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A Strong Constraint on the Neutrino Mass from the Formation of Large Scale Structure in the Presence of the Primordial Magnetic Field

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Placing constraints on the neutrino mass is an important goal in modern physics. One important limit on the neutrino mass can be deduced from the cosmological constraint on the formation of large scale structure as the neutrinos become nonrelativistic at late times. On the other hand we have shown that the development of large scale structure and the limits on the neutrino mass are also affected by the existence of the primordial magnetic field. We have made an analysis of limits on the neutrino mass which includes the formation of large scale structure in the presence of the primordial magnetic field. We find that the combined constraint from the formation of large-scale structure and the limits on the primordial magnetic field imply an upper limit on the mass of the neutrino of $m_\nu < 0.8$ eV($N_\nu = 3$).

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[†] A footnote may follow.

1. Introduction

Magnetic fields have been observed [1, 2, 3, 4] in clusters of galaxies with a strength of $0.1-1.0\ \mu$ G. One possible explanation for such magnetic fields in galactic clusters is the existence of a primordial magnetic field (PMF) of order 1 nG whose field lines collapse as structure forms. The origin and detection of the PMF is, hence, a subject of considerable interest in modern cosmology[5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20].

If dynamically significant large-scale magnetic fields were present in the early universe, they would have affected the formation and evolution of the observed structure. Thus, some signatures of the existence of a PMF should be apparent in the presently observed cosmic structure.

In this regard, the alternative normalization parameter σ_8 is of particular interest. It is defined [21] as the root-mean-square of the matter density fluctuations in a comoving sphere of radius $8h^{-1}$ Mpc. It is determined by a weighted integral of the matter power spectrum. Observations which determine σ_8 provide information about the physical processes affecting the evolution of density-field fluctuations and the formation of structure on the cosmological scales. The mechanisms by which a PMF can affect the density field fluctuations on cosmological scales has been described in our previous work [14]. The upper limit of mass of neutrinos is, also, expected orders of $1\sim0.1$ eV[22, 23]. In this case, since velocity distributions of neutrinos become very large, a growth of density fluctuations in the free-streaming scale of neutrinos will be interfered by such neutrinos. Therefore, σ_8 is affected by the presence of the PMF and neutrinos. In this article we show that by considering the effect of the PMF and neutrinos on σ_8 and comparing theoretically estimated values for σ_8 with the observed range, we can obtain constraints on the parameters of the PMF and mass of the neutrino.

2. Model

Since the trajectories of plasma particles are bent by Lorentz forces in a magnetic field, photons are indirectly influenced by the magnetic field through Thomson scattering. The energy density of the magnetic field can be treated as a first order perturbation upon a flat Friedmann-Robertson-Walker (FRW) background metric. In the linear approximation, the magnetic field evolves as a stiff source. Therefore, we can discard all back reactions from the magnetohydrodynamic (MHD) fluid onto the field itself. The conductivity of the primordial plasma is very large, so that the magnetic field is "frozen-in" [6]. Furthermore, we can neglect the electric field, i.e. $E\sim0$, and can decouple the time evolution of the magnetic field from its spatial dependence, i.e. $\mathbf{B}(\tau,\mathbf{x})=\mathbf{B}(\mathbf{x})/a^2$ for very large scales , where a is the scale factor. We assume that the PMF is statistically homogeneous, isotropic and random. For such a magnetic field, the fluctuation power spectrum can be taken as a power-law $S(k)=<B(k)B^*(k)>\propto k^{n_\mathrm{B}}$ [6] where n_B is the power-law spectral index of the PMF. The index n_B can be either negative or positive depending upon the physical processes of magnetic field creation. From Ref. [6], a two-point correlation function for the PMF can be defined by

$$\left\langle B^i(\boldsymbol{k})B^{j*}(\boldsymbol{k}')\right\rangle = \frac{(2\pi)^{n_\mathrm{B}+8}}{2k_\lambda^{n_\mathrm{B}+3}}\frac{B_\lambda^2}{\Gamma\left(\frac{n_\mathrm{B}+3}{2}\right)}k^{n_\mathrm{B}}P^{ij}(k)\delta(\boldsymbol{k}-\boldsymbol{k}'),\ \ k<k_C\ \ , \tag{2.1}$$

where $P^{ij}(k)=\delta^{ij}-\frac{k^ik^j}{k^2}$. Here, B_λ is the magnetic comoving mean-field amplitude obtained by smoothing over a Gaussian sphere of comoving radius λ, and $k_\lambda=2\pi/\lambda$ ($\lambda=1$ Mpc in this paper).

The cutoff wave number k_C in the magnetic power spectrum is defined by [24],

$$k_C^{-5-n_{\rm B}}(\tau) = \begin{cases} \frac{B_\lambda^2 k_\lambda^{-n_{\rm B}-3}}{4\pi(\rho+p)} \int_0^\tau d\tau' \frac{l_\gamma}{a}, \ \tau < \tau_{\rm dec} \\ k_C^{-5-n_{\rm B}}(\tau_{\rm dec}), \ \tau > \tau_{\rm dec}, \end{cases} \tag{2.2}$$

where l_γ is the mean free path of photons, and $\tau_{\rm dec}$ is the conformal time of the decoupling of photons from baryons.

For this article we have constructed a numerical program, "PriME: Program for primordial Magnetic Effects", with which we can evaluate the PMF source power spectrum using the numerical method described in Refs. [14, 15, 25]. Using this, we can quantitatively evaluate the time evolution of the cut off scale and thereby reliably calculate the effects of the PMF.

We use an adiabatic initial conditions for the evolution of primary density perturbations and when estimating the CMB anisotropy in the presence of the PMF. We fix the best fit cosmological parameters of the flat Universe CDM model[26] as given in h=65.7, Ω_b=0.0523, Ω_c=0.2627, n_S= 0.95, τ_C= 0.084, where h denotes the Hubble parameter in units of 100 km s^{-1} Mpc^{-1}, Ω_b and Ω_c are the baryon and cold dark matter densities in units of the critical density, n_S is the spectral index of the primordial scalar fluctuations, and τ_C is the optical depth for Compton scattering.

3. Results and Discussions

We can study the physical processes of density field fluctuations on cosmological scales within the linear regime to determine σ_8. Recently σ_8 has been constrained by observations [27, 28, 29, 30, 31] to be in the range $0.7 < \sigma_8 < 0.9$. From this we can obtain strong constraint for the PMF parameters by numerically calculating σ_8 under the influence of PMF effects.

We expect that the discrepancy between theoretical estimates and observational temperature fluctuations of the CMB for higher multipolarity ($\ell > 1000$) is solved by combining a PMF of strength 2.0 nG $< |B_\lambda| <$ 3.0 nG and the SZ effects[15, 16]. In this case, σ_8 derived by such a field strength for the PMF is $0.77-0.88$. This is consistent with our assumed prior in the range σ_8 as $0.7 < \sigma_8 < 0.9$. Since σ_8 is affected by other cosmological parameters, Ω_b, $\Omega_{\rm CDM}$, $n_{\rm S}$, and $A_{\rm S}$, we should consider the degeneracy between the PMF and other cosmological parameters as mentioned above. Fortunately, these cosmological parameters are constrained by recent CMB observations on larger scales ($\ell < 1000$) [32, 33, 34], while, as it was shown in our previous work[12, 14, 15], the effect of the PMF mainly affects the CMB anisotropies on smaller scales ($\ell > 1000$). Hence, we expect that the degeneracy between the PMF parameters and the other cosmological parameters is small. For this reason in the present analysis we are justified in fixing the other cosmological parameters at their best fit values.

Figure 1 shows the behavior of the PMF parameters B_λ and Σm_ν for various constant values of σ_8 as labeled. Since the PMF power spectrum depends on $n_{\rm B}$, PMF effects on density fluctuations for small scales decrease with lower values for $n_{\rm B}$.

The upper limit of mass of neutrinos is expected orders of 1$\sim$0.1 eV[22, 23]. Neutrinos decrease matter density fluctuations[23], while the PMF increases matter density fluctuations[14]. Furthermore, the PMF of more than 1 nG for $n_{\rm B}$, which is within ranges constrained by previous works[11, 12], effectively affects matter density fluctuations(Fig. 1). Therefore, the mass of neutrinos constrained from matter density fluctuations in consideration of the PMF is larger than the mass determined without including the PMF[23].

The expected parameters of the PMF from the CMB and magnetic fields in cluster of galaxies are 2.0nG$< B_\lambda <$3.0nG and $n_{\rm B} < -1.0$[11, 12], and the value of σ_8 constrained by observations is 0.7$< \sigma_8 <$0.9 as mentioned above. In this case, the mass of neutrinos is constrained to

$$m_\nu < 0.8 \mathrm{eV} \mathrm{for} N_\nu = 3, \tag{3.1}$$

which is larger than previous constrains on it because the effect of the PMF cancels out the effect of neutrinos on the density fluctuations.

If we constrain PMF parameters and σ_8 from the future cosmological observations, e.g. Quiet, Planck, SDSS, We will obtain not only the upper but the lower limits of the mass of the neutrino from cosmology with the PMF.

References

[1] P. P. Kronberg, J. J. Perry, and E. L. H. Zukowski, ApJ. **387**, 528 (1992).

[2] A. M. Wolfe, K. M. Lanzetta, and A. L. Oren, ApJ. **388**, 17 (1992).

[3] T. E. Clarke, P. P. Kronberg, and H. Boehringer, Astrophys. J. **547**, L111 (2001).

[4] Y. Xu, P. P. Kronberg, S. Habib, and Q. W. Dufton, Astrophys. J. **637**, 19 (2006).

[5] D. Grasso and H. R. Rubinstein, Phys. Rept. **348**, 163 (2001).

[6] A. Mack, T. Kahniashvili, and A. Kosowsky, Phys. Rev. **D 65**, 123004 (2002).

[7] K. Subramanian and J. D. Barrow, Mon. Not. Roy. Astron. Soc. **335**, L57 (2002).

[8] A. Lewis, Phys. Rev. **D 70**, 043011 (2004).

[9] R. Gopal and S. K. Sethi, Phys. Rev. **D 72**, 103003 (2005).

[10] D. G. Yamazaki, K. Ichiki, and T. Kajino, Nucl. Phys. A **758**, 791 (2005a).

[11] D. G. Yamazaki, K. Ichiki, and T. Kajino, Astrophys. J. **625**, L1 (2005b).

[12] D. G. Yamazaki, K. Ichiki, T. Kajino, and G. J. Mathews, Astrophys. J. **646**, 719 (2006a).

[13] D. G. Yamazaki, K. Ichiki, T. Kajino, and G. J. Mathews, PoS(NIC-IX). p. 194 (2006b).

[14] D. G. Yamazaki, K. Ichiki, K. I. Umezu, and H. Hanayama, Phys. Rev. **D 74**, 123518 (2006c).

[15] D. G. Yamazaki, K. Ichiki, T. Kajino, and G. J. Mathews, Phys. Rev. **D 77**, 043005 (2008).

[16] D. G. Yamazaki, K. Ichiki, T. Kajino, and G. J. Mathews, Phys. Rev. **D 78**, 123001 (2008).

[17] C. G. Tsagas and R. Maartens, Phys. Rev. **D 61**, 083519 (2000).

[18] M. Giovannini, Phys. Rev. **D 70**, 123507 (2004).

[19] H. Tashiro, N. Sugiyama, and R. Banerjee, Phys. Rev. **D 73**, 023002 (2006).

[20] S. K. Sethi, B. B. Nath, and K. Subramanian (2008), `arXiv:0804.3473`.

[21] P. J. E. Peebles, *The Large-Scale Structure of the Universe* (Princeton University Press, 1980).

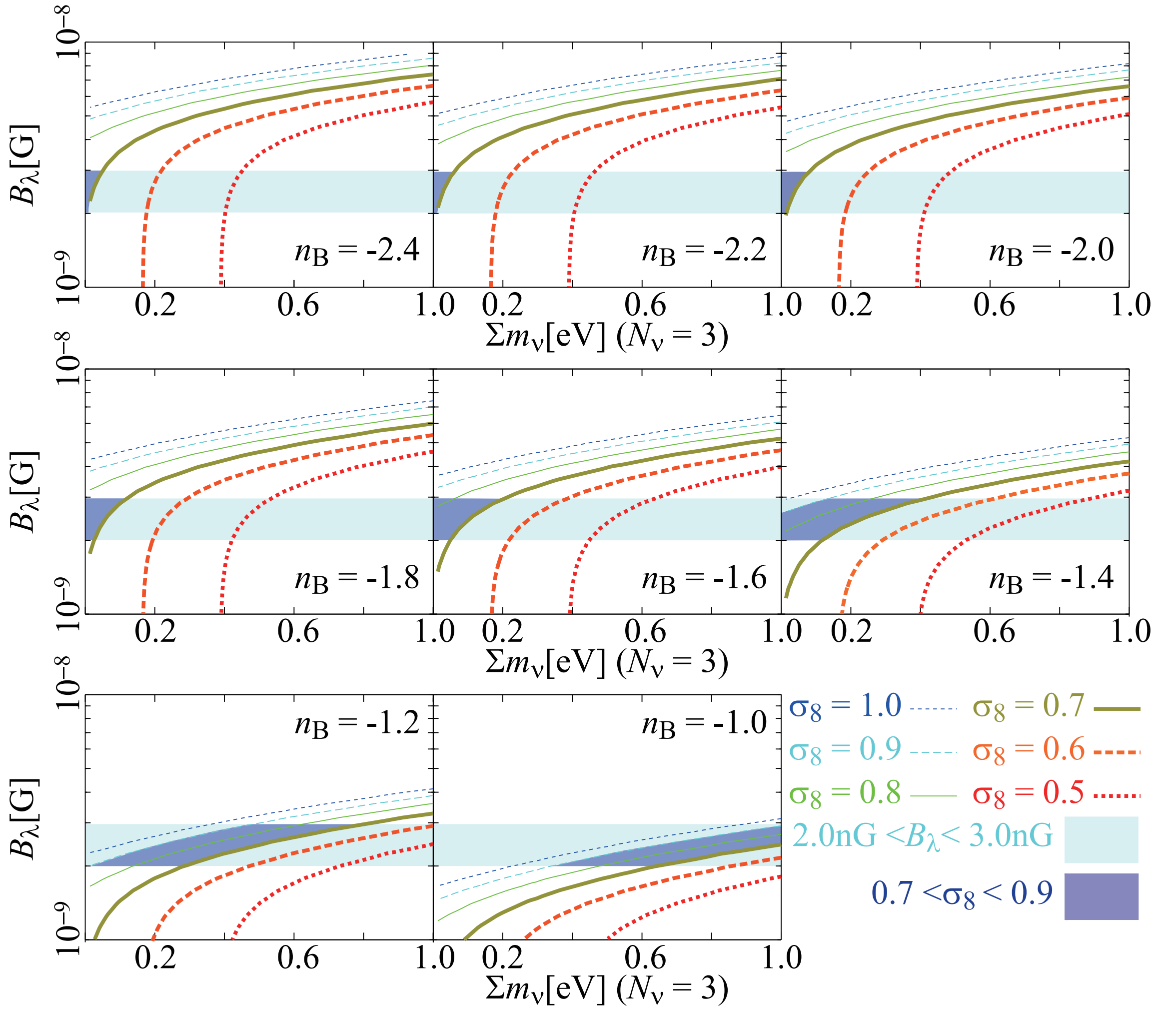

Figure 1: Curves of constant values for σ_8 in the parameter plane of PMF amplitude B_λ vs. mass of neutrinos $\Sigma m_\nu (N_\nu = 3)$. Thin-dotted-blue, thin-dashed-aqua, thin-green, bold-dark-green, bold-dashed-orange, and bold-dotted-red curves show constant values of σ_8 =1.0, 0.9, 0.8, 0.7, 0.6 and 0.5, respectively. An aqua region shows the allowed range for 2.0 nG$< B_\lambda <$ 3.0nG, and a blue region shows the allowed range for 0.7 $< \sigma_8 <$0.9 and 2.0 nG$< B_\lambda <$ 3.0nG.

[22] E. W Otten, and C. Weinheimer *Neutrino mass limit from tritium β decay* Reports on Progress in Physics **71**, 086201 (2008).

[23] K. Ichiki, and Y. Y. Keum *Neutrino Masses from Cosmological Probes in Interacting Neutrino Dark-Energy Models* JHEP **06**, 058 (2008).

[24] K. Subramanian and J. D. Barrow, Phys. Rev. **D 58**, 083502 (1998b).

[25] D. G. Yamazaki, (2008b), in preparation.

[26] J. Dunkley and others, arXiv:0803.0586 (2008b).

[27] S. Cole et al. (The 2dFGRS), Mon. Not. Roy. Astron. Soc. **362**, 505 (2005), `astro-ph/0501174`.

[28] U. Seljak et al. (SDSS), Phys. Rev. **D 71**, 103515 (2005).

[29] M. Tegmark et al. (SDSS), Phys. Rev. **D74**, 123507 (2006), `astro-ph/0608632`.

[30] E. Rozo et al. (2007), `astro-ph/0703571`.

[31] A. J. Ross, R. J. Brunner, and A. D. Myers (2008), `0804.3325`.

[32] D. Spergel et al., Astrophys. J. Suppl. **170**, 377 (2007).

[33] G. Hinshaw et al., Astrophys. J. Suppl. **170**, 288 (2007).

[34] L. Page et al., Astrophys. J. Suppl. **170**, 335 (2007).