Systematic Distortion in Cosmic Microwave Background Maps

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ABSTRACT

To minimize instrumentally induced systematic errors, cosmic microwave background (CMB) anisotropy experiments measure temperature differences across the sky using pairs of horn antennas, temperature maps are recovered from temperature differences obtained in sky survey through a map-making procedure. To inspect and calibrate residual systematic errors in recovered temperature maps is important as most previous studies of cosmology are based on these maps. By analyzing pixel-ring coupling and latitude dependence of CMB temperatures, we find notable systematic deviation from CMB Gaussianity in released Wilkinson Microwave Anisotropy Probe (WMAP) maps. The detected deviation can not be explained by the best-fit ΛCDM cosmological model at a confidence level above 99% and can not be ignored for a precision cosmology study.

Subject headings: Cosmology: cosmic microwave background - Methods: data analysis

1. Introduction: differential observation and scan-ring

To minimize instrumentally induced systematic errors, the WMAP mission measures temperature differences across the sky using pairs of horn antennas with a fixed separation angle \(\theta\), temperature maps are recovered from raw time-ordered temperature differences obtained in sky survey with a map-making algorithm\(^[1]\). When an antenna points to a sky pixel \(i\), the scan path of the other one will draw a ring \(R_{\theta}(i)\) in the sky with angular radius \(\theta\) to the center pixel \(i\). The map temperature \(t(i)\) of a pixel \(i\) should be in some extent correlated to measured temperatures in its scan-ring \(R_{\theta}(i)\) through the map-making procedure. The beam separation angle of WMAP radiometers is \(\theta \sim 141^\circ\). The off-diagonal

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terms of noise covariance matrixes have been inspected by the WMAP team with two-point correlation functions and small positive blips of order 0.3% of the diagonal elements have been found at 141° pixel separation angle\(^{[2,3]}\).

Instead of the pixel-pixel noise coupling, in this work we inspect the pixel-ring temperature coupling, and find in released WMAP CMB maps that notable temperature distortions exist on scan-rings of hot foreground sources: scan-rings of hot sources are significantly cooled (presented in §2) and strongest anti-correlations between pixel and scan-ring temperatures appear at a separation angle \(\theta \sim 141°\) (§3). In §4 we find a systematic deviation from CMB isotropy in Galactic latitude distributions of released WMAP maps, which can be understood by pixel-ring temperature coupling found in §2 and §3. Finally we give a brief discussion in §5.

2. Cold scan-rings of hot sources

We choose 2000 brightest pixels that are close to the galactic plane from five year WMAP (WMAP5) intensity maps\(^{[4]}\) with HEALPix resolution parameter \(N_{side} = 512\)\(^{[5]}\) and almost the same for different bands, and draw their scan-rings of 0.5° width, shown in Fig. 2. The Kp0 mask is used to exclude bright galactic sources. All the scan-rings in Fig. 2 form a sample (shortened as “sample 1” henceforth) that covers about 15% of the entire celestial sphere. Generally speaking, sample 1 is large enough to merge most CMB anisotropy and the expectation of average temperature should be very close to zero.

For the WMAP5 Q-, V- and W- band foreground-reduced maps and ILC map\(^{[6]}\) we calculate the average temperature of sample 1 (“ring temperature” hereafter) respectively. The results are listed in Table 1. To estimate their significances we simulate observed

![Fig. 1.— The scan-rings of 2000 hottest pixels in the Q-band WMAP5 map in Galactic coordinates after using the Kp0 mask. The ring width is 0.5°.](image)
CMB temperature maps with the synfast program in HEALPix software package (available at [http://healpix.jpl.nasa.gov](http://healpix.jpl.nasa.gov)) from the best fit ΛCDM model power spectrum with proper beam function and noise property. For each input map, 1000 simulated maps are created and their ring temperatures calculated. The average ring temperature and its standard deviation is shown in the bottom row of Table 1 for each input map. From this table we can see that, for the four maps the ring temperatures are all notably lower than the expectation with a confidence level higher than 99%. With these results, it is obvious that map temperatures on scan-rings of hot sources suffer systematical distortion, and the observed violence to CMB Gaussianity should come, at least partially, from the combined effect of hot foreground sources and WMAP’s differential nature.

We have also rotated WMAP5 ILC temperature map (by rotating the north pole to other pixels) to place sample 1 to other locations and compute the new average temperatures. The original sample 1 is known to be abnormal; therefore it is excluded together with the KP0 foreground mask. The objective of this test is to check the variances given in Table 1 with the original map, and the result should be close to simulation; otherwise the simulation is suspicious. The north pole of WMAP5 ILC map is rotated to all 3072 sky pixels in HEALPix resolution \( N_{\text{side}} = 16 \) and the expectation and RMS fluctuation of the average temperature of sample 1 are \(-0.5\ \mu\text{K}\) and \(4.3\ \mu\text{K}\) respectively. This is consistent with Table 1; therefore, the simulation and Table 1 are reliable.

3. Pixel-ring temperature coupling

We use \( t_R(i, \theta) \) to denote the average temperature over the scan ring of a pixel \( i \) with a separation angle \( \theta \), i.e. \( t_R(i, \theta) = \langle t(k) \rangle \) where \( k \in R_\theta(i) \). For a temperature map with \( N_{\text{side}} = 128 \), we calculate the cross-correlation coefficient \( C(\theta) \) between \( t(i) \) and \( t_R(i, \theta) \) for a designed separation angle \( \theta \)

\[
C(\theta) = \frac{\sum_i (t(i) - \bar{t})(t_R(i, \theta) - \bar{t}_R)}{\sqrt{\sum_i (t(i) - \bar{t})^2(t_R(i, \theta) - \bar{t}_R)^2}}.
\]

Table 1: Temperatures (\( \mu\text{K} \)) averaged over scan-rings of hot sources

|               | Q-band  | V-band  | W-band  | ILC map |
|---------------|---------|---------|---------|---------|
| WMAP5         | -11.67  | -12.62  | -12.92  | -11.34  |
| Simulation    | 0.09 ± 4.7 | -0.09 ± 4.7 | 0.09 ± 4.8 | 0.04 ± 4.4 |
| Significance  | 2.5\sigma | 2.7\sigma | 2.7\sigma | 2.7\sigma |
Fig. 2.— Separation angle dependence of pixel-ring temperature correlation. The vertical coordinate shows the correlation coefficient between temperature $t(i)$ of pixel $i$ and average temperature $t_R(i, \theta)$ of the ring with separation angle $\theta$ to $i$. The abscissa marks the separation angle $\theta$ in degree. Filled square: pixel $i$ only within the foreground mask Kp12. Square: for whole sky. Triangle: for the sky region out of the mask Kp0. Top panel: WMAP5 Q-band. Middle panel: WMAP5 V-band. Bottom panel: WMAP5 W-band.
First, we limit pixel $i$ only within the region of foreground mask Kp12 where contain hottest foreground sources and calculate $C(\theta)$ at different $\theta$ and for WMAP5 Q, V and W band maps separately. The obtained correlation distributions are shown by filled squares in Fig. 2, where the strongest negative correlation appear around $141^\circ$ separation for each band. The separation angle dependence of pixel-ring temperature correlation is also obtained from the WMAP5 ILC map, which is similar with what from the WMAP5 Q, V and W band maps shown in Fig. 2. The correlation coefficients at $141^\circ$ separation, $C(\theta = 141^\circ)$, from WMAP5 Q-, V- and W-band maps are listed in Table 2. The bottom row of Table 2 comes from 1000 simulations for each band. The foreground emission maps\cite{6} have to be used in the simulation calculation because we need the original recovered temperatures (without foreground reduction) for $t(i)$, which is the reason that we do not give the result for ILC map in Table 2 (ILC map does not have corresponding foreground emission map). From Table 2 we can see that the negative correlation at $\theta = 141^\circ$ has a significance from $2.2\sigma$ to $3.9\sigma$.

In the sky region out of the Galaxy plane (out of Kp0 mask) the correlation dip around the $141^\circ$ separation almost completely disappear (shown by triangles in Fig. 2), indicating again that the detected correlation structure is most possibly a combined effect of WMAP differential observation and Galactic hot emission. The broad feature of the correlation dip around the $141^\circ$ separation can be caused by finite width and noncircular response of instrument beam, structure of hot emission regions, and diffusion of temperature distortion in map-making process. The anti-correlation between temperatures of Galactic plane and its $141^\circ$ scan-rings is consistent with the detected fact that $141^\circ$ scan-rings of hot sources being cold (shown in §2).

Since the noise in WMAP temperature maps is known to be correlated at $141^\circ$\cite{2,3}, it is necessary to check pixel-ring correlation with the same noise maps they used (e.g., Q1-Q2, V1-V2). The pixel-ring correlation inside KP12 mask is computed for both bands V1 & V2, and compared with the result from noise map (V1-V2). As we expect, the V1 and V2 results are very close to the V-band result in Fig. 2; however, in the noise map result, the pixel-ring

|          | Q-band   | V-band   | W-band   |
|----------|----------|----------|----------|
| WMAP5    | -0.234   | -0.223   | -0.262   |
| Simulation | $0.001 \pm 0.106$ | $-0.001 \pm 0.101$ | $-0.002 \pm 0.066$ |
| Significance | $2.2\sigma$ | $2.2\sigma$ | $3.9\sigma$ |
correlation coefficients go to nearly 0. Therefore, the pixel-ring correlation is unaffected by known 141° noise correlation.

4. Latitude dependence of CMB temperatures

The four graphs in Fig. 3 show the Galactic latitude dependence of average temperature $\langle t \rangle$ from the foreground cleaned WMAP5 Q-, V-, W-band maps and ILC map respectively, where for $|b| = 85^\circ$, $\langle t \rangle$ is calculated over the two regions $\pm(80^\circ, 90^\circ)$, and for $|b| < 80^\circ$ over $\pm(|b| - 2.5^\circ, |b| + 2.5^\circ)$. From Fig. 3 we can see systematic distortions existing in WMAP foreground cleaned maps evidently. The relationships of average temperature vs. Galactic latitude in the four WMAP maps are highly consistent: all maps have $\langle t \rangle < 0$ for the nine latitude intervals in $10^\circ < |b| < 55^\circ$ (listed in Table 3), and, contrarily, $\langle t \rangle > 0$ for the region of $|b| > 55^\circ$. That the turning at $|b| \sim 55^\circ$ and the negativity of WMAP CMB maps in $|b| < 55^\circ$ can be understood by the detected cooling effect of hot sources on their scan-rings (shown in §2 ans §3) with the fact that most of 141° rings of Galactic hot sources are contained in the region of $|b| < 55^\circ$ as shown by Fig. 1.

5. Discussion

The magnitude of temperature distortion of the hottest Galactic sources upon their scan-rings can be estimated to be $> 10\mu K$ from Table 1 (the corresponding region covers about 15% of the entire celestial sphere after removing KP0 mask region), and the average distortion for the region of $|b| < 55^\circ$ to be $\sim 5\mu K$ from Table 4 (the corresponding region covers > 80% of the entire celestial sphere or > 60% after removing KP0 mask region). Such a wide-spread effect with considerable strength can not be ignored for a precise cosmology study and need to be further investigated.

Table 3: Average temperatures $\langle t \rangle$ ($\mu K$) over Galactic latitude regions $|b| \pm 2.5^\circ$

| $|b|$ (deg) | 12.5 | 17.5 | 22.5 | 27.5 | 32.5 | 37.5 | 42.5 | 47.5 | 52.5 |
|-----------|------|------|------|------|------|------|------|------|------|
| Q band    | -3.4 | -1.2 | -4.2 | -4.0 | -5.7 | -6.3 | -7.6 | -4.2 | -3.8 |
| V band    | -4.4 | -1.9 | -5.2 | -4.3 | -5.2 | -6.3 | -7.8 | -4.1 | -3.5 |
| W band    | -4.9 | -2.6 | -5.7 | -4.5 | -6.7 | -6.1 | -7.7 | -4.0 | -3.1 |
| ILC map   | -3.8 | -1.8 | -4.9 | -3.8 | -5.0 | -5.0 | -6.7 | -3.0 | -1.7 |
Fig. 3.— Average temperature vs. absolute Galactic latitude in WMAP5 maps with the Kp0 mask, from top to bottom for Q, V, W band and ILC map respectively. The standard deviations of average temperatures are shown in the graphs, they are small and hard to be recognized.

Table 4: Average temperatures of foreground-cleaned WMAP5 maps over 10° < |b| < 55°

| Map       | Q-band (µK) | V-band (µK) | W-band (µK) | ILC (µK) |
|-----------|-------------|-------------|-------------|----------|
| Simulation| 0.05 ± 2.1  | 0.03 ± 2.2  | -0.02 ± 2.4 | 0.01 ± 2.0 |
| Significance| 2.2σ     | 2.3σ        | 2.2σ        | 2.1σ     |
The detected large scale distortion from CMB Gaussianity is closely connected with the Galactic hot sources and the WMAP beam separation angle, which is hard to explain by the best-fit ΛCDM cosmological model and most possibly comes from foreground effect and map-making. To mitigate errors produced by effects from the hot foreground sources, the WMAP team used the Kp8 mask as a ”processing mask” during the map-making process[2,7]. However, the detected temperature coupling between hot sources and their scan-rings indicates that the Kp8 mask might be not wide enough to exclude all unwanted effect in the map-making process, a broader mask, e.g. Kp0, might be better. The future CMB observation project Planck is designed to measure the CMB anisotropy with completely different mode to WMAP, therefore, it is expected to be totally unaffected by such distortion.

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