New Limit on Pseudoscalar-Photon Mixing from WMAP Observations

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The pseudoscalar-photon mixing in presence of large scale magnetic field induces polarization in light from distant cosmological sources. We study the effect of these pseudoscalars or axion like particles (ALPs) on Cosmic Microwave Background Radiation (CMBR) and constrain the product of mixing strength $g_\phi$ times background magnetic field $B$. The background magnetic field has been assumed to be primordial and we assume large scale correlations with the correlation length of 1 Mpc. We use WMAP seven year foreground reduced polarization and temperature data to constrain pseudoscalar-photon mixing parameter. We look for different mass limits of the pseudoscalars and find $g_\phi B \leq 1.6 \times 10^{-15} GeV^{-1} nG$ with ALPs of mass $10^{-18} eV$ and $g_\phi B \leq 3.4 \times 10^{-15} GeV^{-1} nG$ for ultra light ALPs of mass $10^{-13} eV$.

I. INTRODUCTION

The pseudoscalar-photon mixing and its effects on distant cosmological sources have been studied in literature [1-21]. These hypothetical axion like particles (ALPs), arise naturally as pseudo-Goldstone bosons in theories with spontaneously broken global symmetries [22-30]. ALPs have an interaction vertex with two photons and hence in an external magnetic field ALPs can convert into a photon and vice versa [31-42]. Although this effect is very small, it becomes significant at cosmological scales and leads to many interesting signatures on electromagnetic radiation. This pseudoscalar-photon mixing phenomena causes changes in intensity as well as polarization in radiation from distant sources [1-21]. The contribution of this effect has been investigated for CMBR [11,43], radio [1,9,44,45] and optical [16,46-50] sources. Various experiments are looking for these pseudoscalars and providing limit on the coupling constant $g_\phi$ and their masses [1,2,42,51,70].

In the present paper we study the effect of pseudoscalar-photon mixing on CMBR multipoles. We show, using WMAP observations that this leads to a new constraint on the product of magnetic field $B$ and the pseudoscalar-photon coupling $g_\phi$. We consider the background as a large number of correlated magnetic field domains and do a complete 3D-simulation to calculate the Stokes parameters for CMBR. The origin of background magnetic field is considered as primordial [71,72] and we assume a smooth variation of the magnetic field over the scale of 1 Mpc. The magnetic field correlations are assumed to obey a power law with spectral index $n_B$. The details for the background magnetic field model are discussed in Sec. III. As we do simulation over a very large distances (redshift 1000), we choose domain size around 16 Mpc. The strength of magnetic field in each domain is assumed to be order of nG [7,8,11].

The initial pseudoscalar density is assumed to be zero or negligible as compared to photon density as assumed by most authors [16,40,43,46]. We made this assumption as the pseudoscalars are likely to decouple from cosmic plasma at very early times. After pseudoscalar decoupling, photon density would be enhanced by many processes such as QCD phase transition, $e^-e^+$ annihilation etc. It may not even be in equilibrium after inflation. Hence, it is reasonable to assume pseudoscalar density as negligible as compared to photon density.

We compare our result with the WMAP 7-year data and constrain the coupling parameter $g_\phi$ times $B$. The limit presented in the paper is bound to certain assumptions. We list all of them as follows:
1) The background magnetic field follows a simple cosmological evolution.
2) We have assumed a definite value for the spectral index $n_B = -2.37$ which correspond to the best fit of matter and CMBR power spectrum [70]. However we also determine its dependence on $n_B$. 
3) CMBR is assumed to be unpolarized initially and the initial density for pseudoscalars is zero.

The paper is organized as follows. In Sec II we briefly review the pseudoscalar-photon mixing in presence of plasma and uniform magnetic field in a flat expanding universe. In Sec III we model the background magnetic field, which is correlated in real space and discuss the numerical method for generating the 3D magnetic field. In Sec IV we present our simulation result and compare with the WMAP observations. Finally, in Sec V we conclude and compare our results with available literatures.

II. PSEUDOSCALAR-PHOTON MIXING

A. Basic Formulation

In this section we briefly describe the propagation of electromagnetic waves coupled to a pseudoscalar field. The basic action for the coupling of pseudo-scalar field $\phi$
to electromagnetic field in the flat expanding universe is given as [10, 77, 78],
\[
S = \int d^4x \sqrt{-g} \left[ -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} g_{\phi}\phi F_{\mu\nu} \bar{F}^{\mu\nu} + \frac{1}{2} (\omega_\mu^p a^{-3}) A_\mu A^\mu + \frac{1}{2} g_{\phi\mu\nu} \phi,\phi_{\mu\nu} - \frac{1}{2} m_\phi^2 \phi^2 \right].
\] (1)

Here \( F_{\mu\nu} \) is the electromagnetic field tensor and \( \bar{F}^{\mu\nu} \) the dual tensor, \( g_{\phi} \) is the coupling constant between \( \phi \) to photon field and \( 'a' \) the usual cosmological scale factor. In above action Eq. (1), we have a plasma frequency \( \omega_p \) term as \( \frac{1}{2} (\omega_\mu^p a^{-3}) A_\mu A^\mu \), which acts as an effective mass term for photon. We may note that this term scales as \( a^{-3}(volume^{-1}) \), as \( \omega_p^2 \) is proportional to the plasma number density.

We choose a fixed coordinate system such that the \( z \) axis lies along the direction of propagation. We define \( \mathcal{A} = \frac{(a^7 E)}{c} \) where \( E \) is the usual electric field vector and \( \omega \) is the radiation frequency. Only the component of \( \mathcal{A} \) parallel to \( B \) transverse mixes with the pseudoscalar field \( \phi \). We replace \( \phi \) by \( \frac{A}{a} \) and the mixing of \( \mathcal{A} \) to \( \chi \) can be written as,
\[
(\omega^2 + \partial_\perp^2) \left( \begin{array}{c} A \parallel \\ \chi \end{array} \right) - M \left( \begin{array}{c} A \parallel \\ \chi \end{array} \right) = 0,
\] (2)
where \( M \) is the ‘mixing matrix’ as,
\[
M = \left( \begin{array}{cc} \frac{\omega^2}{m_\phi^2} - \frac{2}{a^2} (a^2 B_L) \omega & -\frac{2}{a^2} (a^2 B_L) \omega \\ -\frac{2}{a^2} (a^2 B_L) \omega & \frac{\omega^2}{m_\phi^2} - \frac{2}{a^2} (a^2 B_L) \omega \end{array} \right).
\] (3)

\[
\rho(0) = \begin{pmatrix} < A_\parallel(0) A_\parallel^*(0) > & < A_\parallel(0) A_\perp(0) > & < A_\parallel(0) \chi^*(0) > \\ < A_\perp(0) A_\parallel^*(0) > & < A_\perp(0) A_\perp(0) > & < A_\perp(0) \chi^*(0) > \\ < \chi(0) A_\parallel^*(0) > & < \chi(0) A_\perp(0) > & < \chi(0) \chi^*(0) > \end{pmatrix}.
\] (4)

\[
P(z) = e^{i(\omega + \Delta A) z} \begin{pmatrix} 1 - \gamma \sin^2 \theta & 0 & \gamma \cos \theta \sin \theta \\ 0 & e^{-i[\omega + \Delta A](\omega^2 - \omega_\mu^p)^{1/2} z} & 0 \\ \gamma \cos \theta \sin \theta & 0 & 1 - \gamma \cos^2 \theta \end{pmatrix}.
\] (5)

B. Propagation and Polarization

In this section we briefly review the propagation of the mixed \( \mathcal{A} \) and \( \chi \) field in presence of an external magnetic field. A detailed description is given in Ref. [40, 43]. We start with some initial densities of \( \mathcal{A} \) and \( \chi \) mixed fields and calculate the same after a propagation of distance \( z \). An appropriate and general representation is given as,

Here \( m_\phi \) is the pseudoscalar mass, \((a^2 B_L)\) is the transverse component of magnetic field and the factor \( a^2 \) is scaling the magnetic field in expanding universe model.

We follow the procedure described in Ref. [40, 43] for solving Eq. (2).

\[
I(z) = < A_\parallel(z) A_\parallel^*(z) > < A_\perp(z) A_\perp^*(z) > < A_\parallel(z) \chi(z) > < A_\perp(z) \chi(z) > < \chi(z) \chi^*(z) > \] (6)

\[
Q(z) = < A_\parallel(z) A_\parallel^*(z) > < A_\perp(z) A_\perp^*(z) > < A_\parallel(z) \chi(z) > < A_\perp(z) \chi(z) > < \chi(z) \chi^*(z) > \] (7)

\[
U(z) = < A_\parallel(z) A_\parallel^*(z) > < A_\perp(z) A_\perp^*(z) > < A_\parallel(z) \chi(z) > < A_\perp(z) \chi(z) > < \chi(z) \chi^*(z) > \] (8)

\[
V(z) = i( < A_\parallel(z) A_\parallel^*(z) > + < A_\perp(z) A_\perp^*(z) > < A_\parallel(z) \chi(z) > < A_\perp(z) \chi(z) > ) \] (9)

We assume that the CMBR is unpolarized at \( z = 1000 \) and set initial density for pseudoscalars to be zero. Initially the plasma density is supposed to be very low \((n_e = 3.24 \times 10^{-10} a^{-3} cm^{-3})\) as the universe has gone through the recombination \((z \approx 1100)\) era and almost all the electrons and protons have been combined to form neutral hydrogen. At redshift \( z \approx 6 \),

\[
I(z) = < A_\parallel(z) A_\parallel^*(z) > < A_\perp(z) A_\perp^*(z) > < A_\parallel(z) \chi(z) > < A_\perp(z) \chi(z) > < \chi(z) \chi^*(z) >.
\] (10)

\[
Q(z) = < A_\parallel(z) A_\parallel^*(z) > < A_\perp(z) A_\perp^*(z) > < A_\parallel(z) \chi(z) > < A_\perp(z) \chi(z) > < \chi(z) \chi^*(z) >.
\] (11)

\[
U(z) = < A_\parallel(z) A_\parallel^*(z) > < A_\perp(z) A_\perp^*(z) > < A_\parallel(z) \chi(z) > < A_\perp(z) \chi(z) > < \chi(z) \chi^*(z) >.
\] (12)

\[
V(z) = i( < A_\parallel(z) A_\parallel^*(z) > + < A_\perp(z) A_\perp^*(z) > < A_\parallel(z) \chi(z) > < A_\perp(z) \chi(z) > )\] (13)
We compute multipole anisotropy in E and B modes and constrain \( g_{\phi}B \) by demanding consistency with CMBR observations.

III. BACKGROUND MAGNETIC FIELD

It is reasonable to assume the origin of background magnetic field as primordial \([71–75, 81]\). A two-point correlation function for a homogeneous and isotropic magnetic field is given as,

\[
\langle b_i(k)b_j^*(q) \rangle = \delta_{k,q} P_{ij}(k) M(k) \tag{12}
\]

where \( b_j(k) \) is the \( j \)th component of the magnetic field in wave vector space. The real space magnetic field \( B_j(r) \) can be written as a Fourier transform of \( b_j(k) \). Here \( P_{ij}(k) = \left( \delta_{ij} - \frac{k_i k_j}{k^2} \right) \) is the projection operator and function \( M(k) \) is given as,

\[
M(k) = Ak^{n_B}, \tag{15}
\]

where \( n_B \) is power spectral index and the constant \( A \) is a normalization. The numeric value for \( A \) is such as \( \sum_n < B_i(r)B_i(r) >= B_0^2 \), where \( B_0 \) is the strength of the magnetic field, often assumed to be \( 1nG \) \([72, 76]\) on a comoving scale of 1 Mpc. We do not impose any cutoff on correlations in real space and simply choose \( r_{\text{max}} \) larger than our system. In other words the lower limit on wave vectors \( k_{\text{min}} = r_{\text{max}}^{-1} \) tends to zero.

We split the space in \( 1024 \times 1024 \times 1024 \) equal volume domains and generate the 3D k-space magnetic field in each domain using the spectral distribution as in Eq.\([12]\). We use polar coordinate \((k, \theta, \phi)\) in wave vector space. In k-space the domains are uncorrelated and for any wave vector \( k \), \( b_k \) and \( b_\phi \) are uncorrelated. Hence, we can generate the \( b_\theta \) and \( b_\phi \) independently for each domain using a smooth Gaussian distribution \([16, 46]\).

\[
f(b_\theta(k), b_\phi(k)) = N \exp \left[ -\left( \frac{b_\theta^2(k) + b_\phi^2(k)}{2M(k)} \right) \right]. \tag{16}\]

Here \( N \) is a normalization factor. We use this to generate full 3D k-space magnetic field for each domain and do a Fourier transformation to get the three Cartesian components of the magnetic field in real space.

\[\text{[1]} \text{ The real and wave vector space field transformation are as follows,} \]

\[
B_j(r) = \frac{1}{(2\pi)^3} \sum b_j(k)e^{ik \cdot r}, \tag{13}
\]

\[
b_j(k) = \frac{1}{2} \sum B_j(r)e^{-ik \cdot r}. \tag{14}\]

IV. SIMULATION AND RESULT

We propagate CMBR from redshift 1000 and do the simulation for the pseudoscalar-photon mixing in the correlated magnetic field background. We perform our computation on a 3D grid of \( 1024 \times 1024 \times 1024 \). Since the total linear distance for redshift 1000 correspond to a very large comoving distance \( 8104 \) Mpc (matter dominated universe), we set one domain size to be \( 16 \) Mpc. However, we still keep the correlation length fixed to \( 1 \) Mpc. This domain size is very large as compared to the oscillation length \( (0.4 \text{ Kpc}) \) for the CMBR. The domain size dependence has been studied in Ref.\([16]\) and a very small statistical variations have been reported. Hence we do not expect any significant dependence on the domain size. We use HEALPix to generate angular positions of the sources with resolution parameter \( N \text{side} = 256 \). Next, we propagate all these sources through each domain and determine the Stoke’s parameters.

We compare our simulations to seven year foreground reduced WMAP CMBR observations. We use W-band since it contains the least foreground contamination. We demand that the pseudoscalar coupling introduces the temperature fluctuation less than \( 10^{-5} \). Furthermore we demand that the mixing mechanism generates E and B mode less than or equal to the observed values. In our analysis we always have the coupling constant \( g_\phi \) multiplied with the background magnetic field \( B \) and so we are able to put a limit only on the term \( g_\phi B \). We simulate the CMBR polarization with the following parameters:-

1. \( B_T = 1 \) nG
2. Plasma density \( n_e = 10^{-8} a^{-3} \text{ cm}^{-3} \) for \( z < 6 \) and \( n_a = 3.64 \times 10^{-15} a^{-3} \text{ cm}^{-3} \) for \( z \geq 6 \) \([79]\)
3. CMBR frequency for W-band = 90 GHz
4. Pseudoscalar mass \( = 10^{-10} \text{ eV} \) and \( 10^{-11} \text{ eV} \)

It turns out that most of the polarization and anisotropy is generated at high redshift. At low redshift the mixing is negligible as shown in Fig.\([12]\). We simulate the mixing effect for \( m_\phi = 10^{-10} \text{ eV} \) and \( m_\phi = 10^{-11} \text{ eV} \). We find that the pseudoscalar mass is a very significant parameter and the predicted CMBR polarization increases rapidly with decreasing pseudoscalar mass unless it touches the plasma mass limit. For the ultra light pseudoscalar \( (m_\phi = 10^{-15} \text{ eV}) \) the plasma mass term dominate and hence the mixing is controlled by plasma density. This can be seen in Fig.\([2]\) where we have a sudden dip at \( a \approx 0.14 \), which correspond to reionization era at which the plasma number density increases roughly by a factor of \( 30 \sim 40 \).

CMBR fluctuations are analysed by decomposition in terms of spherical harmonics, which allows us to compute the power in different multipoles. We generate a full

\[\text{[2]} \text{http://healpix.jpl.nasa.gov/}\]
We show our results in Fig. (3, 4) for the limit is fixed to be $g m \leq 10^{-13} GeV^{-1} nG$. Alternatively if we choose ultra light pseudoscalar of mass $m_{\phi} \leq 10^{-15} eV$, we obtain $g m B \leq 3.4 \times 10^{-15} GeV^{-1} nG$. We present the temperature multipole anisotropy in Fig. (5, 6), the upper curve (gray) is the WMAP observation and the lower (black) one is our simulation. We find that the simulated temperature anisotropy is below the WMAP data. Our constrain on pseudoscalar-photon mixing is obtained from the E, B modes of CMBR.

The above results correspond to spectral index $n_B = -2.37$, which is derived from the best fit of matter and CMBR power spectrum [76]. Also the results are bound to the assumption that the background magnetic field has gone through a simple cosmological evolution. We have simulated the limits for $n_B = -2.20, -2.60$ and $-2.90$ also and observe a slight deviation in values. We present these results in Table I.

| $m_{\phi}(eV)$ | $g_{\phi} B(GeV^{-1}nG)$ |
|---------------|--------------------------|
| $n_B = -2.20$ | $n_B = -2.37$ | $n_B = -2.60$ | $n_B = -2.90$ |
| $10^{-10}$ | $1.55 \times 10^{-13}$ | $1.60 \times 10^{-13}$ | $1.70 \times 10^{-13}$ | $1.80 \times 10^{-13}$ |
| $10^{-15}$ | $3.20 \times 10^{-15}$ | $3.40 \times 10^{-15}$ | $3.80 \times 10^{-15}$ | $4.80 \times 10^{-15}$ |

TABLE I. The effect of spectral index $n_B$ on $g_{\phi} B$ limits.

FIG. 1. The mixing angle ($\theta$) in flat expanding universe, with parameters $m_{\phi} = 10^{-10} eV$, $g_{\phi} B = 1.6 \times 10^{-13} GeV^{-1} nG$.

FIG. 2. The mixing angle ($\theta$) in flat expanding universe, with parameters $m_{\phi} = 10^{-15} eV$, $g_{\phi} B = 3.4 \times 10^{-15} GeV^{-1} nG$. Here plasma mass term ($\omega_p^2/a^2$) is dominating over pseudoscalar mass term ($m_{\phi}^2/a^2$).

FIG. 3. The simulated (black) and WMAP observed (gray) E mode multipole, using $m_{\phi} = 10^{-10} eV$, $g_{\phi} B = 1.6 \times 10^{-13} GeV^{-1} nG$.

FIG. 4. The simulated (black) and WMAP observed (gray) B mode multipole, using $m_{\phi} = 10^{-10} eV$, $g_{\phi} B = 1.6 \times 10^{-13} GeV^{-1} nG$.
V. DISCUSSION

We have done full 3D simulation of pseudoscalar-photon mixing for CMBR at a very high resolution over the full sky. A comparison with WMAP observation results in a new and more stringent limit on the factor $g_{\phi}B$. It depends on the pseudoscalar mass and we simulate the limit on the factor $g_{\phi}B$ for two different masses of pseudoscalars.

Recently, a bound on factor $g_{\phi}B$ as $g_{\phi}B \leq 10^{-11}GeV^{-1}nG$ has been derived from ultraviolet photon polarization emerging from active galactic nuclei. Here the derived limit corresponds to ultra light ALPs($m_{\phi} \leq 10^{-15}eV$). In Ref. 62, the limits on $g_{\phi}B$ has been studied through CMBR spectral distortion, giving $g_{\phi}B \leq 10^{-13} \sim 10^{-11}GeV^{-1}nG$ for ALPs masses between $10^{-15}eV$ and $10^{-4}eV$. The pseudoscalar-photon mixing may also contribute to the dimming of Type Ia supernovae.6, 7, 83. The phenomenon fixes $g_{\phi}B$ to $10^{-11}GeV^{-1}nG$ for an axion of mass $10^{-16}eV$.

We may constrain $g_{\phi}$ form our bound on $g_{\phi}B$. However the constrain on $g_{\phi}$ is subject to uncertainties in the background magnetic field. Assuming the background magnetic field $B_0$ as $1nG$, our results bound $g_{\phi} \leq 1.6 \times 10^{-13}GeV^{-1}$ and $g_{\phi} \leq 3.4 \times 10^{-15}GeV^{-1}$ for the ALPs of $10^{-10}eV$ and $10^{-15}eV$ respectively.

Our limits can be compared with the direct experimental limits from SN1987A, which is $g_{\phi} \leq 10^{-11}GeV^{-1}$ and $g_{\phi} \leq 3 \times 10^{-12}GeV^{-1}$ for very light ALPs ($\leq 10^{-9}eV$). We also recall the results from CAST, $g_{\phi} \leq 8.8 \times 10^{-11}GeV$ for the ALPs of 0.02$eV$, which of course is not for the ultralight ALPs and can not be directly compared with our results.

We conclude that the CMBR multipole anisotropy imposes a stringent constraint on the pseudoscalar-photon coupling. We have obtained the lowest value of $g_{\phi}B$ as
compared to available literatures.

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