of our model on the nature of the ionising sources.

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