ANOMALOUS PARITY ASYMMETRY OF THE WILKINSON MICROWAVE ANISOTROPY PROBE POWER SPECTRUM DATA AT LOW MULTIPOLES

Jaiseung Kim and Pavel Naselsky
Niels Bohr Institute & Discovery Center, Blegdamsvej 17, DK-2100 Copenhagen, Denmark; jkim@nbi.dk

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ABSTRACT

We have investigated non-Gaussianity of our early universe by comparing the parity asymmetry of the Wilkinson Microwave Anisotropy Probe (WMAP) power spectrum with simulations. We find that odd-parity preference of the WMAP data (2 ≤ l ≤ 18) is anomalous at 4-in-1000 level. We find it likely that low quadrupole power is part of this parity asymmetry rather than an isolated anomaly. Further investigation is required to find out whether the origin of this anomaly is a cosmological or a systematic effect. The data from Planck Surveyor, which has systematics distinct from WMAP, will help us to resolve the origin of the anomalous odd-parity preference.

Key words: cosmic background radiation – methods: data analysis

Online-only material: color figures

1. INTRODUCTION

For the past few years, there have been great successes in the measurement of cosmic microwave background (CMB) anisotropy by ground and satellite observations (Hinshaw et al. 2009; Nolta et al. 2008; Dunkley et al. 2009; Runyan et al. 2003; Reichardt et al. 2009; Ade et al. 2008; Pryke et al. 2009; Hinderks et al. 2009; Brown et al. 2009). Recently, Planck Surveyor has been successfully launched, and is measuring CMB temperature and polarization anisotropy with very fine angular resolution. Using CMB data, we may test cosmological hypotheses and impose significant constraints on cosmological models (Dodelson 2003; Liddle & Lyth 2000; Mukhanov 2005). For the past few years, Wilkinson Microwave Anisotropy Probe (WMAP) data have gone through scrutiny, and various anomalies have been reported (Cruz et al. 2005, 2006, 2007, 2008; de Oliveira-Costa et al. 2004; Copi et al. 2004, 2006, 2007; Schwarz et al. 2004; Land & Magueijo 2005a, 2007; Rakić and Schwarz 2007; Park 2004; Chiang et al. 2003; Naselsky et al. 2004; Eriksen et al. 2004; Hansen et al. 2009; Hofuft et al. 2009; Kim & Naselsky 2009). In direct relevance to this Letter, Land et al. have noted odd point-parity preference in WMAP data, but found that its statistical significance was not high, given their estimator (Land & Magueijo 2005b). In this Letter, we revisit the point parity of the WMAP data with a slightly different estimator, and report the odd-parity preference of the WMAP power spectrum data at 99.6% level.

2. ANALYSIS OF THE WMAP DATA

For a whole-sky CMB analysis, temperature anisotropy T(θ, φ) is conveniently decomposed in terms of spherical harmonics Y_{lm}(θ, φ):

\[ T(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n}), \]

where \( a_{lm} \) is a decomposition coefficient and \( \hat{n} \) is a sky direction. For a Gaussian seed fluctuation model, decomposition coefficients satisfy the following statistical properties:

\[ \langle a_{lm} \rangle = 0 \]
\[ \langle a_{lm}^* a_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}, \]

where \( \langle \cdots \rangle \) denotes the average over the ensemble of universes. Given a standard cosmological model, we expect Sach–Wolf plateau for CMB power spectrum on low multipoles (Dodelson 2003):

\[ l(l + 1)C_l \sim \text{const.} \quad (1) \]

In Figure 1, we show the WMAP 5 year, 3 year data, and the theoretical power spectrum of the WMAP concordance model (Hinshaw et al. 2007; Nolta et al. 2008; Komatsu et al. 2009). In comparison with WMAP 3 year data, WMAP 5 year data are expected to have more accurate calibration and less foreground contamination (Hinshaw et al. 2009; Nolta et al. 2008; Hill et al. 2009).

Spherical harmonics behave under parity inversion as follows (Arfken & Weber 2000):

\[ Y_{lm}(\hat{n}) = (-1)^l Y_{lm}(-\hat{n}). \]

Therefore, power asymmetry between even and odd multipoles may be thought as power asymmetry between even and odd parity map, because a map consisting of even (odd) multipoles possesses even (odd) parity. Hereafter, we will denote it as “parity asymmetry.” In Figure 2, we show \((-1)^l(l+1)/2\pi (C_l - C_l^{\Lambda CDM})\) at low multipoles. As shown in Figure 2, most of them possess negative values, which indicate that there exists power deficit (excess) in comparison to the \(\Lambda\)CDM model at most of even (odd) multipoles. In the case of WMAP5 data, there are only three points of positive values among 18 data points. An order-of-magnitude estimation shows that such events require the odd multipoles of \(18!/3!15!2^1! \approx 0.003\). However, power spectrum is estimated from cut-sky data to avoid diffuse Galactic foreground contamination. Therefore, statistical fluctuation in estimated \(C_l\) is correlated among multipoles. In order to investigate odd multipoles of the parity asymmetry rigorously, we have produced \(10^4\) simulated CMB maps (HEALPix Nside = 8) of the Gaussian \(\Lambda\)CDM model. We have degraded the WMAP processing mask (Nside = 16) to Nside = 8, and set pixels to zero, if any of their daughter pixels is zero. After applying the mask, we have estimated power spectrum from cut-sky maps by a pixel-based maximum likelihood method. Instrument noise is neglected in simulation, since noise is subdominant on multipoles of interest (e.g., signal-to-noise ratio \(\sim 100\) for \(C_l\) at \(l = 30\); Nolta et al. 2008). Bearing Equation (1) in mind, we
We have estimated the following quantities:

\[ P^+ = \sum (l + 1 - 2 \left\lfloor \frac{l + 1}{2} \right\rfloor) l(l + 1)/2\pi C_l, \]  

(2)

\[ P^- = \sum (l - 2 \left\lfloor \frac{l}{2} \right\rfloor) l(l + 1)/2\pi C_l, \]  

(3)

where \( \left\lfloor \cdots \right\rfloor \) denotes the greatest integer smaller than or equal to the argument. Using the WMAP power spectrum data and simulations, respectively, we have computed the ratio \( P^+ / P^- \) for various multipole ranges \( 2 \leq l \leq l_{\text{max}} \), where \( l_{\text{max}} \) is between 3 and 23. By comparing \( P^+ / P^- \) of the WMAP data with simulation, we have estimated \( p \)-value, where \( p \)-value denotes fractions of simulations as low as \( P^+ / P^- \) of the WMAP data.

In Figure 3, we show the \( p \)-value of WMAP5 and WMAP3, respectively, for various \( l_{\text{max}} \). Figure 3 shows the lowest \( p \)-value for \( l_{\text{max}} = 18 \), where \( p \)-values are 0.004 and 0.0099 for WMAP5 and WMAP3, respectively. In other words, there exists anomalous odd-parity preference at multipoles \( 2 \leq l \leq 18 \). As shown in Figure 3, WMAP5 possesses more anomalous odd-parity preference than WMAP3, while WMAP5 data have more accurate calibration and less foreground contamination (Hinshaw et al. 2009; Hill et al. 2009; Nolta et al. 2008). Therefore, we find it unlikely that calibration or foregrounds are the source of the anomaly. It should also be noted that the anomaly is associated with the WMAP power spectrum data, in which most efforts have been exerted to minimize systematics.

It has been known that the CMB quadrupole power of WMAP data is unusually low, compared with the theoretical value (de Oliveira-Costa et al. 2004). Therefore, one may attribute the anomalous parity asymmetry of the WMAP data to low quadrupole power. As shown in Figure 3, the parity asymmetry persists over extended range of multipoles, and the parity asymmetry on multipoles \( 2 \leq l \leq 18 \) is most anomalous. Therefore, we may not simply attribute the parity asymmetry to low quadrupole power. For multipole range \( 2 \leq l \leq 18 \), we find \( P^+ / P^- \approx 1.1 \) is most likely, while \( P^+ / P^- \) of WMAP5 and WMAP3 are 0.69 and 0.734, respectively. In Figure 4, we show \( P^+ / P^- \) values of WMAP data and cumulative distribution of \( P^+ / P^- \) for \( 10^4 \) simulated maps.

We have also estimated \( p \)-value, using whole-sky simulation (i.e., no mask), and obtained it as 0.0024. The difference from the cut-sky result is attributed to the increased statistical fluctuation in cut-sky \( C_l \) estimation. By using whole-sky simulations, we have also investigated \( p \)-value for \( l_{\text{max}} \gg 23 \), but have not found the statistical significance as high as \( l_{\text{max}} = 18 \).
3. DISCUSSION

In the previous study (Land & Magueijo 2005b), the parity asymmetry under point reflection as well as mirror reflection was noted, but point parity was not given enough attention, since they found the statistical significance was not high. Investigating the WMAP power spectrum with a slightly different estimator, we found the odd-parity preference of the WMAP data \((2 \leq l \leq 18)\) at 99.6% level (mask) and at 99.76% level (no mask). Higher parity asymmetry in WMAP data indicates that WMAP systematics is unlikely to be the source for the parity asymmetry. However, we do not completely rule out non-cosmological origins, and defer a rigorous investigation on cosmological or non-cosmological origin to a separate publication.

One may attribute low \(P^+ / P^-\) of the WMAP data simply to low quadrupole power. However, as shown in Figure 3, the anomalous parity asymmetry (i.e., low \(p\)-value) persists over extended range of multipoles. Therefore, we find it rather likely that low quadrupole power is part of this parity asymmetry anomaly. It was also shown that hemispherical power asymmetry is much more anomalous at multipoles \((2 \leq l \leq 19)\) than multipoles \((20 \leq l \leq 40)\; (\text{Eriksen et al. 2004})\). Given all these circumstantial evidences, we find it likely that there exists an underlying common origin for the anomalies (e.g., hemispherical power asymmetry, low quadrupole power, and parity asymmetry), whether it may be cosmological or WMAP systematics.

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