Parity in Planck full-mission CMB temperature maps

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Introduction

Cosmological Principle

The universe is homogeneous and isotropic on a large distance scale, of the order of 100 Mega parsec.

One of the best probes is the CMB (Cosmic Microwave Background) which has been observed to be isotropic to one part in $10^5$.

What is CMB?
CMB ANISOTROPY

There exist many observations which suggest that the postulate is violated. Some of them are

Virgo alignment puzzle
(Oliveira-Costa et al 2003; Jain & Ralston 1999, 2004,; Jain et al. 2004; Samal etal 2008)

Optical polarizations
(Hutsemekers 1998; Hutsemekers & Lamy 2001)

Hemispherical power asymmetry
(Eriksen et al. 2004; Prunet et al. 2005; Hansen et al. 2009; Hanson & Lewis 2009; Hofuft et al. 2009; Rath & Jain 2013; Akrami et al. 2014; Aiola et al. 2015; Rath et al. 2015)

Region of significant temperature decrement (cold spot)
(Vielva et al. 2004; Cruz et al. 2005, 2006, 2008; Zhao 2013; Nadathur et al. 2014; Aluri & Rath 2016)

Parity asymmetry
(Land & Magueijo 2005; Kim & Naselsky 2010, 2011; Aluri & Jain 2012; Zhao 2014; Aluri et al. 2017)
Focusing on odd power excess in CMB angular power spectrum,

CMB anisotropies are conventionally expanded in terms of spherical harmonics as

$$\Delta T(\hat{n}) = \sum_{l=2}^{\infty} \sum_{m=-1}^{l} a_{lm} Y_{lm}(\hat{n})$$

Here $\Delta T(\hat{n})$ are the fluctuations in CMB temperature anisotropies around the mean sky temperature.

$a_{lm}$ are the coefficients of expansion in the spherical harmonic basis $Y_{lm}(\hat{n})$.

Under inversion i.e. $\hat{n} \rightarrow -\hat{n}$, the spherical harmonic coefficients transform as

$$a_{lm} \rightarrow (-1)^l a_{lm}$$

Hence the maps

$$T^\pm = \frac{T(\hat{n}) \pm T(-\hat{n})}{2}$$

Contain only even and odd multipoles respectively.
The mean power i.e. $\sum_l C_l = \sum_m \frac{|a_{lm}|^2}{(2l+1)}$ can be decomposed as $C_l^+ + C_l^-$ and $C_l^\pm$ is the power in even and odd multipoles respectively.

Excess power in either of these modes will lead to an inversion parity symmetry/asymmetry preference in the data which is not expected in the standard cosmological model.

**Point Parity Asymmetry**

It is related to antipodal correlations of CMB sky (P. Naselsky 2012).

The two-point correlation function $C(\theta) = \langle \Delta T(\hat{n}) \Delta T(\hat{n}') \rangle$ is

$$C(\theta) = \sum_l \frac{2l+1}{4\pi} C_l P_l(\cos \theta)$$

Taking $\theta = \pi$, we have $C(\pi) = \sum_l (-1)^l \frac{2l+1}{4\pi} C_l = \sum_{l+} c_l^+ - \sum_{l-} c_l^-$

$c_l$ is normalized and $\sum_{l\pm} c_l^\pm$ is corresponding power in even/odd multipole.

The odd parity preference i.e., the excess power in odd multipoles compared to even multipoles in the data is evident by the negative correlation in the two-point correlation function.
Statistics Used

Point Parity Statistic

→ Using, (J. Kim et. al. (2010) & P.K. Aluri et. al. (2012)) statistics, i.e.

\[ P^{\pm}(l_{\text{max}}) = \frac{1}{N^{\pm}} \sum_{l=2}^{l_{\text{max}}} \frac{[1 \pm (-1)^{l}]}{2} D_l = \frac{p^{+}(l_{\text{max}})}{p^{-}(l_{\text{max}})} \]

Here

\( P^{\pm}(l_{\text{max}}) \) is the mean power in even/odd only multipoles upto \( l_{\text{max}} \).

\( D_l = l(l + 1)C_l/2\pi \) and \( N^{\pm} \) are the number of even/odd multipoles.

→ Using (P.K. Aluri et. al. (2012)) another statistic is defined as the average ratio of the power in adjacent even over odd multipoles up to a chosen maximum multipole.

\[ Q(l_{\text{odd}}) = \frac{2}{l_{\text{odd}} - 1} \sum_{l=3}^{l_{\text{odd}}} \frac{D_{l-1}}{D_l} \]
Mirror Parity Statistic

Mirror parity corresponds to reflection (a)symmetry with respect to a chosen plane.

It corresponds to the nature of the field, under the operation of

\((\theta, \varphi) \rightarrow (\pi - \theta, \varphi)\)

with respect to the \(z\)-axis with \(x\)-\(y\) plane acting as the mirror.

In harmonic space, modes with even or odd ‘\(l + m\)’ combinations correspond to mirror reflection (a)symmetry with respect to the equatorial plane of the chosen coordinate system in which the CMB map is represented.

Summarizing Mirror parity Statistics

\[
E_l = \frac{\langle |a_{lm}|^2 \rangle_{l+m=\text{even}}}{C_l^{\text{th}}}
\]

\[
O_l = \frac{\langle |a_{lm}|^2 \rangle_{l+m=\text{odd}}}{C_l^{\text{th}}}
\]

\[
R_l = \frac{\langle |a_{lm}|^2 \rangle_{l+m=\text{even}}}{\langle |a_{lm}|^2 \rangle_{l+m=\text{odd}}}
\]

\[
D_l = \frac{\langle |a_{lm}|^2 \rangle_{l+m=\text{even}} - \langle |a_{lm}|^2 \rangle_{l+m=\text{odd}}}{C_l^{\text{th}}}
\]
Data Used

Out of four foreground reduced CMB Temperature maps, we study only the *SMICA* map provided by the Planck 2015 collaboration.

Two masks viz. the **UT78 common analysis mask** and **Smica mask** is used to omit foreground residual.

To study the mirror parity (a)symmetry, we apply an *inpainting* method, which can be thought of as a 2D interpolation on the sphere.

The $a_{lm}$’s are extracted from the inpainted/pseudo full-sky SMICA CMB map, and tested for even/odd/no mirror parity preference in the data.

We only apply inpainting on the data maps. These masked, inpainted maps are used to assess point parity preferences in the data i.e., we use $C_l$ obtained from these inpainted (pseudo) full-sky CMB maps.
The significance of our parity statistics is estimated by comparing the data estimated values with 1000 simulated CMB maps added with appropriate noise. The random CMB realizations were generated as follows:

- We first generate the best-fitting theoretical angular power spectrum ($C_l$) using Planck 2015 best-fit cosmological parameters as input to CAMB software.

- Using these theoretical $C_l$, we generated 1000 random CMB realizations with a beam resolution of a Gaussian beam of $FWHM = 5$ (arcmin).

- Each of these CMB maps are then added with 1000 SMICA-like noise realization obtained from Planck PR2.
Cleaned SMICA map provided by Planck team having $N_{\text{side}} = 2048$
All maps are in $N_{\text{side}} = 2048$.

**UT78 common temperature mask**

**SMICA component separation specific mask**
Inpainted SMICA map masked with UT78 mask.

Inpainted SMICA map masked with SMICA mask.

All maps are in $N_{\text{side}} = 2048$. 
The even-odd multipole power asymmetry in the SMICA temperature map in the multipole range $l = [2, 101]$ . The asymmetry is computed using both the $P(l_{max})$ (Left) and $Q(l_{odd})$ (Right) statistics. Each panel has three data curves corresponding to the cleaned SMICA map as provided by Planck collaboration (blue), inpainted SMICA map after masking with UT78 mask (maroon), and inpainted SMICA CMB map after masking with SMICA component separation specific mask (orange).
\( p \)-value estimates of parity asymmetry in data as quantified by the statistics \( P(l_{\text{max}}) \) and \( Q(l_{\text{odd}}) \) used in our study. This plot is organized and color coded in the same way as previous figure. The data statistic values were compared with 1000 simulations to compute these \( p \)-values.
Mirror Parity and its Significance
The values of mirror parity statistics $E_l, O_l, R_l$ and $D_l$ computed from data are shown. Each panel has the statistic value computed for each harmonic mode, $l$, of SMICA map as is provided (green), inpainted SMICA map after applying UT78 mask (red), and inpainted SMICA map after applying SMICA mask (blue). The horizontal solid gray line in each panel is the theoretically expected value for the statistic at each multipole.
$p$-value estimates of mirror parity statistics $E_l, O_l, R_l$ and $D_l$ are shown here for each harmonic mode, $l$, of SMICA map (green), inpainted SMICA map after applying UT78 mask (red), and inpainted SMICA map after applying SMICA procedure specific confidence mask (blue) in each panel.
Conclusions

The objective of our work was to probe point and mirror parity (a)symmetry preferences with standard model expectations in the CMB data from Planck. Appropriate statistics were used to probe any presence of these (a)symmetries.

- The data is expected to show no preference for odd over even point or mirror parity and vice versa.

- An odd point parity preference i.e., more power in odd multipoles compared to even multipoles, is found to persist even in the Planck full-mission data.

- Both the statistics, become maximally anomalous for the multipole range $\approx [2, 29]$. The statistic values and their significances show the same pattern and level as found previously (in P.K Aluri, 2012) using WMAP data.

- We then studied the full-mission SMICA CMB temperature map for the presence of any mirror parity preferences in the data. We find no significant even or odd mirror parity preferences in the data at most multipoles $l$. Thus with respect to the galactic plane, the SMICA CMB map from Planck PR2 doesn’t display a statistically significant mirror parity (a)symmetry.
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Thank You!