

# Primordial magnetic field constrained from CMB anisotropies, and its generation and evolution before, during and after the BBN

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The primordial magnetic field (PMF) can strongly affect the cosmic microwave background (CMB) power spectrum and the formation of large scale structure. In this presentation, we calculate the CMB temperature anisotropies generated by including a power-law magnetic field at the photon last scattering surface (PLSS). We then deduce an upper limit on the primordial magnetic field based upon our theoretical analysis of the power excess on small angular scales. We have taken into account several important effects such as the modified matter sound speed in the presence of a magnetic field. An upper limit to the field strength of  $|B_\lambda| \lesssim 4.7$  nG at the present scale of 1 Mpc is deduced. This is obtained by comparing the calculated theoretical result including the Sunyaev-Zeldovich (SZ) effect with recent observed data on the small scale CMB anisotropies from the Wilkinson Microwave Anisotropy Probe (WMAP), the Cosmic Background Imager (CBI) and the Arcminute Cosmology Bolometer Array Receiver (ACBAR). We discuss several possible mechanisms for the generation and evolution of the PMF before, during and after the BBN.

*International Symposium on Nuclear Astrophysics — Nuclei in the Cosmos — IX*  
*June 25-30 2006*  
*CERN, Geneva, Switzerland*

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†A footnote may follow.

## 1. Introduction

A possible existence of primordial magnetic field (PMF) is an important consideration in modern cosmology. Recently the origin of the PMF has been studied [1, 2, 3, 4, 5], and several semi-analytic and numerical studies [6, 7, 8, 9, 10, 11, 12, 13, 14] also indicate that the effect of the PMF is one of new physical process in early Universe which could affect the structure formation on small angular scales for higher  $l$ . However, there is still no satisfactory understanding of the effects on the PMF, especially on the origin and connection with the observable magnetic field  $0.1 - 1.0 \mu\text{G}$  in the clusters of galaxies [15, 16]. There is a discrepancy of the magnetic field between theory and observation in galactic cluster scale.

Temperature and polarization anisotropies in the CMB provide very precise information on the physical processes in operation during the early Universe. However, the best-fit cosmological model to observed CMB data sets has recently indicated a potential discrepancy between theory and observation at higher multipoles  $l \geq 1000$ . This discrepancy is difficult to account for by a simple tuning of cosmological parameters. One possible interpretation of such excess power at high multipoles is the thermal SZ effect [17]. However, it has not yet been established conclusively that this is the only possible interpretation of the small scale power [18]. Indeed, the best value of the matter fluctuation amplitude,  $\sigma_8$ , to fit the excess power at high multipoles is near the upper end of the range of the values deduced by the other independent methods [19, 20]. Toward the solution of this problem, it has recently been reported that a bump feature in the primordial spectrum way gives a better explanation for both the CMB and matter power spectra at small scales [21].

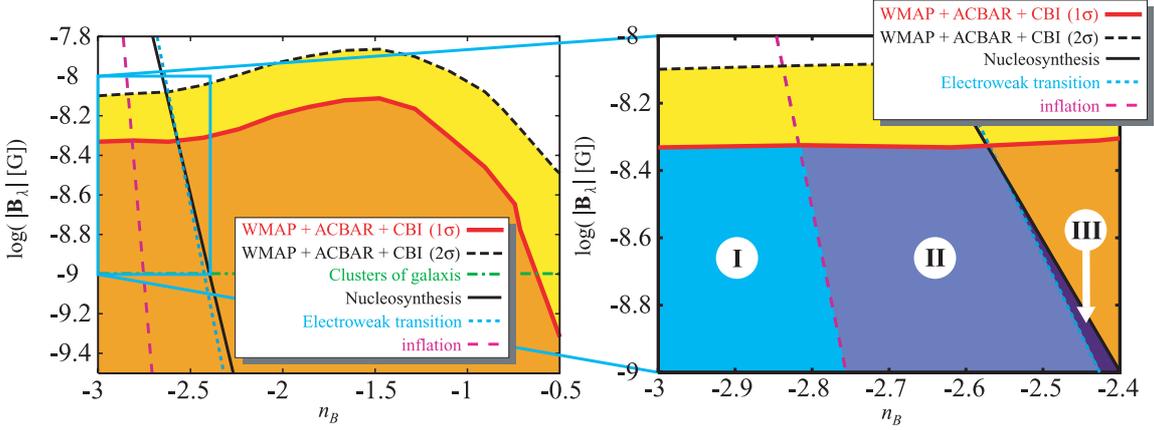
In order to solve these problems, we study the PMF by likelihood analysis with the Markov Chain Monte Carlo (MCMC) method using data of the Wilkinson Microwave Anisotropy Probe (WMAP) [22], the Cosmic Background Imager (CBI) [23] and the Arcminute Cosmology Bolometer Array Receiver (ACBAR) [24]. We then discuss several possible mechanisms for the generation and evolution of the PMF before, during and after the BBN.

## 2. Limits on the PMF

In Fig. 1 we show results [14] of our MCMC analysis using the WMAP, ACBAR and CBI data in the two parameter plane  $|B_\lambda|$  vs.  $n_B$ , where  $|B_\lambda|$  is the comoving mean-field amplitude of the PMF obtained by smoothing over a Gaussian sphere of comoving radius  $\lambda$  ( $\lambda = 1\text{Mpc}$  in this paper), and  $n_B$  is the spectral index of the power spectrum of fluctuations from a homogeneous and isotropic distribution of the PMF. The  $1\sigma$  (68%) and  $2\sigma$  (95.4%) C.L. excluded regions are bounded above by the thick curves as shown. We could not find a lower boundary of the allowed region at the  $1\sigma$  or  $2\sigma$  confidence level. Note, however, that we find a very shallow minimum with a reduced  $\chi^2 \simeq 1.08$ . From Fig. 1 we obtain an upper limit to the strength of the PMF at the  $1\sigma$  (95.4%) C.L. of

$$|B_\lambda| \lesssim 7.7 \text{ nG at } 1\text{Mpc} . \quad (2.1)$$

This upper limit is particularly robust as we have considered all effects on the CMB anisotropies, i.e. the SZ effect and the effects from both the scalar and vector modes on the magnetic field, in the present estimate of  $|B_\lambda|$  and  $n_B$ .



**Figure 1:** Results of the MCMC method constrained by the WMAP, ACBAR, and CBI data[14]. Excluded and allowed regions at the  $1\sigma$ (68%) C.L. and  $2\sigma$ (95.4%) C.L. are shown in the two parameter plane of  $|B_\lambda|$  vs.  $n_B$ . Solid and dotted curves are for  $\Delta\chi^2 = 2.3$  and 6.17, respectively. The green dash-dotted horizontal line displays the lower limit of the field strength  $B_\lambda = 1$  nG deduced for the galaxy cluster scale at the PLSS [15, 16]. The black-solid, skyblue-dotted, and pink-dashed lines are the upper limit of the produced PMF at the big-bang nucleosynthesis, the electroweak transition, and the inflation epochs, respectively[25]. If the PMF is produced at the epochs of big-bang nucleosynthesis, the electroweak transition, or inflation, respectively, the region of I+II+III, II+III, or III on the right hand side are allowed by these constraints on the PMF for the galaxy cluster scale at the PLSS and the MCMC method with WMAP, ACBAR, and CBI data.

### 3. PMF Generation and Evolution

In this section we discuss a multiple generation and evolution scenario of the cosmological primordial magnetic field that is motivated by the results of the present study.

To begin with we adopt the following three constraint conditions:

1. A PMF strength  $|B_\lambda| \lesssim 7.7 \text{ nG} (1\sigma)$  at 1Mpc as deduced above by applying the MCMC method to the WMAP, ACBAR, and CBI data.
2. The magnetic field strength in galaxy clusters is  $0.1 \mu\text{G} < |B_{CG}| < 1 \mu\text{G}$  [15, 16]. Hence, if the isotropic collapse is the only process which amplifies the magnetic field strength, the lower limit to the PMF is  $\sim 1 - 10$  nG for the PLSS.
3. The gravity wave constraint on the PMF from Caprini and Durrer (2002)[25] of 0.1 Mpc, however our  $\lambda$  is for 1Mpc. Thus, inclinations of lines in Figs. 1 are smaller than Caprini and Durrer (2004)[25]. The big-bang nucleosynthesis of the light elements depends on a balance between the particle production rates and the expansion rate of the universe. Since the energy density of the gravity waves  $\rho_{\text{GW}}$  contributes to the total energy density. However,  $\rho_{\text{GW}}$  is constrained so that the expansion rate of the universe does not spoil the agreement between the theoretical and observed light element abundance constraints for deuterium,  $^3\text{He}$ ,  $^4\text{He}$ , and  $^7\text{Li}$ [26].

Figures 1 summarize the various constraints on the PMF by these three conditions. The region bounded by the upper red-solid curve is constrained by condition (I) as indicated, the green-dash-dotted horizontal line corresponds to the lower limit to the PMF from condition (II), and the Black-solid, sky-blue-dotted, and pink-dashed lines, respectively, are the upper limit of the produced PMF from big-bang nucleosynthesis, the electroweak transition, and the inflation epoch. The right hand side of figure. 1 shows the allowed or excluded regions according to these multiple constraints depending upon when the PMF was generated:

(A). Nucleosynthesis: I+II+III region

$$1.0 \text{ nG} \lesssim |B_\lambda| \lesssim 4.7 \text{ nG}$$

$$-3 \lesssim n_B \lesssim -2.40$$

(B). Electroweak transition: II+III region

$$1.0 \text{ nG} \lesssim |B_\lambda| \lesssim 4.7 \text{ nG}$$

$$-3 \lesssim n_B \lesssim -2.43$$

(C). Inflation: III region

$$1.0 \text{ nG} \lesssim |B_\lambda| \lesssim 4.7 \text{ nG}$$

$$-3 \lesssim n_B \lesssim -2.76$$

Obviously, the upper limits on both  $|B_\lambda|$  and  $n_B$  become more stringent if the PMF is produced during an earlier epoch. Moreover, the limits we deduce are the strongest constraints on the PMF that have yet been determines. However, we caution that the evolution of the generation of the PMF during the LSS epoch is not well understood. Thus, if there are other effective physical processes for the generation and evolution of the PMF during the formation of LSS, our lower limit of the PMF parameters may decrease. In order to constrain the PMF parameters accurately, we should study the PMF not before but after the PLSS.

#### 4. Conclusion

In order to constrain the PMF, we evaluate likelihood function of the WMAP TT, CBI, and ACBAR data in a wide range of parameter of the magnetic field strength  $|B|_\lambda$  at 1 Mpc and the power-law spectral index  $n_B$ , along with six cosmological parameters, the Hubble parameter, the baryon and cold dark matter densities, the spectral index and the amplitude of primordial scalar fluctuation, and the optical depth, in flat Universe models, using the technique of the MCMC method.

For the first time we have studied scalar mode effects of the PMF on the CMB[14]. We have confirmed numerically without approximation that the excess power in the CMB at higher  $l$  can be explained by the existence of a PMF. For the first time a likelihood analysis utilizing the WMAP, ACBAR and CBI data with a MCMC method has been applied to constrain the upper limit on the strength of the PMF to be

$$|B_\lambda| < 7.7 \text{ nG} .$$

We have also considered three conditions on the generation and evolution of the cosmological PMF: 1) our result; 2) the lower limit of the PMF from the magnetic field of galaxy clusters; and 3) the constraint on the PMF from gravity waves. Combining these, we find the following concordance region for the the PMF parameters;

$$1 \text{ nG} < |B_\lambda| < 4.7 \text{ nG} \quad , \quad -3.0 < n_B < -2.4 \quad .$$

The PMF also affects the formation of large scale structure. For example, magnetic pressure delays the gravitational collapse. It is thus very important to constrain the PMF as precisely as possible. If we combine our study and future plans to observe the CMB anisotropies and polarizations for higher multipoles  $l$ , e.g. via the *Planck Surveyor*, we will be able to constrain the PMF more accurately, and explain the evolution and generation of the magnetic field on galaxy cluster scales along with the formation of the LSS.

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