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A novel constraint on the Primordial Magnetic Fields using 21-cm line absorption signal

Teppei Minoda*
Department of Physics and Astrophysics, Nagoya University, Nagoya 464-8602, Japan
E-mail: minoda.teppei@d.mbox.nagoya-u.ac.jp

Hiroyuki Tashiro
Department of Physics and Astrophysics, Nagoya University, Nagoya 464-8602, Japan

Tomo Takahashi
Department of Physics, Saga University, Saga 840-8502, Japan

The observation of redshifted 21-cm absorption signal enables us to constrain the intergalactic medium (IGM) gas thermal history. According to the standard scenario of the cosmological structure formation, the sky-averaged (global) 21-cm line signal is expected to be detected as an absorption signal during the Dark Ages. In this paper, we study a possible constraint on the primordial magnetic fields (PMFs) strength with global 21-cm line observation. PMFs can heat up the IGM gas in the Dark Ages due to magnetohydrodynamic energy dissipation mechanisms. The global 21-cm absorption signal can be detected only when the IGM gas is cooler than the cosmic microwave background (CMB) photons. We solve the evolution equations for the IGM gas temperature, ionization fraction and the magnetic field strength, and investigate the global 21-cm signal with the PMFs. Moreover, we demonstrate that, if the redshift of the 21-cm absorption signal is detected at $z \simeq 17$, the PMF strength smoothed on 1 Mpc can be constrained as $B_{1\mathrm{Mpc}} \lesssim 10^{-10}$ Gauss.

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*Speaker.

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1. Introduction

Thanks to a lot of observations, a wide variety of astronomical objects from planets and stars to galaxies and galaxy clusters are magnetized, but the origin of such magnetic fields remains unknown. One possibility is to create weak magnetic fields in the early universe, and such fields are generally called "Primordial Magnetic Fields (PMFs)". So far, many types of mechanisms have been studied to produce PMFs before the recombination epoch (for detailed reviews, see references [1, 2]). On the other hand, constraints on PMFs are also investigated well. For example, observations of the cosmic microwave background (CMB) have given a constraint on PMFs as $B_{1\mathrm{Mpc}} \lesssim 4.4$ nG [3]. Recently, Saga *et al.* [4] suggested that PMF strength on smaller scale than 1 kpc is strongly constraint by considering the magnetic reheating process, as $B_{1\mathrm{kpc}} \lesssim 10^3$ nG. They investigated the increase of the baryon-to-photon ratio between the era of Big Bang Nucleosynthesis (BBN) and the recombination epoch due to the energy dissipation of the PMFs. If PMFs survive after the recombination epoch, they could also affect the intergalactic medium (IGM) gas considerably [5], and its signature is perhaps probed by the 21-cm line observation [6].

The purpose of this study is to investigate the thermal history of the IGM gas with the PMF dissipation, and to give a prediction for a constraint on the PMF strength from the global 21-cm line signal. Recently EDGES has reported the global 21-cm absorption signal at $z \sim 17$ was detected [7]. We demonstrate that, if this signal will be confirmed, the global 21-cm signal provides a great impact on the PMF constraint. The detailed calculation methods are described in our previous papers [8, 9, 10] and we adopt the flat-ΛCDM cosmology with *Planck* 2015 cosmological parameters [11] as $h = 0.678$, $\Omega_c h^2 = 0.1186$ and $\Omega_b h^2 = 0.02226$, where h, Ω_c, Ω_b are the reduced Hubble constant, and the cold dark matter and baryon density parameters respectively.

2. Methods

The global differential brightness temperature at redshift z is given by

$$\delta T_b(z) \propto x_{\mathrm{HI}}(z) \left[1 - \frac{T_\gamma(z)}{T_{\mathrm{S}}(z)}\right] (1+z)^{1/2} , \tag{2.1}$$

where x_{HI} is the neutral fraction of hydrogen atoms, T_γ is the background radiation temperature, and T_{S} is the spin temperature of hydrogen, which is determined by population ratio between two hyperfine levels. After the first stars formed and emitted strong Ly-α photons, T_{S} is considered to couple with the kinetic gas temperature T_{K} due to the so-called Wouthuysen-Field effect [12, 13]. A detection of the global 21-cm absorption signal suggests that $\delta T_b < 0$, which means that T_{K} and T_{S} are lower than the CMB temperature T_γ.

In this study, we evaluate the cosmological history of T_{K} with effects of PMF dissipation, and we aim to put a constraint on the PMF models from the 21-cm absorption condition $T_{\mathrm{K}} < T_\gamma$. The time evolution of T_{K} is calculated as

$$\dot{T}_{\mathrm{K}}(t) = -2H(t)T_{\mathrm{K}}(t) + \frac{x_{\mathrm{i}}(t)}{1+x_{\mathrm{i}}(t)} \frac{8\rho_\gamma(t)\sigma_{\mathrm{T}}}{3m_e c}[T_\gamma(t) - T_{\mathrm{K}}(t)] + \frac{2}{3k_{\mathrm{B}} n_{\mathrm{H}}(t)}[\dot{Q}_{\mathrm{AD}}(t) + \dot{Q}_{\mathrm{DT}}(t)] . \tag{2.2}$$

Now we denote the Hubble parameter, ionization fraction of hydrogen, Thomson scattering cross-section, the rest mass of an electron, the speed of light, Boltzmann constant and number density

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of the hydrogen atoms by $H(t)$, $x_i(t)$, $\rho_\gamma(t)$, σ_T, m_e, c, k_B, and $n_H(t)$, respectively. The first term is adiabatic cooling from the cosmic expansion, and the second one is heating (or cooling) caused by Compton scattering with CMB photons. The last term represents the PMF heating rate due to ambipolar diffusion (AD) and the decaying turbulence (DT), and given by

$$\dot{Q}_{\rm AD}(t) = \frac{|[\nabla\times\mathbf{B}(t)]\times\mathbf{B}(t)|^2}{16\pi^2\xi(t)\rho_{\rm H}^2(t)}\frac{1-x_{\rm i}(t)}{x_{\rm i}(t)}, \tag{2.3}$$

$$\dot{Q}_{\rm DT}(t) = \frac{3w_B}{2}H(t)\frac{|\mathbf{B}(t)|^2}{8\pi}a^4(t)\,\frac{[\ln(1+t_d/t_{\rm rec})]^{w_B}}{[\ln(1+t_d/t_{\rm rec})+\ln(t/t_{\rm rec})]^{w_B}}. \tag{2.4}$$

Here, ξ is the drag coefficient of AD and t_d is the typical time-scale of DT, and their values are given in [14, 15]. $\rho_H(t)$ is the hydrogen energy density, $a(t)$ is the cosmic scale factor, and t_{rec} is the recombination time. We also assume $w_B = 2(n_B+3)/(n_B+5)$ is constant (see equation (2.5) for the definition of n_B).

To calculate the equations (2.3) and (2.4), we need the spatial distribution of PMFs. The PMF strength distribution differs from mechanisms of the magnetogenesis. In this paper, we assume that the scale dependence of the PMFs is given by a power-law of coherent wavenumber k as

$$B_\lambda = B_{\rm 1Mpc}\left(\frac{k}{k_n}\right)^{(n_B+3)/2}, \tag{2.5}$$

with the spectral index n_B, and the pivot scale k_n is set to 2π Mpc^{-1} here. We mention that PMF is expected to have the smallest scale due to the radiative viscosity in the early universe, and it is approximately given by

$$\left(\frac{k_{\rm cut}}{k_n}\right)^{n_B+5} = 1.32\times10^{-3}\left(\frac{B_{\rm 1Mpc}}{\rm 1nG}\right)^2. \tag{2.6}$$

Now we can statistically estimate $|\mathbf{B}|$ and $|(\nabla\times\mathbf{B})\times\mathbf{B}|$ by integrating all scales larger than k_{cut}.

3. Results and Discussion

We solve the equation (2.2) for various combinations of B_{1Mpc} and n_B. Because the 21-cm absorption signal can be observed when the kinetic gas temperature T_K is lower than the CMB temperature T_γ, we can put a constraint on PMF models by giving the redshift of the 21-cm absorption signal. Here, we show the resultant PMF constraint for the absorption redshift $z_{abs} = 17.0$ in the figure 1. We obtained the upper limit of the PMF normalized amplitude as $B_{1Mpc} \lesssim 1.2\times10^{-10}$ G for $n_B = -2.9$, $B_{1Mpc} \lesssim 6.3\times10^{-12}$ G for $n_B = -2.0$ and $B_{1Mpc} \lesssim 2.0\times10^{-13}$ G for $n_B = -1.0$. We also plot other constraints on the PMFs in the figure 1, which are the CMB anisotropy constraint with the grey-dotted line [3] and the magnetic reheating one with the grey-dashed line [4]. As obviously shown in the figure 1, our constraint is the most stringent among them for the magnetic spectral index $-3 < n_B < -2$.

4. Summary

In this work, we investigated the effect of the PMFs on the global 21-cm signal. The PMFs may heat up the IGM gas considerably due to the MHD dissipation mechanisms. When the IGM

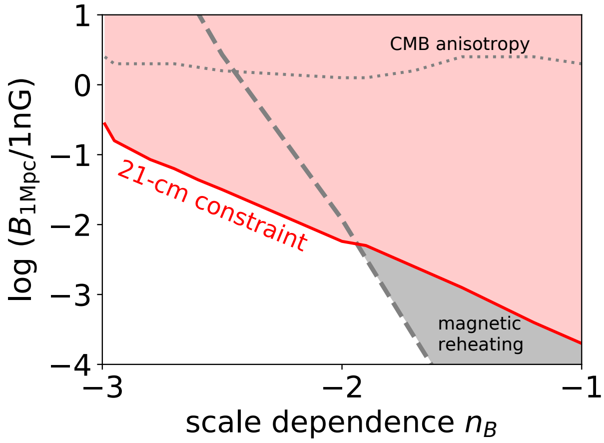

Figure 1: A constraint on the PMF amplitude and scale dependence from the 21-cm line absorption signal. The horizontal and vertical axes give n_B and $B_{1\mathrm{Mpc}}$, the red solid line shows the 21-cm constraint for $z_{\mathrm{abs}} = 17.0$.

kinetic gas temperature surpasses the CMB temperature, the 21-cm absorption signal is no longer detected. In this study, we numerically solved the thermal history of the IGM gas during the Dark Ages with MHD dissipation effects. Finally we found that the condition $T_{\mathrm{K}} < T_\gamma$ at $z = 17.0$ gives a strong constraint on the PMFs roughly as $B_{1\mathrm{Mpc}} \lesssim 10^{-10}$ G.

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