

NEW CONSTRAINTS ON COSMIC POLARIZATION ROTATION FROM THE ACTPol COSMIC MICROWAVE BACKGROUND B-MODE POLARIZATION OBSERVATION AND THE BICEP2 CONSTRAINT UPDATE

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ABSTRACT

Recently, ACTPol measured the cosmic microwave background (CMB) B-mode and E-mode polarizations and obtained TE, EE, BB, TB, and EB power spectra in the multipole range 225–8725. In our previous paper (Paper I), we jointly analyzed the results of three experiments on the CMB B-mode polarization—SPTpol, POLARBEAR, and BICEP2—to include in the model, in addition to the gravitational lensing and inflationary gravitational waves components, the fluctuation effects induced by cosmic polarization rotation (CPR) if it exists within the upper limits at the time. In this paper, we fit both the mean CPR angle $\langle\alpha\rangle$ and its fluctuation $\langle\delta\alpha^2\rangle$ from the new ACTPol data, and update our fitting of CPR fluctuations using the BICEP2 data taking the new Planck dust measurement results into consideration. We follow the same method used in Paper I. The mean CPR angle is constrained from the EB correlation power spectra to $|\langle\alpha\rangle| < 14$ mrad (0:8) and the fluctuation (rms) is constrained from the BB correlation power spectra to $\langle\delta\alpha^2\rangle^{1/2} < 29.3$ mrad (1:68). Assuming that the polarization angle of Tau A does not change from 89.2 to 146 GHz, the ACTPol data give $\langle\alpha\rangle = 1.0 \pm 0.63$. These results suggest that the inclusion of the present ACTPol data is consistent with no CPR detection. Using the new Planck dust measurement, we update our fits of the BICEP2 CPR fluctuation constraint to be 32.8 mrad (1:88). The joint ACTPol-BICEP2-POLARBEAR CPR fluctuation constraint is 23.7 mrad (1:36).

Key words: cosmic background radiation – cosmological parameters – early universe – gravitation – inflation – polarization

1. INTRODUCTION

The ACTPol collaboration (Naess et al. 2014) recently measured the cosmic microwave background (CMB) B-mode and E-mode polarizations in three regions of sky consisting of several tens of square degrees and obtained TE, EE, BB, TB, and EB power spectra in the multipole range 225–8725 using three months of observations; they detected six peaks and six troughs of acoustic oscillation in both the TE correlation power spectrum and the EE correlation power spectrum providing further empirical support for the Λ CDM cosmology. PLANCK (Ade et al. 2014a) resolves seven Doppler peaks in the TT power spectrum. ACTPol resolves six peaks in the EE spectra and six peaks/troughs in the TE cross spectra. The ACTPol data fit the standard Λ CDM model well, and the measurements of the E-mode spectrum are precise enough to confirm Λ CDM alone. Within the last scattering region, three processes can produce B-mode polarization or convert E-mode polarization to B-mode polarization in CMB: (i) local quadrupole anisotropies in the CMB due to large-scale gravitational waves (GWs; Polnarev 1985); (ii) a primordial magnetic field (Kosowsky et al. 2005; Pogosian et al. 2011, 2013); and (iii) cosmic polarization rotation (CPR) due to pseudoscalar-photon interaction (Ni 1973; for a review, see Ni 2010). During propagation, three processes can convert E-mode polarization into B-mode polarization: (a) gravitational lensing (Zaldarriaga & Seljak 1997); (b) Faraday rotation due to the magnetic field (including the galactic magnetic field); and (c) CPR due to pseudoscalar-photon interaction. The cause of both (i) and (a) is gravitational deflection; the cause of both (ii) and (b) is the magnetic field. CPR is independent of frequency while Faraday rotation is dependent on frequency. Therefore, Faraday rotation can be corrected for using observations at different frequencies.

However, it is negligible at CMB frequencies and corrections do not need to be applied. As for the foreground, the Galactic dust B-mode emission needs to be subtracted in the CMB B-mode polarization measurements (e.g., Adam et al. 2014). CPR is currently constrained to be less than about a couple of degrees by measurements of the linear polarization of radio galaxies and of the CMB (see di Serego Alighieri et al. 2010; di Serego Alighieri 2011; di Serego Alighieri et al. 2014, hereafter Paper 1; di Serego Alighieri 2015 for a review). However, CPR, if it existed at a level compatible with its current upper limits, would produce a non-negligible B-mode polarization in the CMB and affect its EB and TB correlation power. Paper I included the CPR effect when fitting the BICEP2 data (Ade et al. 2014b) to look for new constraints on the CPR and to investigate the robustness of the BICEP2 fit. TE, TB, and EB correlations could potentially provide mean values of the CPR angle $\langle\alpha\rangle$, while the contribution of CPR effects to the B-mode power could potentially give $\langle\alpha\rangle^2$ plus the variations of the CPR angle squared $\langle\delta\alpha^2\rangle$ (Paper I). However, both BICEP2 and POLARBEAR applied uniform angle derotation (EB-nulling) to their measured CMB for Q and U maps to compensate for inaccurate calibrations of the polarization angle, as first suggested by Keating et al. (2013). Since instrument pixel rotation and CPR are degenerate in the derotation, this procedure will not provide the mean CPR angle separately. Paper I fitted CPR effects to the B-mode power for BICEP2 and POLARBEAR to obtain new constraints for the CPR fluctuations. Paper I also used a CPR-SPTpol correlation parameter to find a constraint for the CPR fluctuations from SPTpol observational results (Hanson et al. 2013; Holder et al. 2013).

The announced ACTPol data have not been treated with polarization derotation. In this paper, we will follow the discussions in the ACTPol paper (Naess et al. 2014) and use the E–B-mode-coupling method combined with the instrumental calibration accuracy of ACTPol (Naess et al. 2014) to infer a constraint on the uniform CPR angle. We will also follow Paper I to fit the B-mode power to obtain a constraint on the CPR fluctuations $\langle \delta\alpha^2 \rangle$.

In Section 2, we review pseudoscalar-photon interaction, its associated electromagnetic propagation effect on the CPR of the CMB, and how to extract the mean CPR angle and the CPR fluctuations. In Section 3, we present the results of our phenomenological fit to the ACTPol data. In Section 4, we update our constraints from Paper I on the CPR fluctuations from BICEP2, incorporating the Planck dust measurement (Adam et al. 2014); we also fit the CPR fluctuation $\delta\alpha^2$ to various joint combinations of the ACTPol BB power (Naess et al. 2014), the BICEP2 BB power (Ade et al. 2014b), and the POLARBEAR BB power (Ade et al. 2014c). In Section 5, we conclude with a look toward the future.

2. PSEUDOSCALAR-PHOTON INTERACTION, POLARIZATION ROTATION, MEAN CPR ANGLE, AND CPR FLUCTUATIONS

In cosmology, general relativity is normally used as a baseline theory. In general relativity and in metric theories of gravity, the Einstein Equivalence Principle (EEP) plays a fundamental role and dictates the interaction of radiation and matter with gravity. For photons/electromagnetic waves, EEP tells us that, independent of energy (frequency) and polarization, photons with the same initial position and direction follow the same world line (i.e., no birefringence; Galileo equivalence for photons/electromagnetic waves, universality of trajectory), with no change of polarization relative to local inertial frame (i.e., no polarization rotation). This is observed to high precision for no birefringence ($\sim 10^{-38}$; Ni 2015). As for the polarization rotation, it is constrained from previous astrophysical tests using the radio and optical/UV polarization of radio galaxies and the CMB E-mode polarization in the astrophysical electromagnetic propagation: the mean CPR angle is constrained to about 20 mrad (1:15). In Paper I, we used the newly reported CMB B-mode polarization results of the SPTpol, POLARBEAR, and BICEP2 experiments to constrain the CPR fluctuation for the observed sky areas to 27 mrad (1:55). No amplification or dissipation in the CMB propagation to distort the CMB blackbody spectrum constrains Type I skewons to about 10^{-35} (Ni 2014a).

In Paper I, we also review the pseudoscalar-photon interaction. CPR would be created by the pseudoscalar-photon interaction of the axion field. This CPR is proportional to the difference of the pseudoscalar field at the observation point and at emission (the last scattering surface in the case of CMB). The proportionality can be set to equality when the pseudoscalar field is appropriately normalized (we will do so in the rest of this paper).

The pseudoscalar-photon interaction contains the interaction Lagrangian density:

$$\begin{aligned} L_l^{(\text{EM}-A_x)} &= -(1/(16\pi))\varphi e^{ijkl}F_{ij}F_{kl} \\ &= -(1/(4\pi))\varphi_{,i}e^{ijkl}A_jA_{k,l} \pmod{\text{div}}. \end{aligned} \quad (1)$$

with ‘‘mod div’’ meaning related by integration by parts (Ni 1973, 1974, 1977). The modified Maxwell Equations (Ni 1973, 1977) become

$$F^{ik}_{;k} + (-g)^{-1/2}e^{ikml}F_{km}\varphi_l = 0. \quad (2)$$

The derivation ‘‘;’’ is with respect to the Christoffel connection.

Using a local inertial frame of the g metric, we solved for the dispersion relation and obtained $k = \omega + (n^\mu\varphi_{,\mu} + \varphi_{,0})$ for the right circularly polarized wave together with $k = \omega - (n^\mu\varphi_{,\mu} + \varphi_{,0})$ for the left circularly polarized wave, where n^μ is a unit three vector in propagation direction (Ni 1973, 2010). The group velocity

$$v_g = \partial\omega/\partial k = 1 \quad (3)$$

is independent of polarization. There is no birefringence (see, e.g., Ni 1973, 2010, 2014b; Hehl et al. 2003; Itin 2013). Since waves with different helicity picked up opposite phases, a linearly polarized electromagnetic wave would then rotate by an angle of $\alpha = \Delta\varphi = \varphi(P_2) - \varphi(P_1)$ with $\varphi(P_1)$ and $\varphi(P_2)$ being the values of the scalar field at the beginning and at end of the wave. This effect is called CPR.

The variations and fluctuations in CPR of CMB observations due to pseudoscalar-modified propagation are expressed as $\delta\varphi(P_2) - \delta\varphi(P_1)$; $\delta\varphi(P_1)$ is the variation/fluctuation at the last scattering surface; the present observation point P_2 is fixed, which implies that the variation/fluctuation $\delta\varphi(P_2)$ is zero. Hence, the covariance of the fluctuation $\langle [\delta\varphi(P_2) - \delta\varphi(P_1)]^2 \rangle$ is equal to the covariance of $\delta\varphi^2(P_1)$ at the last scattering surface.

E-mode polarization in propagation will rotate into B-mode polarization in the pseudoscalar field with a $\sin^2 2\alpha$ ($\approx 4\alpha^2$ for small α) fraction of power. For uniform rotation across the sky, we know that the azimuthal eigenvalue l does not change. For small angles,

$$\begin{aligned} \alpha &= \varphi(P_2) - \varphi(P_1) = [\varphi(P_2) - \varphi(P_1)]_{\text{mean}} \\ &+ \delta\varphi(P_1) = \langle \alpha \rangle + \delta\alpha, \end{aligned} \quad (4)$$

$$\begin{aligned} \underline{\alpha}^2 \equiv \langle \alpha^2 \rangle &= \left([\varphi(P_2) - \varphi(P_1)]_{\text{mean}} \right)^2 \\ &+ \delta\varphi^2(P_1) = \langle \alpha \rangle^2 + \delta\alpha^2, \end{aligned} \quad (5)$$

with $\underline{\alpha} \equiv \langle \alpha^2 \rangle^{1/2}$ being the rms polarization rotation angle, $[\varphi(P_2) - \varphi(P_1)]_{\text{mean}} = \langle \alpha \rangle$, and $\delta\alpha = -\delta\varphi(P_1)$ (Paper I).

As stated in Paper I, when converting the CMB power function to the azimuthal spectrum l , we need to insert a nonlinear conversion a factor of $\zeta(l) \approx 1$ in front of $\delta_l\varphi^2(P_1)$ due to fluctuations. For a uniform rotation across the sky, the rotation of (original) C_l^{EE} into $C_l^{\text{BB,obs}}$, $C_l^{\text{EB,obs}}$, etc. is given by (see, e.g., Keating et al. 2013):

$$C_l^{\text{BB,obs}} = C_l^{\text{BB}} \cos^2(2\alpha) + C_l^{\text{EE}} \sin^2(2\alpha), \quad (6a)$$

$$C_l^{\text{EB,obs}} = (C_l^{\text{EE}} - C_l^{\text{BB}}) \sin(2\alpha) \cos(2\alpha), \quad (6b)$$

$$C_l^{\text{TB,obs}} = -\sin(2\alpha)C_l^{\text{TE}}, \quad (6c)$$

$$C_l^{\text{EE,obs}} = C_l^{\text{BB}} \sin^2(2\alpha) + C_l^{\text{EE}} \cos^2(2\alpha), \quad (6d)$$

$$C_l^{\text{TE,obs}} = \cos(2\alpha)C_l^{\text{TE}}. \quad (6e)$$

The rotation of C_l^{BB} into the E-mode power $C_l^{EE,obs}$ and the EB correlation power $C_l^{EB,obs}$ is negligibly small since the ratio of the B-mode and E-mode is small at the last scattering surface. In case there is an instrumental polarization rotation angle offset β , α in the above formulas needs to be replaced by α_β defined as $(\alpha-\beta)$. We denote Equations (6a)–(6e) with α replaced by α_β as (6a–6e) $_\beta$. The present ACTPol data group 50 or more azimuthal eigenmodes into one band with the lowest azimuthal contribution from $l = 225$; $\zeta(l)$ is virtually equal to one. We will set this to one in our analysis. In a patch of sky, the observed B-mode l -power spectrum $C_l^{BB,obs}$, the observed EB correlation power spectrum $C_l^{EB,obs}$, and others in (6a)–(6e) for small CPR angle α with small fluctuation $\delta\alpha$ are accurately given by

$$\begin{aligned} C_l^{BB,obs} &= C_l^{BB} \langle \cos^2(2\alpha) \rangle + C_l^{EE} \langle \sin^2(2\alpha) \rangle \\ &\approx C_l^{BB} (1 - 4\langle \alpha^2 \rangle) + 4C_l^{EE} \langle \alpha^2 \rangle \\ &\approx C_l^{BB} + 4\langle \alpha^2 \rangle C_l^{EE} \\ &= C_l^{BB} + 4\alpha^2 C_l^{EE}, \end{aligned} \quad (7a)$$

$$\begin{aligned} C_l^{EB,obs} &\approx (C_l^{EE} - C_l^{BB}) \langle \sin(2\alpha) \cos(2\alpha) \rangle \\ &\approx 2(\langle \alpha \rangle - (8/3)\langle \alpha^3 \rangle) (C_l^{EE} - C_l^{BB}) \\ &\approx 2\langle \alpha \rangle C_l^{EE}, \end{aligned} \quad (7b)$$

$$C_l^{TB,obs} = -\langle \sin(2\alpha) \rangle C_l^{TE} \approx -2\langle \alpha \rangle C_l^{TE}, \quad (7c)$$

$$\begin{aligned} C_l^{EE,obs} &\approx C_l^{BB} \langle \sin^2(2\alpha) \rangle + C_l^{EE} \langle \cos^2(2\alpha) \rangle \\ &\approx C_l^{EE}, \end{aligned} \quad (7d)$$

$$\begin{aligned} C_l^{TE,obs} &= \langle \cos(2\alpha) \rangle C_l^{TE} \approx (1 - 2\langle \alpha^2 \rangle) C_l^{TE} \\ &\approx C_l^{TE}. \end{aligned} \quad (7e)$$

For a small instrumental polarization rotation angle offset β , Equations (7a)–(7e) $_\beta$ (with α replaced by α_β in (7a)–(7e)) are valid. If there is an instrument polarization rotation offset β but no CPR, then the uniform CPR rotation angle $\langle \alpha \rangle$ should be replaced by $-\beta$ (if there is no CPR, then $\langle \alpha \rangle = 0$) in the Equations (6a)–(6e); Keating et al. 2013). When both the instrument polarization offset β and cosmic polarization rotation are present, the uniform CPR rotation angle $\langle \alpha \rangle$ should be replaced by $(\langle \alpha \rangle - \beta)$ in Equations (6a)–(6e) and Equations (7a)–(7e). Some CMB polarization projects (Kaufman et al. 2014; Ade et al. 2014b, 2014c) applied a uniform derotation to their Q and U maps by minimizing the TB power and the EB power to compensate for the insufficient calibrations in the polarization angle, as first suggested by Keating et al. (2013). This procedure automatically eliminated the sum of any systematic error in the polarization angle calibration and any uniform CPR, if it exists. If the calibration errors of the polarization angle were small compared to the uniform CPR, then any residual EB power and TB power would provide an estimate of $\langle \alpha \rangle$ (Paper I). In Section 3.1, we follow ACTPol (Naess et al. 2014) in using this E–B-mode-coupling method to find $(\langle \alpha \rangle - \beta)$ from the ACTPol polarization, and then an estimate of β from the ACTPol calibration (Naess et al. 2014) provides a constraint on the uniform CPR angle $\langle \alpha \rangle$.

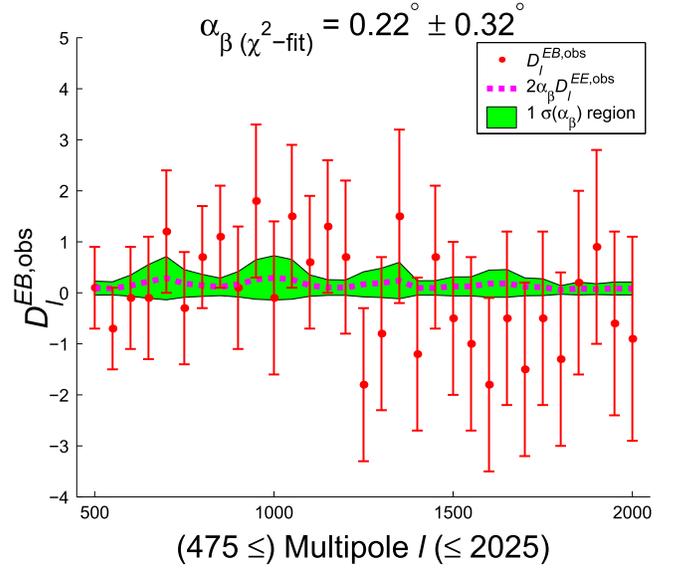


Figure 1. EB power correlation spectra for fitting α_β (the mean polarization rotation with instrument offset). The ACTPol observation $D_l^{EB,obs}$ data points are shown as red dots with error bars. The fitted α_β times $2D_l^{EE,obs}$ (purple dotted line) is plotted as the green area showing the 1σ region. The least-square method is used to fit α_β from Equation (8a) for the $D_l^{EB,obs}$ and $D_l^{EE,obs}$ data ($475 < l < 2025$) from ACTPol (Naess et al. 2014). The result is $\alpha_\beta = 0:22 \pm 0:32$.

3. MODELING THE ACTPOL DATA WITH CPR

In this section, we model the three months of available ACTPol data for the BB, EB, TB, EE, and TE power spectra with the three components mentioned in Section 1, i.e., gravitational lensing, relic GWs, and CPR. The dust level measured in ACTPol was shown to be consistent with the Planck 353 GHz maps (Abergel et al. 2014) at the 30% level. The predicted contribution of dust to the temperature anisotropy power spectrum was measurable but small, less than $2 \mu K^2$ at $l = 2000$. ACTPol did not correct for this in the maps or likelihood at this stage. We follow ACTPol in the present paper as well. In Section 3.1, we use the E-to-B-mode-coupling method together with offset calibration to obtain the constraint on the CPR mean angle. In Section 3.2, we fit the BB power data for the CPR fluctuation power $\langle \delta\alpha^2 \rangle$ using Equation (7a).

3.1. CPR Mean Angle $\langle \alpha \rangle$

From (7d) and (7e), we have $C_l^{EE,obs} \approx C_l^{EE}$ and $C_l^{TE,obs} \approx C_l^{TE}$. Hence, (7b) and (7c) provide

$$C_l^{EB,obs} \approx 2\langle \alpha \rangle C_l^{EE,obs}, \quad (8a)$$

$$C_l^{TB,obs} \approx -2\langle \alpha \rangle C_l^{TE,obs}. \quad (8b)$$

In the case with a non-zero instrument polarization offset β , we use (8a) $_\beta$ and (8b) $_\beta$ with α replaced by α_β . Now, using (i) the observed EB and EE power spectra or (ii) the observed TB and TE spectra, we can fit for the parameter α_β . Naess et al. (2014) used ACTPol E and B spectra from $500 < l < 2000$ to constrain the parameter $(\beta - \langle \alpha \rangle)$ to be $-0:2 \pm 0:5$. (They did not consider CPR, so in their interpretation, the parameter $(\beta - \langle \alpha \rangle)$ is simply the instrument polarization rotation offset

Table 1

Results of Least-square-fitting of the Mean CPR Rotation Angle with Instrument Offset, i.e., $\alpha_\beta (= \langle \alpha \rangle - \beta)$, to the EB, EE, TB, and TE Polarization Data of ACTPol (Naess et al. 2014) using Equations (8a) $C_l^{\text{EB,obs}} \approx 2 \alpha_\beta C_l^{\text{EE,obs}}$, and (8b) $C_l^{\text{TB,obs}} \approx -2 \alpha_\beta C_l^{\text{TE,obs}}$. N is the Number of Data Points; n is the Number of Fit Parameters

Data Used	Fitted Parameter α_β (mrad)	χ_{\min}^2 [reduced χ^2] ($N-n$)	1 σ Upper Limit on $ \alpha_\beta $ (mrad)
$D_l^{\text{EB,obs}}$ and $D_l^{\text{EE,obs}}$ ($l = 475-2025$)	3.8 ± 5.7 ($0^\circ:22 \pm 0^\circ:32$)	14.2 [0.49] (31-1)	9.5 ($0^\circ:54$)
$D_l^{\text{TB,obs}}$ and $D_l^{\text{TE,obs}}$ ($l = 475-2025$)	-7.5 ± 64.6 ($-0^\circ:43 \pm 3^\circ:70$)	38.7 [1.33] (31-1)	72 ($4^\circ:1$)

angle β .) EB has a fundamentally lower noise and will always provide a tighter constraint than TB, as discussed in Keating et al. (2013) and Naess et al. (2014).

Since ACTPol data are given in multipole bands, we use their data from the band with mid-multipole 500 to mid-multipole 2000 to do the fitting. The ACTPol collaboration used D_l ($\equiv l(l+1)C_l/2\pi$) when presenting their data; replacing C_l with D_l , all of the formulas in this section and the last section are still valid. The spectra range of $D_l^{\text{EB,obs}}$ and $D_l^{\text{EE,obs}}$ and the fit results from (8a) $_\beta$ are shown in Figure 1 and in the second row of Table 1. The CPR with an offset from the fit is $\alpha_\beta = -(\beta - \langle \alpha \rangle) = 0^\circ:22 \pm 0^\circ:32$, which is consistent with the ACTPol estimate. The sign of the polarization angle position is in the IAU convention (see, e.g., Haymaker & Bregman 1996; di Serego Alighieri & Ni 2014).

From the figure and the table, the reduced χ_{\min} is determined to be less than one for the EB + EE case. This shows that the uncertainty is probably over-estimated for this case. We take the result from Figure 1 (row 2 in Table 1) to be the value of α_β . The third row of Table 1 is included for comparison purposes. According to ACTPol (Naess et al. 2014), their optical modeling procedure is free of systematic errors at the $0^\circ:5$ level or better. Assuming this, β should be within $\pm 0^\circ:5$ and we have $\langle \alpha \rangle = -(\beta - \langle \alpha \rangle) + \beta = 0^\circ:22 \pm 0^\circ:32 \pm 0^\circ:5 \approx 0.2 \pm 0.6$. That is, $|\langle \alpha \rangle| \leq 0.8$.

ACTPol observed the radio source Tau A (Crab Nebula) and made a new measurement of the polarization of the Crab Nebula to determine the consistency of the instrument polarization rotation offset independently at 146 GHz (Naess et al. 2014). This is achieved by comparing the ACTPol observation and the IRAM results at 89.2 GHz (Aumont et al. 2010).

Let us discuss in detail the accuracy of the calibration of the ACTPol experiment relative to the Aumont et al. (2010) Tau A measurement reference.

- i. Aumont et al. (2010) measure a mean polarization angle of $\theta_{\text{TauA_Aumont}} = 149.9 \pm 0.2$ and a polarization fraction of $P = 8.8 \pm 0.2\%$ for Tau A at 89.2 GHz on a 5 arcmin circular beam. We take this as a reference angle.
- ii. ACTPol, using the calibration of the polarization angle based on the nulling procedure, smoothing to a 5 arcmin beam, measure for Tau A at 146 GHz a mean polarization angle of $\theta_{\text{TauA_ACTPol-nulling}} = 150.9 \pm 0.6$.

This second result is slightly different from what was reported at the end of the Abstract of Naess et al. (2014; 150.7 ± 0.6). The explanation for this is that the polarization direction is $150^\circ:7$ at the intensity peak, but the polarization direction at the pulsar position (which is a less ambiguous coordinate) is $150^\circ:9$ (M. Hasselfield 2014, private

communication). The difference between the two measurements listed above could be due to the CPR and/or to the difference in the emitted polarization at 146 and 89.2 GHz. If the Aumont et al. measurement was also valid at 146 GHz (see Section 6 of Aumont et al. 2010), then the difference would be $\text{CPR } \langle \alpha \rangle = (150.9 \pm 0.6) - (149.9 \pm 0.2) = 1.0 \pm 0.63$. Given the uncertainty in the assumption that the polarization angle of Tau A does not change from 89.2 to 146 GHz, we should not regard this as a CPR detection but just as another measurement of CPR consistent with zero and with the value $|\langle \alpha \rangle| \leq 0.8$, which we obtained by assuming the validity of the ACTPol optical modeling. Nevertheless, further observations of Tau A and other radio sources at CMB frequencies and better modeling of the polarization source are needed to clarify this issue.

3.2. CPR Fluctuation $\langle \delta \alpha^2 \rangle$

As in Paper I, we model the available data for the BB power spectrum with the three effects (GW, lensing, and CPR) mentioned in the Introduction. The theoretical spectrum of the inflationary GWs and the lensing contribution to the B-mode are extracted from the BICEP2 paper (Ade et al. 2014b). The power spectrum $C_l^{\text{BB,obs}}$ induced by any existing CPR angle (Equation (7a)) is obtained from the theoretical E-mode power spectrum C_l^{EE} of Lewis & Challinor (2006). We fit the CPR fluctuation power $\langle \delta \alpha^2 \rangle$ to the BB power data. A least-square method is used to fit $\langle \delta \alpha^2 \rangle$ from Equation (7a) $_\beta$ for the $D_l^{\text{BB,obs}}$, $\sigma(D_l^{\text{BB,obs}})$, and $D_l^{\text{EE,obs}}$ data of ACTPol from l from 250 to 2925 (Naess et al. 2014). Since $\alpha_\beta = 0^\circ:22 \pm 0^\circ:32$ is small, the CPR and instrument polarization rotation contribute less than $\pm 0.04\%$ of the power to $D_l^{\text{EE,obs}}$ according to (7d) $_\beta$, and hence the difference between D_l^{EE} and $D_l^{\text{EE,obs}}$ can be ignored. Therefore, we could use the data for $D_l^{\text{EE,obs}}$ in place of the specific model D_l^{EE} . The fitting result is $\langle \delta \alpha^2 \rangle = -182 \pm 1041$ mrad 2 and is listed together with χ_{\min}^2 in the third row of Table 2. In Table 2, we also list the various results from Section 4.

4. UPDATING THE BICEP2 CPR FLUCTUATION CONSTRAINT INCLUDING THE PLANCK DUST MEASUREMENT

Paper I fitted the BICEP2 B-mode data with two parameters—the tensor-to-scalar ratio r and the rms-sum CPR fluctuation $\langle \delta \alpha^2 \rangle^{1/2}$. In September, PLANCK announced its intermediate results on the angular power spectrum of the polarized dust emission at intermediate and high Galactic latitudes (Adam et al. 2014). The PLANCK results showed that even in the faintest dust-emitting regions, there are no “clean” windows in

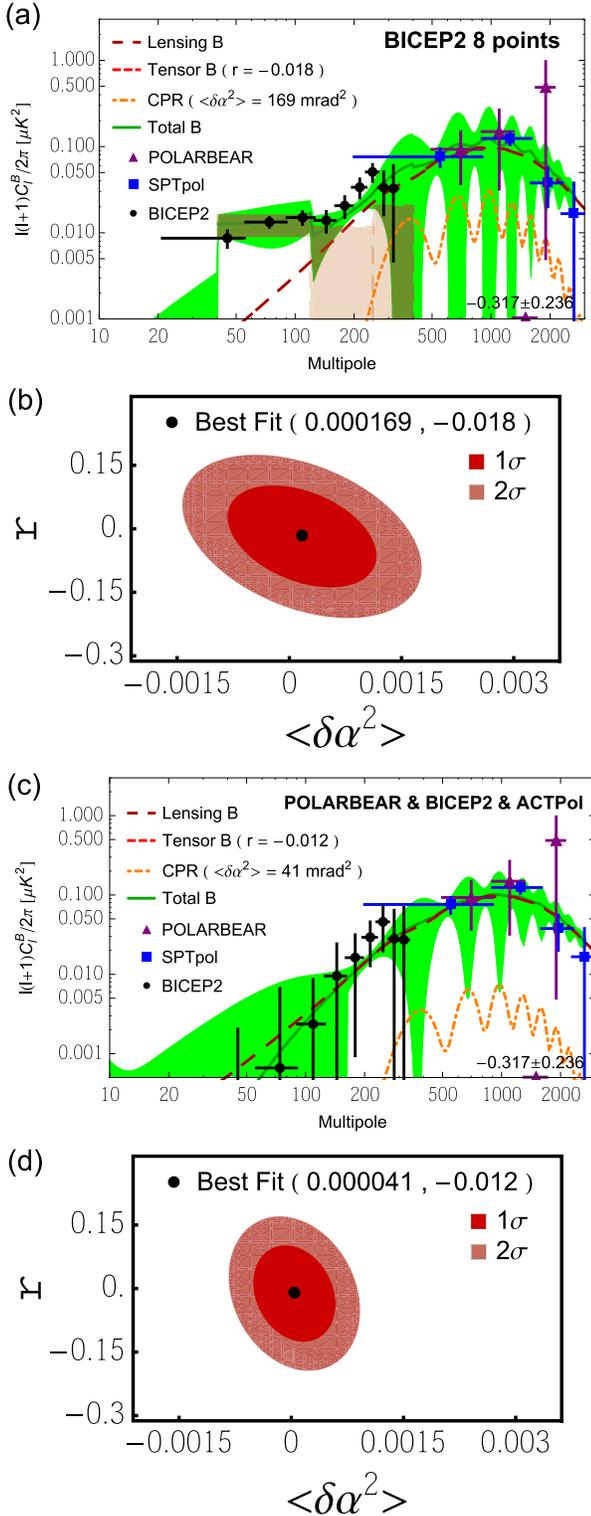


Figure 2. (a) CMB B-Mode power spectrum with data points and models including the tensor-to-scalar ratio r , lensing, CPR, and dust (pink shaded areas) contributions. (b) The 1σ and 2σ contours of the joint constraint on the tensor-to-scalar ratio r and the rms-sum of the CPR angle due to pseudoscalar-photon interaction for (a). (c) and (d) Representing the joint ACTPol + BICEP2 + POLARBEAR fitting. In (a), the dust effect is contained in the BICEP2 data points; in (c), the dust effect is already subtracted in the BICEP2 data points. From (b) and (d), one can see that the degeneracy (correlation in fitting) between r and the CPR fluctuation is mild. The power of the second highest multipole band of POLARBEAR (1 from 1300 to 1700) is negative, i.e., $-0.317 \pm 0.236 \mu\text{K}^2$; we show the binning interval on the horizontal axis with the data value in Arabic numerals above the binning interval in (a) and (c).

the sky where primordial CMB B-mode polarization measurements could be made neglecting foreground emission. In the same paper, they investigate the level of dust polarization in the specific field targeted by the BICEP2 experiment. Extrapolation of the Planck 353 GHz data to 150 GHz provides a dust power C_l^{BB} CMB over the multipole range of the primordial recombination bump ($40 < l < 120$). To take care of the polarized dust emission, we include the Planck measurement when fitting the tensor-to-scalar ratio r and the rms-sum CPR fluctuation $\langle \delta\alpha^2 \rangle^{1/2}$ from the BICEP2 data.

PLANCK has no dust information lower than $l = 40$ in their paper (Adam et al. 2014), so we ignore the first data point of BICEP2 and perform the eight point fit. The dust contribution determined from PLANCK is subtracted from the BICEP2 data with uncertainties added in quadrature. The PLANCK dust contribution has fewer bins; we attribute an equal uncertainty to each l in a single bin in the uncertainty assignment. The results are listed in the fourth row of Table 2 and shown in Figure 2(a) and (b). We also fit various combinations and the results are shown in rows 6–9 of Table 2 together with the POLARBEAR results (row 5) from Paper I. Those for the joint ACTPol + BICEP2 + POLARBEAR fitting are also shown in Figure 2(c) and (d).

5. DISCUSSION AND OUTLOOK

Following the method of Paper I, we continued to investigate the possibility of detecting CPR or setting new constraints upon it, using its imprints on the CMB B-mode polarization from the ACTPol experiment for $250 \leq l \leq 2925$ (Naess et al. 2014). Using the method of derotation and the independent determination of the calibration offset and assuming the validity of ACTPol optical modeling, we obtain a constraint on the mean CPR angle of $|\langle \alpha \rangle| \leq 0.8$. On the other hand, if the Tau A polarization angle does not change from 89.2 to 146 GHz, then the ACTPol data provide $\langle \alpha \rangle = 1.0 \pm 0.63$. Using the B-mode power, we find that CPR is constrained to $\langle \delta\alpha^2 \rangle^{1/2} < 29.3$ mrad ($1:68$). These results support the claim that the inclusion of the present ACTPol data is consistent with no CPR detection. Using the PLANCK dust measurement, we update our fits of the BICEP2 constraint on CPR fluctuations to be 32.8 mrad ($1:88$), which is close to the value of 28.2 mrad ($1:61$) obtained in Paper I. The joint ACTPol-BICEP2-POLARBEAR constraint on CPR fluctuations is 23.7 mrad ($1:36$).

While waiting for improvements to the detection/constraints on CPR (Gruppuso et al. 2012) in the near future from the analyzed results of the Planck mission (<http://www.cosmos.esa.int/web/Planck>), we would like to stress that calibration procedures of sufficient accuracy for the polarization orientation are important to detect or constrain CPR as emphasized by Kaufman et al. (2014; see also di Serego Alighieri 2015 for a discussion of Planck effects on CPR). A new generation of ground-, balloon-, and space-based CMB experiments have been proposed and many of these will be implemented, as we heard in the PLANCK 2014 meeting, promising important updates on the CPR issue.

If pseudoscalar-photon interactions exist, then a natural cosmic variation of the pseudoscalar field at the decoupling era is 10^{-5} fractionally. The CPR fluctuation is then of the order of $10^{-5} \varphi_{\text{decoupling-era}}$ (Ni 2008). We will keep looking for possible detections or further constraints in future experiments.

Table 2

Results of Fitting the CPR Fluctuation $\delta\alpha^2$ to the ACTPol BB Power (Naess et al. 2014), the BICEP2 BB Power (Ade et al. 2014b), and the POLARBEAR BB Power (Ade et al. 2014c), Respectively, and with Various Joint Combinations

Experiment	Fitting Parameter		χ_{\min}^2 [reduced χ^2] ($N-n$)	1σ Upper Limit	
	$\langle\delta\alpha^2\rangle$ (mrad ²)	r		$\langle\delta\alpha^2\rangle^{1/2}$ (mrad)	r
ACTPol	-182 ± 1041	...	35.66 [0.87] (43–1)	29.3 (1:68)	...
BICEP2	169 ± 905	-0.018 ± 0.109	1.67 [0.33] (8–2)	32.8 (1:88)	0.091
POLARBEAR	89 ± 535	...	3.73 [1.86] (4–1)	25.0 (1:43)	...
ACTPol + BICEP2	4 ± 683	-0.010 ± 0.109	37.47 [0.78] (51–2)	26.2 (1:50)	0.099
ACTPol + POLARBEAR	-13 ± 640	...	39.49 [0.88] (47–1)	25.0 (1:43)	...
BICEP2+ POLARBEAR	122 ± 604	-0.016 ± 0.109	5.41 [0.60] (12–2)	26.9 (1:54)	0.093
ACTPol+BICEP2+POLARBEAR	41 ± 522	-0.012 ± 0.109	41.22 [0.79] (55–2)	23.7 (1:36)	0.097

Note. N is the number of data points and n is the number of fitting parameters.

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