C. R. Physique 16 (2015) 1018–1026

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Cosmic inflation / Inflation cosmique

Issues on the inflationary magnetogenesis

Inflation et production d'un champ magnétique cosmologique pendant l'inflation

Jun'ichi Yokoyama [a,b,c,*]

[a] *Research Center for the Early Universe (RESCEU), School of Science, The University of Tokyo, Tokyo 113-0033, Japan*
[b] *Department of Physics, School of Science, The University of Tokyo, Tokyo 113-0033, Japan*
[c] *Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), TODIAS, WPI, The University of Tokyo, Chiba 277-8583, Japan*

A R T I C L E   I N F O

Article history:
Available online 11 November 2015

Keywords:
Cosmology
Inflation
Magnetic field
Schwinger effect

Mots-clés :
Cosmologie
Inflation
Champ magnétique
Effet Schwinger

A B S T R A C T

Recent observations of high-energy photons from blazars suggest that there exist magnetic fields with typical amplitude around 10^{-15} G ubiquitously even in void regions. This being the case, it is natural to invoke them to explain the processes occurring during inflation in the early universe. We provide a list of models of magnetogenesis during inflation and consider several problems associated with them.

R É S U M É

L'observation récente de photons ultra-énergétiques en provenance des blazars suggère l'existence de champs magnétiques cosmologiques, d'amplitude typique 10^{-15} G, omniprésents, y compris au sein des vides cosmiques. Il est dès lors naturel de les associer à la physique inflationnaire dans l'univers primordial. Nous donnons une liste de modèles de génération d'un champ magnétique pendant l'inflation et discutons un certain nombre de problèmes qu'ils posent.

1. Introduction

Magnetic fields play important roles in various astrophysical objects. In this article we focus on magnetic fields on cosmological scales. The amplitude of magnetic fields in galaxies and clusters of galaxies have been measured as $B \sim 10^{-5} - 10^{-6}$ G and $10^{-6} - 10^{-7}$ G, respectively (see, e.g., [1–3]). The origin of the galactic magnetic field is usually attributed to the dynamo mechanism, which, however, requires a nonvanishing seed field, although it may be as tiny as $10^{-22} - 10^{-16}$ G [4,5].

For a long time, only upper bounds had been obtained for the amplitude of magnetic fields outside galaxies and clusters or on larger scales. Recently, however, a new method to probe magnetic field was proposed, combining observations of TeV

* Correspondence to: Research Center for the Early Universe (RESCEU), School of Science, The University of Tokyo, Tokyo 113-0033, Japan.
E-mail address: yokoyama@resceu.s.u-tokyo.ac.jp.

http://dx.doi.org/10.1016/j.crhy.2015.08.008
1631-0705/

photons by HESS [6] and GeV photons by Fermi LAT [7] from blazars, which may be interpreted as setting a lower bound on the field amplitude on relatively large scales [8].

The existence of magnetic fields on scales well above the galactic scale and in particular in void regions [9] would motivate us to attribute their origin to the processes during to the inflationary period in the early universe [10–13]. Hence here we review and consider several issues on magnetogenesis during inflation, starting with a review on the observational results in Section 2.

In Section 3 we present an incomplete list of proposed models for inflationary magnetogenesis. Then in Section 4 we describe a model to produce magnetic fields by modifying the kinetic term of the gauge field. In Section 5, we summarize the constraints imposed on such a model mainly by the excessive electric field generated during inflationary magnetogenesis. Next we consider the effect of Schwinger's process [15], which may take place due to the strong induced electric field. Finally Section 7 is devoted to our conclusion.

2. Observational evidence of large-scale magnetic field in empty space

According to the unified model of the accretion disks, we identify them as blazars if they are observed from the polar directions along which jets of high-energy TeV photons are emitted. These photons of energy E_{γ_0} scatter extragalactic background light (EBL) [16], consisting mainly of optical or infrared photons to create electron–positron pairs [17]. This occurs at a typical distance

$$D_\gamma(E_{\gamma_0}, z) = \frac{40\kappa}{(1+z)^2}\left(\frac{E_{\gamma_0}}{20\ \text{TeV}}\right)^{-1}\ \text{Mpc} \tag{1}$$

which is not close to the blazar. Here κ is a numerical parameter ranging between 0.3 and 3. The electron–positron pairs thus created with energy E_e scatter off cosmic microwave background (CMB) radiation with energy E_CMB to create GeV energy photons with typical energy

$$E_\gamma = \frac{4E_\text{CMB}E_\text{e}^2}{3\,(1+z_{\gamma\gamma})} \simeq 0.32\left(\frac{E_{\gamma_0}}{20\ \text{TeV}}\right)^2\ \text{TeV} \tag{2}$$

with $E_\text{e} = E_{\gamma_0}/2$ and the mean free path

$$\begin{aligned} D_\text{e} &\simeq 10^{23}(1+z_{\gamma\gamma})^{-4}\left(\frac{E_\text{e}}{10\ \text{TeV}}\right)^{-1}\ \text{cm} \\ &\simeq 33\left(\frac{E_\text{e}}{10\ \text{TeV}}\right)^{-1}\ \text{kpc} \end{aligned} \tag{3}$$

Thus the high-energy photons travel a long cosmological distance before encountering an extragalactic background photon, but once they create electron–positron pairs, subsequent cascade processes occur almost locally.

If there exists a magnetic field, electron trajectories are bent with the Larmor radius

$$R_L = \frac{E_\text{e}}{eB} \simeq 3\cdot 10^{28}\left(\frac{B_0}{10^{-18}\ \text{G}}\right)^{-1}\left(\frac{E_\text{e}}{10\ \text{TeV}}\right)\text{cm} \tag{4}$$

Hence if the correlation length of the magnetic field, λ_B, satisfies $\lambda_B \gg D_\text{e}$, the deflection angle is given by

$$\delta = \frac{D_\text{e}}{R_L} \simeq 3\cdot 10^{-6}(1+z_{\gamma\gamma})^{-2}\left(\frac{B_0}{10^{-18}\ \text{G}}\right)^{-1}\left(\frac{E_\text{e}}{10\ \text{TeV}}\right)^{-2} \tag{5}$$

If it is much smaller than D_e, the net deflection angle is given by the result of random walks as

$$\delta = \frac{\sqrt{D_\text{e}\lambda_B}}{R_L} \simeq 5\cdot 10^{-7}(1+z_{\gamma\gamma})^{-1/2}\left(\frac{B_0}{10^{-18}\ \text{G}}\right)\left(\frac{E_\text{e}}{10\ \text{TeV}}\right)^{-3/2}\left(\frac{\lambda_B}{1\ \text{kpc}}\right)^{1/2} \tag{6}$$

As a result, GeV photons created by the scatter of electron and positron arrive at the observer with an opening angle $\Theta_\text{ext} \cong D_\gamma\delta/D_\theta$, where D_θ is the distance between the blazar and the observer. The opening angle is given by

$$\Theta_\text{ext} \simeq \frac{0.5^\circ}{(1+z)^2}\left(\frac{\tau_\theta}{10}\right)^{-1}\left(\frac{E_\gamma}{0.1\ \text{TeV}}\right)^{-1}\left(\frac{B_0}{10^{-14}\ \text{G}}\right) \tag{7}$$

for $\lambda_B \gg D_\text{e}$ with $\tau_\theta \equiv D_\theta/D_\gamma$, and

$$\Theta_\text{ext} \simeq \frac{0.07^\circ}{(1+z)^{1/2}}\left(\frac{\tau_\theta}{10}\right)^{-1}\left(\frac{E_\gamma}{0.1\ \text{TeV}}\right)^{-3/4}\left(\frac{B_0}{10^{-14}\ \text{G}}\right)\left(\frac{\lambda_B}{1\ \text{kpc}}\right)^{1/2} \tag{8}$$

for $\lambda_B \ll D_\text{e}$. These are to be compared with the point spread function of Fermi LAT, given by