TESTING CPT SYMMETRY WITH CMB MEASUREMENTS: UPDATE AFTER WMAP5
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Received 2008 March 16; accepted 2008 April 16; published 2008 April 25

ABSTRACT

In this Letter we update our previous results on the test of CPT symmetry with cosmic microwave background (CMB) measurements. A CPT-violating interaction in the photon sector $\mathcal{L}_{cs} \sim p_\mu A_\mu F^{\mu\nu}$ gives rise to a rotation of the polarization vectors of the propagating CMB photons. Recently the WMAP group used the newly released polarization data of WMAP5 to measure this rotation angle $\Delta \alpha$ and obtained $\Delta \alpha = -1.7^\circ \pm 2.1^\circ$ (1 $\sigma$). However, in their analysis the BOOMERANG 2003 data are not included. Here we revisit this issue by combining the full data of WMAP5 and BOOMERANG 2003 angular power spectra for the measurement of this rotation angle $\Delta \alpha$ and find that $\Delta \alpha = -2.6^\circ \pm 1.9^\circ$ at a 68% confidence level.

Subject headings: cosmic microwave background — cosmological parameters — cosmology: theory

Online material: color figure

1. INTRODUCTION

The fundamental CPT symmetry which has been proven to be exact in the framework of the standard model of particle physics and Einstein gravity could be dynamically violated in the expanding universe. This type of cosmological CPT violation mechanism investigated in the literature (Li et al. 2002, 2004; Li & Zhang 2003) has an interesting feature in that the CPT-violating effect at the present time is small enough to satisfy the current laboratory experimental limits, but large enough in the early universe to account for the generation of the matter-antimatter asymmetry. More importantly, it could be accumulated enough to be observable in cosmological experiments (Feng et al. 2005; Li et al. 2007). With the accumulation of high-quality data on CMB measurements, cosmological observations become a powerful tool to test this fundamental symmetry.

For a phenomenological study in the photon sector the CPT violation can be parameterized in terms of an effective Lagrangian (Carroll et al. 1990; Carroll & Field 1991):

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \mathcal{L}_{cs},$$

where $\mathcal{L}_{cs} \sim p_\mu A_\mu F^{\mu\nu}$ is a Chern-Simons term, $p_\mu$ is an external vector, and $F^{\mu\nu} = (1/2)\epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$ is the dual of the electromagnetic tensor. This Lagrangian is not generally gauge invariant, but the action is gauge independent if $\partial_\mu p_\nu = \partial_\mu p_\nu$. This may be possible if $p_\mu$ is constant in spacetime or the gradient of a scalar field in the quintessential baryo-/leptogenesis (Li et al. 2002; Li & Zhang 2003; de Felice et al. 2003) or the gradient of a function of the Ricci scalar in gravitational baryo-/leptogenesis (Li et al. 2004; Davoudiasl et al. 2004). The Chern-Simons term violates Lorentz and CPT symmetries, and also the P and CP symmetries when the background field $p_\mu$ does not vanish.

For the CMB measurements the Chern-Simons term induces a rotation of the polarization (Li et al. 2007; Xia et al. 2008a) with the rotation angle $\Delta \alpha$ given by

$$\Delta \alpha = \int_{l(1100)}^{\infty} \frac{p_0}{a} \frac{dt}{a} = p_0 l(1100)^+, \quad (2)$$

where $p_0$ denotes the time component of $p_\mu$, $l(1100)$ is the comoving distance of the CMB photon emitted at the last scattering surface, and $t_0$ indicates the present time. In equation (2) we have assumed $p_0$ is a constant. For a more general case please see our previous paper (Xia et al. 2008a).

For the standard theory of CMB, the TB and EB cross-correlation power spectra vanish. In the presence of the CPT-violating term (eq. [1]) the polarization vector of each photon is rotated by an angle $\Delta \alpha$, and one expects to observe nonzero TB and EB power spectra, even if they are zero at the last scattering surface. Denoting the rotated quantities with a prime, one gets (Feng et al. 2005; Lue et al. 1999)

$$C_{ij}^{TB} = C_{ij}^{TE} \sin (2\Delta \alpha),$$
$$C_{ij}^{EB} = \frac{1}{2} (C_{ij}^{EE} - C_{ij}^{BB}) \sin (4\Delta \alpha),$$
$$C_{ij}^{TE} = C_{ij}^{TE} \cos (2\Delta \alpha),$$
$$C_{ij}^{EE} = C_{ij}^{EE} \cos^2 (2\Delta \alpha) + C_{ij}^{BB} \sin^2 (2\Delta \alpha),$$
$$C_{ij}^{BB} = C_{ij}^{BB} \cos^2 (2\Delta \alpha) + C_{ij}^{EE} \sin^2 (2\Delta \alpha), \quad (3)$$

while the CMB temperature power spectrum remains unchanged.

In Xia et al. (2008a), using the full data of BOOMERANG 2003 (B03) and the WMAP3 angular power spectra, we have performed an analysis on the determination of the rotation angle $\Delta \alpha$ and find that $\Delta \alpha = -6.2^\circ \pm 3.8^\circ$ (1 $\sigma$). This result improves the measurement given by our previous paper (Feng et al. 2006) and the paper by Cabella et al. (2007). Recently the Wilkinson Microwave Anisotropy Probe (WMAP) experiment has published the 5 year results for the CMB angular power spectra which include the TB and EB information (Hinshaw et al. 2008). For the implications of this measurement on the possible new physics, please also see Liu et al. (2006), Kostelecky & Mewes (2007), Geng et al. (2007), Ni (2007), and Finelli & Galaverni (2008).
et al. 2008; Nolta et al. 2008). They use the polarization power spectra of WMAP5, TE/TB ($2 \leq l \leq 450$) and EE/BB/EB ($2 \leq l \leq 23$), to determine this rotation angle (Komastu et al. 2008) and find that $\Delta \alpha = -1.7^\circ \pm 2.1^\circ$ (1 $\sigma$).

Besides the WMAP measurement, the B03 data also provide the TB and EB polarization power spectra (Jones et al. 2006; Piacentini et al. 2006; Montroy et al. 2006), which have been shown to give an interesting constraint on this rotation angle $\Delta \alpha$ (Feng et al. 2006; Xia et al. 2008a). Thus it is interesting and necessary to combine the full data of these two experiments for the analysis, which is the aim of this Letter.

2. METHOD AND RESULTS

In our study we make a global analysis on the CMB data with the publicly available Markov Chain Monte Carlo package CosmoMC$^5$ (Lewis & Bridle 2002) which has been modified with a new free parameter $\Delta \alpha$ to allow the rotation of the power spectra discussed above. We assume purely adiabatic initial conditions and impose the flatness condition motivated by inflation. In our analysis the most general parameter space is $P \equiv [\omega_b, \omega_c, \Theta, \tau, n_s, \log(10^{10}A_s), r, \Delta \alpha]$, where $\omega_b = \Omega_b h^2$ and $\omega_c = \Omega_c h^2$ are the physical baryon and cold dark matter densities relative to the critical density, $\Theta$ is the ratio of the sound horizon to the angular diameter distance at decoupling, $\tau$ is the optical depth to reionization, $A_s$ and $n_s$ characterize the primordial scalar power spectrum, $r$ is the tensor-to-scalar ratio of the primordial spectrum. For the pivot of the primordial spectrum we set $k_{\text{pivot}} = 0.05$ Mpc$^{-1}$. In our calculation we have assumed that the cosmic rotation angle is constant at all multipoles and does not depend on $l$. Furthermore, we think that this rotation angle is not too large and imposed a conservative flat prior $-\pi/2 \leq \Delta \alpha \leq \pi/2$.

In our calculations we combine the full data of WMAP5 and B03. We calculate the likelihood of CMB power spectra using the routine for computing the likelihood supplied by the WMAP$^6$ and BOOMERANG groups. Furthermore, we make use of the Hubble Space Telescope measurement of the Hubble parameter $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$ by multiplying a Gaussian likelihood function $h = 0.72 \pm 0.08$ (Freedman et al. 2001). We also impose a weak Gaussian prior on the baryon density $\Omega_b h^2 = 0.022 \pm 0.002$ (1 $\sigma$) from big bang nucleosynthesis (Burles et al. 2001). Simultaneously we also use a cosmic age top-hat prior as 10 Gyr $< t_0 < 20$ Gyr.

First we do a consistency test by comparing two methods used by us and the WMAP group. The WMAP group fixed the parameters except for $\Delta \alpha$ and $\tau$ in their analysis (Komastu et al. 2008). The polarization spectra they considered are TE/TB/EE/BB/EB at $2 \leq l \leq 23$ and TE/TB at $24 \leq l \leq 450$. In our analysis, we vary all of the parameters in the parameter space and use the full WMAP5 data including the CMB TT power spectrum. With the WMAP5 data only we find that our result on $\Delta \alpha$ is consistent with that given by the WMAP group (Komastu et al. 2008). Therefore, in the study below, we follow our method to do the calculation with the combination of the WMAP5 and B03 data.

In Figure 1 we plot our one-dimensional constraints on the rotation angle $\Delta \alpha$ from the CMB data. The dashed line shows our previous result on rotation angle from WMAP3 and B03 data. The dash-dotted line shows the limit on $\Delta \alpha$ from the full WMAP5 data. And the solid line is our final result from the full WMAP5 and B03 data. The best-fit value of the rotation angle is $\Delta \alpha = -3.5^\circ$. Marginalizing over the posterior distributions of other parameters, we find that the mean value of the rotation angle is

$$\Delta \alpha = -2.6^\circ \pm 1.9^\circ \ (1 \sigma).$$

This constraint is tighter than all of the previous results on $\Delta \alpha$; the error bar is decreased by a factor of 2, which is the profit from the accurate WMAP5 polarization data. On the other hand, this negative rotation angle is slightly preferred by the TC and GC information from B03. In the B03 data, the TC power at $l \sim 250$ and 350 is negative, whereas it is positive at $l \sim 450$. The GC power is negative in all three cases, $l \sim 250$, 350, and 450. Based on equation (3), we can see that the TC and GC power spectra of B03 really help to obtain this negative rotation angle.

3. SUMMARY

In this Letter we have determined the rotation polarization angle $\Delta \alpha$ with the combined CMB data from BOOMERANG 2003 and the newly released WMAP5 data, and obtained $\Delta \alpha = -2.6^\circ \pm 1.9^\circ$ (1 $\sigma$), which shows a mild detection of a nonzero rotation angle and weak evidence for cosmological CPT violation. With the near future CMB measurements our result on the CPT violation could be confirmed or the CPT symmetry could be verified with higher precision. For example, with the Planck$^7$ and SPIDER measurements (MacTavish et al. 2007) the standard deviation of the rotation angle will be significantly reduced to $\sigma = 0.057^\circ$ (Xia et al. 2008b) and $\sigma = 0.38^\circ$ (J. Q. Xia et al. 2008, in preparation), respectively.

We acknowledge the use of the Legacy Archive for Microwave Background Data Analysis (LAMBDA). Support for LAMBDA is provided by the NASA Office of Space Science. We have performed our numerical analysis in the Shanghai

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$^5$ See http://cosmologist.info/.

$^6$ Legacy Archive for Microwave Background Data Analysis (LAMBDA), http://lambda.gsfc.nasa.gov/.

$^7$ See http://sci.esa.int/science-e/www/area/index.cfm?fareaid=17.
Supercomputer Center (SSC). We thank Yi-Fu Cai, Carlo Contaldi, Eiichiro Komatsu, and Tao-Tao Qiu for discussions. This work is supported in part by National Natural Science Foundation of China under grants 90303004, 10533010, and 10675136 and by the Chinese Academy of Science under grant KJCX3-SYW-N2. G. Z. is supported by National Science and Engineering Research Council of Canada (NSERC).

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