Effect on Cosmic Microwave Background Polarization of Coupling of Quintessence to Pseudoscalar Formed from the Electromagnetic Field and its Dual

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We present the full set of power spectra of cosmic microwave background (CMB) temperature and polarization anisotropies due to the coupling between quintessence and pseudoscalar of electromagnetism. This coupling induces a rotation of the polarization plane of the CMB, thus resulting in a nonvanishing B mode and parity-violating TB and EB modes. Using the BOOMERANG data from the flight of 2003, we derive the most stringent constraint on the coupling strength. We find that in some cases the rotation-induced B mode can confuse the hunting for the gravitational lensing-induced B mode.

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The existence of a dark component with an effective negative pressure, supported by several observations, especially the Hubble diagram for the type-Ia supernovae (see, for example, [1,2]), is still one of the puzzles in cosmology. The cosmological constant is the simplest possibility for such a dark component. However, the observed value of the cosmological constant is completely different from theoretical expectation [3]. An alternative candidate, the so-called quintessence described by a dynamical scalar field ϕ, is naturally considered. The dynamics of ϕ in general quintessence models is governed by a scalar potential $V(\phi)$ which makes the dark energy dominant in the recent epoch. There are many different kinds of proposed potentials, for example, the pseudo Nambu-Goldstone boson, inverse power law, exponential, hyperbolic cosine, and tracking oscillating [4]. To differentiate between the models and finally reconstruct $V(\phi)$ would likely require next-generation observations.

The quintessential potential $V(\phi)$ and the field ϕ itself are difficult to be measured directly. What we can do is to investigate the dark energy density Ω_ϕ and the time evolution for the equation of state (EOS) $w_\phi = P_\phi/\rho_\phi$, both of which are governed by the dynamics of ϕ. Several observations, such as the 157 supernovae in a redshift interval, $0.015 < z < 1.6$, in the "Gold Sample" obtained from a combination of ground-based data and the Hubble Space Telescope [2] and the 115 supernovae with $0.015 < z < 1$ from the Supernova Legacy Survey, provide information about the dark energy [5]. It is rather difficult to determine whether the quintessence is more preferred than the cosmological constant by observations of the CMB temperature anisotropy spectrum only. Joint analysis of CMB data with supernovae or/and large scale structure survey such as SDSS or 2dfGRS can offer better constraints on quintessence models [6]. Recently, the study of the cross correlation of maps between CMB and various tracers of matter through the integrated Sachs-Wolfe effect was also carried out by several groups [7]. However, the intrinsic properties of dark energy are not well constrained so far from the investigations above, thus allowing a very wild range of the EOS, which is strongly model dependent.

An alternative way to study the quintessence is to consider the interaction of ϕ to ordinary matter. Coupling of ϕ to dark matter is considered as a possible solution for the late time coincidence problem [8]. It leaves distinct imprints on the CMB temperature anisotropy and the matter power spectrum due to an excess of cold dark matter at an early epoch when compared to the standard cosmology model [9] (We define the "standard cosmology" as the model without coupling between quintessence and ordinary matter). Of particular interest in this Letter, we study the coupling of ϕ to the pseudoscalar of electromagnetism. Pseudoscalar couplings usually arise from the spontaneous breaking of a compact symmetry group, say, U(1) (see Frieman *et al.* in Ref. [4]). Carroll has argued that the coupling $\beta_{F\tilde{F}}\phi/\bar{M}F_{\mu\nu}\tilde{F}^{\mu\nu}$ leads to the rotation of the polarization vector of propagating photons as ϕ is varying with time. Here $\beta_{F\tilde{F}}$ is the coupling strength, $\bar{M}$ is the reduced Planck mass, and $\tilde{F}^{\mu\nu}$ is the dual of the electromagnetic field strength. This effect is called as the "cosmological birefringence" [10].

Measurements of the polarization of distant astronomical objects would provide information about the cosmological birefringence. Carroll used the rotation of polarization direction for distant radio sources to constrain the coupling strength [10]. Another proposed method is the CMB polarization from the last scattering surface [11,12]. In this Letter, we study the effects of the cosmological birefringence on the power spectra of CMB temperature and polarization. Only assuming the shape of the potential $V(\phi)$, we present the *first* CMB power spectra in the presence of the cosmological birefringence by using the full Boltzmann code.

Thomson scatterings of anisotropic radiation by free electrons give rise to the linear polarization, which is usually described by the Stokes parameters Q and U [13]. In standard cosmology, the time evolution of the polarization perturbation is governed by the Boltzmann equation [14]. When there is a physical mechanism which rotates the polarization plane, the evolution equations for the Fourier modes of the Stokes parameters are modified to

$$\dot{\Delta}_{Q\pm iU}(\mathbf{k},\eta) + ik\mu\Delta_{Q\pm iU}(\mathbf{k},\eta) = n_e\sigma_T a(\eta)\left[-\Delta_{Q\pm iU}(\mathbf{k},\eta)\sum_m \sqrt{\frac{6\pi}{5}}\,{}_{\pm 2}Y_2^m(\hat{\mathbf{n}})S_P^{(m)}(\mathbf{k},\eta)\right] \mp i2\omega\Delta_{Q\mp iU}(\mathbf{k},\eta), \quad (1)$$

where the derivatives are taken with respect to the conformal time η, $\mu = \hat{\mathbf{n}}\cdot\hat{\mathbf{k}}$ is the cosine of the angle between the CMB photon direction and the Fourier wave vector, n_e is the number density of free electrons, σ_T is the Thomson cross section, and a is the scale factor. ${}_sY_l^m$ are spherical harmonics with spin-weight s, where $m = 0, \pm 1, \pm 2$ correspond, respectively, to scalar, vector, and tensor perturbations with the axis of ${}_sY_l^m$ aligned with the wave vector $\mathbf{k}$. $S_P^{(m)}$ is the source term for generating polarization, being composed of the quadrupole components of the temperature and polarization perturbations $S_P^{(m)}(\mathbf{k},\eta) \equiv \Delta_{T,2}^{(m)}(\mathbf{k},\eta) + 12\sqrt{6}\Delta_{+,2}^{(m)}(\mathbf{k},\eta) + 12\sqrt{6}\Delta_{-,2}^{(m)}(\mathbf{k},\eta)$. Here we have followed the notation in Ref. [15]. We have expanded the temperature (Δ_T) and polarization ($\Delta_{Q\pm iU}$) perturbations in terms of Y_l^m and ${}_{\pm 2}Y_l^m$ [16], respectively, and denoted the expansion coefficients by $\Delta_{T,l}^{(m)}$ and $\Delta_{\pm,l}^{(m)}$. The last term in Eq. (1) appears due to the rotation of the polarization plane. The dispersion relation for electromagnetic radiation coupling to the time-varying quintessence field ϕ is given by $E^2 = k^2 \pm k\beta_{F\tilde{F}}\dot{\phi}/(a\bar{M})$, where $\pm$ refer to the right- and left-handed circular polarization, respectively. Therefore, the net angular velocity of the polarization plane is [10]

$$\omega = 2\beta_{F\tilde{F}}\frac{\dot{\phi}}{a\bar{M}}. \quad (2)$$

We are used to decomposing the polarization on the sky into a divergence-free component, the so-called E mode, and a curl component, the so-called B mode because Q and U depend on the choice of a coordinate system. Whether B mode is generated depends on a nonvanishing U of the local mode whose wave vector $\mathbf{k}$ parallels to the $\hat{z}$ axis of the coordinates, whereas Q is defined as the difference in intensities polarized in the $\hat{\theta}$ and $\hat{\psi}$ directions [17]. In particular, for $m = 0$, only Q is generated for the local mode. The axisymmetry of the radiation field about the mode axis guarantees that no B mode can be generated by scalar mode perturbations.

In the presence of cosmological birefringence, we can find two important features in Eq. (1). First, the rotation of the polarization plane generates U contributions to the local mode polarization. This converts the power from the E mode into the B mode. The conversion depends on the degree of rotation from the epoch when the polarization is generated to the present time. Secondly, TB and EB cross correlations are expected to vanish due to the parity [T and E have parity $(-1)^l$ while B has $(-1)^{l+1}$]. The cosmological birefringence violates the parity and thus generates the TB and EB power spectra whose magnitudes depend on the integrated rotation of polarization as well. Substituting the angular velocity of the polarization plane in Eq. (2) into Eq. (1), we compute the T, E, B, TE, TB, and EB power spectra.

These six power spectra form a complete two-point statistics of CMB temperature and polarization anisotropies. To simplify the calculation, we only include the scalar perturbations. That is by setting $m = 0$ in Eq. (1). Without showing the details, we just write down the power spectra which are obtained from the solutions for the line-of-sight integration as

$$\begin{aligned} C_l^{(E,B)} &= (4\pi)^2\frac{9}{16}\frac{(l+2)!}{(l-2)!}\int k^2dk[\Delta_{(E,B)}(k,\eta_0)]^2,\\ C_l^{EB} &= (4\pi)^2\frac{9}{16}\frac{(l+2)!}{(l-2)!}\int k^2dk\Delta_E(k,\eta_0)\Delta_B(k,\eta_0),\\ C_l^{TE} &= (4\pi)^2\sqrt{\frac{9}{16}\frac{(l+2)!}{(l-2)!}}\int k^2dk\Delta_T(k,\eta_0)\Delta_E(k,\eta_0),\\ C_l^{TB} &= (4\pi)^2\sqrt{\frac{9}{16}\frac{(l+2)!}{(l-2)!}}\int k^2dk\Delta_T(k,\eta_0)\Delta_B(k,\eta_0), \end{aligned} \quad (3)$$

where

$$\begin{aligned} \Delta_T(k,\eta_0) &= \int_0^{\eta_0} d\eta g(\eta)S_T(k,\eta)j_l(kr),\\ \Delta_E(k,\eta_0) + i\Delta_B(k,\eta_0) &= \int_0^{\eta_0} d\eta g(\eta)S_P(k,\eta)\\ &\quad\times\frac{j_l(kr)}{(kr)^2}e^{i2\alpha(\eta)}, \end{aligned} \quad (4)$$

where the visibility function $g(\eta)$ describes the probability that a photon scattered at epoch η reaches the observer at the present time, η_0. Similar to $S_P \equiv S_P^{(0)}$, S_T is the source term generating the temperature anisotropy. j_l is the spherical Bessel function and $r = \eta_0 - \eta$. The rotation angle $\alpha(\eta) = \int_\eta^{\eta 0} d\eta'\omega(\eta')$. We do not present the formula for the temperature anisotropy because it is unchanged under the rotation of the polarization plane.

We have modified the public CMBFAST code [18] for our purpose. Here, we consider the potential $V(\phi) = V_0\exp(\lambda\phi^2/2\bar{M}^2)$ for our quintessence model (the hyperbolic cosine potential is also considered, see below), where λ is a parameter determining how shallow the potential is. Hereafter we fix $\lambda = 5$ and we will obtain similar results by choosing other values of λ. We plug the table of the EOS for this quintessence model into the modified CMBFAST code and input the cosmological parameters from the best fit values of the WMAP three-year results [19]. The power spectra are then normalized to the first peak of the temperature anisotropy measured by the three-year WMAP observation [20]. The left panel of Fig. 1 shows the E and B mode power spectra with the coupling

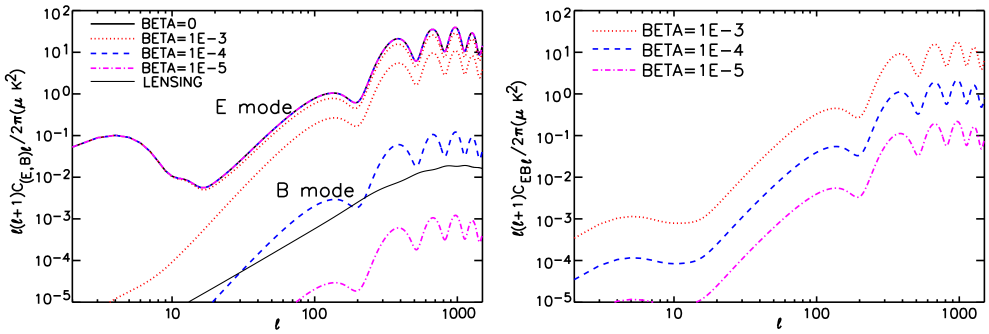

FIG. 1 (color online). E, B (left panel; the lower three thick curves are B modes) and EB (right panel) mode power spectra from the cosmological birefringence with different coupling strength.

strength $\beta_{F\tilde{F}}$ ranging from 10^{-5} to 10^{-3}. The EB mode power spectrum is shown in the right panel. On small scales, increasing coupling strength results in both a suppression of the E mode in the standard model and nonvanishing B and EB modes. Furthermore, the shapes of the B and EB mode power spectra basically follow the standard E mode except the reionization bump on large scales. To explain this, we make a rough estimation in Eq. (3): $C_{Bl} \sim C_{El}\sin^2 2\alpha_l$ and $C_{EBl} \sim 0.5 C_{El} \sin 4\alpha_l$ with α_l being the total rotated angle for certain angular scales $\theta \sim \pi/l$ from the last scattering epoch to today. This α_l, in general, is not constant for all scales. The E mode power on small scales mainly comes from the recombination epoch at $z \sim 1100$. On the other hand, the boosting power on large scales comes from reionization epoch when the CMB photons are rescattered by free electrons at $z \sim 10$ [21]. From Eq. (2) and the evolution of ϕ, we find that the integrated rotation angle from the reionization epoch is much smaller than that from the recombination epoch. Therefore, there is much less power converted from E mode to B mode on large scales than small scales.

If the coupling strength is large enough, the B mode induced by the cosmological birefringence will mix up with the gravitational lensing-induced B mode. Gravitational lensing by large scale structures modifies slightly the primary E mode power spectrum. Most noticeably it generates, through mode coupling, B mode polarization out of pure E mode signal [22]. The lensing-induced B power spectrum, which peaks around $l \sim 1000$, has the roughly similar shape to that from the birefringence. We also show the power spectrum of the lensing-induced B mode in Fig. 1 by a thin solid curve for comparison. The birefringence-induced B mode is indeed compatible with the lensing-induced B mode for $\beta_{F\tilde{F}} \sim 10^{-4}$.

Figure 2 shows the TE and TB power spectra for different coupling strength. Having the complete set of power spectra, we can constrain the coupling strength from observed data. In order to focus on the cosmological birefringence, we do not make the global fit to all the cosmological parameters. It is debatable that $\beta_{F\tilde{F}}$ is degenerate with other cosmological parameters due to the decrement of the TE and E power spectra. As we will see later, the upper limit on the coupling strength prevents it from making a significant change on the TE and E modes.

We use the North American data from the 2003 Antarctic flight of BOOMERANG [23] to calculate the $\chi^2 = \sum_{i,j}(D_i^b - T_i^b)C_{ij}^{-1}(D_j^b - T_j^b)$ fitting for $\beta_{F\tilde{F}}$ while fixing other cosmological parameters, where D_i^b is the ith band power, C_{ij} is the covariance matrix, and $T_i^b = \sum_l C_l W_{il}/l$ is obtained by the theoretical prediction multiplied by the band-power window function W_{il}/l. Those band-power data, including covariance matrices and window functions, are available; see [24]. In practice, we only fit $\beta_{F\tilde{F}}$ to the EB and TB power spectra which come from the parity violation. We do not use the B mode power spectrum because it is contaminated by lensing-induced

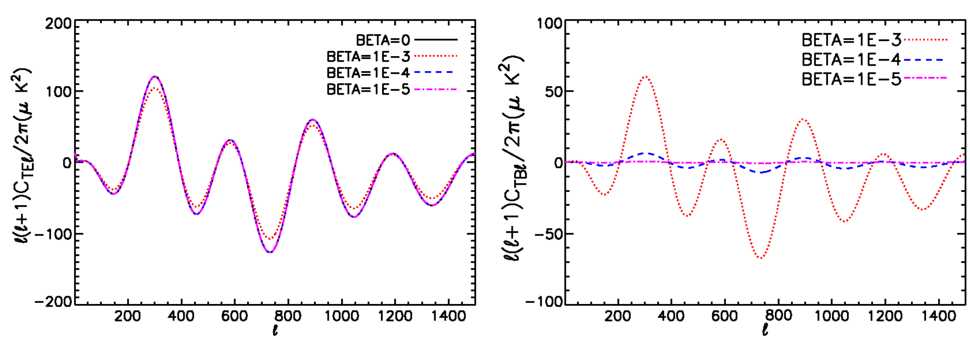

FIG. 2 (color online). TE (left panel) and TB (right panel) mode power spectra from the cosmological birefringence with different coupling strength.

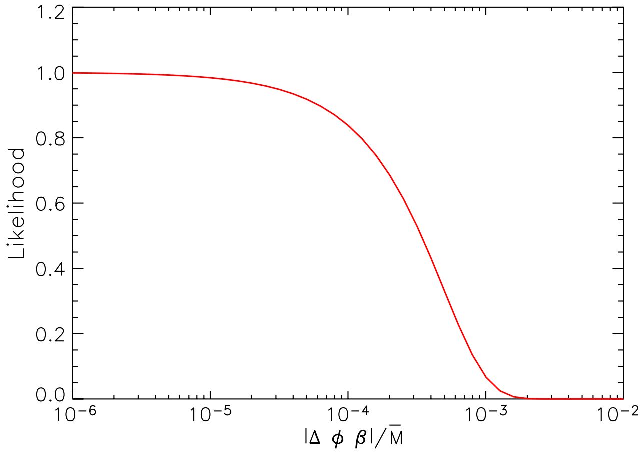

FIG. 3 (color online). Likelihood function of the coupling strength.

signal. If the lensing-induced B mode can be successfully cleaned by appropriate techniques such as those proposed by Seljak and Hirata [25], we expect that including the B mode will give a stronger constraint. We convert χ^2 to the likelihood by $\mathcal{L} = e^{-\chi^2/2}$ and normalize the maximum likelihood value to unity. The result is shown in Fig. 3. The upper limit on the coupling strength is found to be $|\beta_{F\tilde{F}}\Delta\phi|/\bar{M} < 8.32 \times 10^{-4}$ at 95% confidence level, where $\Delta\phi$ is the total change of ϕ until today. This small value of the coupling strength gives an insignificant change on TE and E modes and thus will not affect the determination of the cosmological parameters. We also use the hyperbolic cosine potential $V(\phi) = V_0 \cosh(\lambda\phi/\bar{M})$ for the testing. Even though the quintessence evolution in this potential is different from that in the exponential case, the upper limit value of $|\beta_{F\tilde{F}}\Delta\phi|/\bar{M}$ does not change much. This value is much smaller than the result in Ref. [10], 3×10^{-2}, where $\Delta\phi$ is only from $z = 0.425$ to today. It is remarkable that the rotation-induced B mode with the upper limit value of the coupling strength exceeds the lensing-induced B mode. Therefore, careful measurements of TB and EB are necessary for separating the two effects.

Several authors have studied the effect of parity violation on the CMB power spectra by assuming a constant rotation angle α [11,12]. They obtained a new set of rotated power spectra from combining the power spectra in the standard model with the sine or cosine function of α. Furthermore, taking the rotation angle as a free parameter, Feng *et al.* [12] constrained the rotation angle using the data made by the first year WMAP and BOOMERANG observations. However, the time-varying scalar field ϕ in their work is constrained such that the integrated rotation angle should be very small from the recombination to the reionization epoch. Therefore, it is less supported by general quintessence models.

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[1] N. A. Bahcall, J. P. Ostriker, S. Perlmutter, and P. J. Steinhardt, Science **284**, 1481 (1999).
[2] A. G. Riess *et al.*, Astrophys. J. **607**, 665 (2004).
[3] See, for example, S. Weinberg, Rev. Mod. Phys. **61**, 1 (1989).
[4] B. Ratra and P. J. E. Peebles, Phys. Rev. D **37**, 3406 (1988); J. A. Frieman, C. T. Hill, A. Stebbins, and I. Waga, Phys. Rev. Lett. **75**, 2077 (1995); V. Sahni and L. Wang, Phys. Rev. D **62**, 103517 (2000); S. Lee, K. A. Olive, and M. Pospelov, Phys. Rev. D **70**, 083503 (2004); G. Olivares, F. Atrio-Barandela, and D. Pavon, Phys. Rev. D **71**, 063523 (2005).
[5] P. Astier *et al.*, Astron. Astrophys. **447**, 31 (2006).
[6] J.-Q. Xia, G.-B. Zhao, B. Feng, H. Li, and X. Zhang, Phys. Rev. D **73**, 063521 (2006); K. Ichikawa and T. Takahashi, Phys. Rev. D **73**, 083526 (2006).
[7] See, for example, P. Fosalba and E. Gaztañaga, Mon. Not. R. Astron. Soc. **350**, L37 (2004); P. S. Corasaniti, T. Giannantonio, and A. Melchiorri, Phys. Rev. D **71**, 123521 (2005).
[8] J. P. Uzan, Phys. Rev. D **59**, 123510 (1999); L. Amendola, Phys. Rev. D **62**, 043511 (2000).
[9] S. Lee, G.-C. Liu, and K.-W. Ng, Phys. Rev. D **73**, 083516 (2006).
[10] S. M. Carroll, Phys. Rev. Lett. **81**, 3067 (1998).
[11] A. Lue, L. Wang, and M. Kamionkowski, Phys. Rev. Lett. **83**, 1506 (1999); B. Feng, H. Li, M. Li, and X. Zhang, Phys. Lett. B **620**, 27 (2005).
[12] B. Feng, M. Li, J.-Q. Xia, X. Chen, and X. Zhang, Phys. Rev. Lett. **96**, 221302 (2006).
[13] S. Chandrasekar, *Radiative Transfer* (Dover, New York, 1960).
[14] P. J. E. Peebles and J. T. Yu, Astrophys. J. **162**, 815 (1970); J. R. Bond and G. Efstathiou, Astrophys. J. **285**, L45 (1984); C.-P. Ma and E. Bertschinger, Astrophys. J. **455**, 7 (1995).
[15] G.-C. Liu, N. Sugiyama, A. J. Benson, C. G. Lacey, and A. Nusser, Astrophys. J. **561**, 504 (2001).
[16] E. Newman and R. Penrose, J. Math. Phys. (N.Y.) **7**, 863 (1966).
[17] W. Hu, New Astron. Rev. **2**, 323 (1997).
[18] U. Seljak and M. Zaldarriaga, Astrophys. J. **469**, 437 (1996).
[19] D. N. Spergel *et al.*, astro-ph/0603449.
[20] G. Hinshaw *et al.*, astro-ph/0603451.
[21] L. Page *et al.*, astro-ph/0603450.
[22] M. Zaldarriaga and U. Seljak, Phys. Rev. D **58**, 023003 (1998); K. Benabed, F. Bernardeau, and L. van Waerbeke, Phys. Rev. D **63**, 043501 (2001).
[23] F. Piacentini *et al.*, Astrophys. J. **647**, 833 (2006); T. E. Montroy *et al.*, Astrophys. J. **647**, 813 (2006).
[24] Band-power data, including covariance matrices and window functions, are available at http://cmb.phys.cwru.edu/boomerang.
[25] U. Seljak and C. M. Hirata, Phys. Rev. D **69**, 043005 (2004).