SIGNIFICANT FOREGROUND UNRELATED NON-ACOUSTIC ANISOTROPY ON THE 1 DEGREE SCALE IN WILKINSON MICROWAVE ANISOTROPY PROBE 5-YEAR OBSERVATIONS

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Received 2009 May 26; accepted 2009 November 3; published 2009 December 11

ABSTRACT

The spectral variation of the cosmic microwave background (CMB) as observed by WMAP was tested using foreground reduced WMAP data, by producing subtraction maps at the 1° angular resolution between the two cosmological bands of V and W, for masked sky areas that avoid the Galactic disk. The resulting V−W map revealed a non-acoustic signal over and above the WMAP pixel noise, with two main properties. First, it possesses quadrupole power at the ≈1 μK level which may be attributed to foreground residuals. Second, it fluctuates also at all values of ℓ > 2, especially on the 1° scale (200 ≲ ℓ ≲ 300). The behavior is random and symmetrical about zero temperature with an rms ≲7 μK, or 10% of the maximum CMB anisotropy, which would require a “cosmic conspiracy” among the foreground components if it is a consequence of their existence. Both anomalies must be properly diagnosed and corrected if “precision” cosmology is the claim. The second anomaly is, however, more interesting because it opens the question on whether the CMB anisotropy genuinely represents primordial density seeds.

Key words: cosmic microwave background – ISM: clouds – methods: data analysis

Online-only material: color figure

1. INTRODUCTION

Studies of the cosmic microwave background (CMB; Penzias & Wilson 1965), the afterglow radiation of the big bang, are currently in a period of renaissance after the breakthrough discovery of anisotropy by the COBE mission (Smoot et al. 1992). Confirmed with much improved resolution and statistics by WMAP (Hinshaw et al. 2009), the phenomenon provides vital information on the primordial “seeds” of structure formation. The anisotropy is attributed to frequency shift of CMB light induced by these “seed” density perturbations, which has the unique property that it leads to changes in the temperature of the blackbody spectrum and not the shape of it. The CMB has maximum anisotropy power at the 1° scale, or harmonic number ℓ ≈ 220, with lower amplitude secondary and tertiary peaks at higher ℓ.

The ΛCDM cosmological model (Spergel et al. 2007) explains the entire power spectrum remarkably using six parameters, by attributing the peaks to acoustic oscillations of baryon and dark matter fluids, as long wavelength modes of density contrast enter the horizon and undergo causal physical evolution. The anisotropy is attributed to frequency shift of CMB light with no accompanying distortion of the functional form of B itself, the expected δB at constant δT is then the “dipole spectrum” ∂B/∂T which is well measured by COBE–FIRAS (Mather et al. 1994). Moreover, the WMAP data are calibrated with respect to this dipole response.

A noteworthy point about the acoustic peaks is that one needs to employ the technique of cross correlation to reduce the noise contamination at high ℓ, especially the harmonics of the second and higher acoustic peaks. Specifically, one computes the all-sky cross power spectrum

\[ C_{l}^{ij} = \frac{1}{2l+1} \sum_{m} a_{lm}^i a_{lm}^j \quad (1) \]

where the indices i and j denote independent data streams with uncorrelated noise that arise from a pair of maps at different frequency bands (or same band but taken at different times), and \( a_{lm}^i = \delta T_{lm}^i \) is the apparent CMB temperature anisotropy for the spherical harmonics (ℓ, m) as recorded by observation i. Since the use of multiple passbands is crucial to the accurate profiling of the acoustic oscillations, it is important that we do compare them with care, down to the level of measurement uncertainties. Only a priori statistically consistent maps should be cross correlated, in the sense that any real discrepancies between such maps may carry vital information about new physical processes that their cross power spectrum does not reveal. In one previous attempt to address this point (see Figure 9 of Bennett et al. 2003a), WMAP1 data downgraded to an angular resolution commensurate with COBE were used to produce a difference (subtraction) map between the two missions. When displayed side by side with the map of the expected noise for each resulting pixel, the two maps did appear consistent. Nevertheless, this powerful method of probing the CMB anisotropy does, in the context of the specific data sets used by Bennett et al. (2003a), suffer from one setback: it is limited by the sensitivity and resolution of COBE.

In another test of a similar kind, we observe that each amplitude \( a_{lm}^i \) can further be factorized as \( a_{lm}^i = a_{lm} b_{l}^i \), where
the array $b^i_j$, accounts for the smoothing effects of both the beam and the finite sky map pixel size, and $a_{lm} = \delta T_{lm}$ is the true amplitude of the CMB anisotropy. The results (see Figure 13 of Hinshaw et al. 2007) indicate agreement of the variance $C_{ij}^{(ij)}$, hence $\delta T_\ell$, within the margin of a few percent for $\ell \lesssim 400$ among the many cross power spectra formed by the various possible combinations of pairs of all-sky maps. This offers more ground for optimism, but to be definitive the remaining discrepancy needs to be demonstrably attributed to noise, instrumental systematics, or foreground emission.

The purpose of our investigation is to perform further, more revealing comparisons than the two past ones described above, initially by focusing upon the angular scale of the first acoustic peak, which is $\sim 1^\circ$. Our analysis will be done in both real (angular) and harmonic domains, because while most of the effort has hitherto been pursued in the latter, the former is the domain in which the raw data were acquired and organized.

### 2. THE ALL_SKY DIFFERENCE MAP BETWEEN THE WMAP V AND W BANDS

We adopted the Healpix pixelization scheme to ensure that all pixels across the sky have the same area (or solid angle). First, the W band data are smoothed to the $W$ band resolution. Then the whole sky map is downgraded to $\approx 1^\circ$ diameter (corresponding to $n_{side}$ of 64 in the parameterization of the WMAP database), which is not only commensurate with the scale of global maximum $\delta T$ power, but also large enough to prevent data oversampling due to the use of too high resolution, as the size is comfortably bigger than the beam width of the WMAP $V$ band (61 GHz) larger than that of the $W$ band.

The resulting $\delta T$ values for the two cosmological passbands of $V$ and $W$ span $\approx 35,000$ clean (i.e., $\text{ext}$-masked$^5$ and foreground subtracted$^5$) pixels, from which a $V - W$ difference map at this $\approx 1^\circ$ resolution was made. After removing the monopole and dipole residuals (the latter aligned with the original COBE dipole), this map is displayed in Figure 1 along with the corresponding pixel noise map for reference; the latter represents the expected appearance of the $V - W$ map if the CMB anisotropy is genuinely acoustic in nature, so that the map would consist only of null pixels should the WMAP instruments that acquired them be completely noise free. When comparing the real data map of Figure 1(a) with the simulated map of Figure 1(b), the former appears visibly noiser on the resolution scale $\approx 1^\circ$; moreover, the Leo and Aquarius (i.e., the first and third) sky quadrants contain more cold pixels than the other half of the sky, indicative of the existence of a quadrupole residual.

The extra signals revealed by the $V - W$ subtraction map are elucidated further in respect of their aforementioned properties by examining the statistical distribution of the pixel values across the four sky quadrants. As shown in Figure 2, the distribution of the $1^\circ$ anisotropy is considerably wider than that expected from the WMAP5 pixel noise for all the quadrants, by $\approx 10\mu$K, which is $\sim 10\%$ of the $\approx 75\mu$K power in the first acoustic peak, and is therefore very significant. A detailed confirmation by Gaussian curve fitting is given in Table 1.

The $V - W$ quadrupole is more subtle, and is evident in the residual plots at the bottom of each graph in Figure 2, from which a slight skewness of the data to the right is apparent in quadrants 1 and 3 (the quadrants of the CMB dipole), with 2 and 4 exhibiting the opposite behavior. For this reason, the effect does not manifest itself as shifts in the Gaussian mean value $\mu$ of Table 1. Rather, the high statistical significance of both the quadrupole and the degree-scale signals, with the former having a magnitude of $\approx 1\mu$K, are established by computing the cross power spectra of the temperature difference maps (Figure 4). This was performed at the resolution of $n_{side} = 64$ using the PolSpice software.$^8$

**Figure 1.** ext-masked and point source subtracted WMAPS V−W map, viz., the difference map between the CMB anisotropy as measured in the $V$ band and the $W$ band, for the real data after the removal of residual monopole and dipole components (top), and simulated pixel noise that reflect precisely the observational condition (bottom). Both maps are plotted in Galactic coordinates with the Galactic center ($l, b$) = (0, 0) in the middle and Galactic longitude $l$ increasing to the left. To avoid the problems of beam size variation from one band to the next, the $W$ band data are smoothed to the $V$ band resolution, then the pixels were downgraded to the common resolution of $n_{side} = 64$ using the foreground-reduced WMAPS data (see Section 2); this resolution undersamples the data in both bands. The color scale is coded within a symmetrical range: those pixels with values beyond $\pm 40 \mu$K are displayed in the same (extreme) color; most of such pixels are around the masked regions. The existence of additional non-blackbody signal in the real data can readily be seen from this comparison, as the simulated map is noticeably quieter.

\[ \delta T(\theta, \phi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta, \phi), \]  

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$^5$ See http://healpix.jpl.nasa.gov.$^6$

$^7$ ext is short for external temperature analysis.

$^8$ Available from http://www.planck.fr/article141.html.
Figure 2. Data points show quadrant sky occurrence frequency distribution of the difference in the degree-scale \( n_{\text{side}} = 64 \) anisotropy between the WMAP5 V and W bands, while the errors in the data are due to the WMAP5 pixel noise for the same ext-masked quadrant sky area, i.e., they are the statistical fluctuations in the various parts of the solid line, which gives the mean histogram of this noise. The orientation of each quadrant follows the same convention as the sky maps of Figure 1, with the 1st and 3rd quadrants marking the COBE dipole.

Table 1

Parameters for the Gaussian Curves that Fitted the WMAP5 Data and the Pixel Noise Histograms (The Latter are the Solid Lines) of Figure 2

| Quadrant | Simulation | WMAP5 | Difference | Simulation | WMAP5 | Difference | Simulation | WMAP5 | Difference | Simulation | WMAP5 | Difference |
|----------|------------|-------|------------|------------|-------|------------|------------|-------|------------|------------|-------|------------|
| 1        | 0.00       | 0.23  | 0.15       | 0.00       | 0.11  | 0.12       | 0.00       | 0.11  | 0.12       | 0.00       | 0.11  | 0.12       |
| 2        | -0.04      | 0.24  | 0.12       | -0.04      | 0.11  | 0.12       | -0.04      | 0.11  | 0.12       | -0.04      | 0.11  | 0.12       |
| 3        | 0.03       | -0.11 | 0.16       | 0.03       | -0.14 | 0.16       | 0.03       | -0.14 | 0.16       | 0.03       | -0.14 | 0.16       |
| 4        | -0.01      | 0.40  | 0.13       | -0.01      | 0.40  | 0.13       | -0.01      | 0.40  | 0.13       | -0.01      | 0.40  | 0.13       |

Notes. Each parameter uncertainty is set by the \( \chi^2_{\text{min}} + 1 \) criterion, which represents the usual 68% (or unit standard deviation) confidence interval for one interesting parameter, when the error bars shown in Figure 2, are employed for fitting both the real and pixel noise data. The difference in the width \( \sigma \) between the two models, which gives the distribution width of the additional random signal, is given by \( (\Delta \sigma)^2 = \sigma_r^2 - \sigma_s^2 \). The smaller simulated Gaussian widths for quadrants 2 and 4 (relative to 1 and 3) are due to the higher exposure times there (which contain the heavily scanned ecliptic poles) leading to lower pixel noise.

Table 2

Orientation of the Quadrupole in the WMAP5 V − W Map of Figure 3

| Hot/Cold | V − W Quadrupole Location (\( l, b \)) |
|----------|----------------------------------------|
| Hot      | (-132.1, -14.4), (48.0, 14.4)          |
| Cold     | (-81.5, 68.0), (98.5, -68.0)           |

and evaluating at \( \ell = 2 \) the amplitude

\[
\delta T_\ell(\theta, \phi) = \sum_m a_{\ell m} Y_{\ell m}(\theta, \phi),
\]

(note \( \delta T_\ell(\theta, \phi) \) is always a real number if the original data \( \delta T(\theta, \phi) \) are real). The ensuing whole sky map is in Figure 3, and the coordinates of the axes are in Table 2.

3. INTERPRETATION OF RESULTS

The WMAP5 V − W map reveals two principal anomalies to be explained: (1) the quadrupole at \( \ell = 2 \), with an amplitude of \( \approx 1 \ \mu K \) and (2) the higher harmonic signals, especially the \( \approx 8 \ \mu K \) anisotropy at \( \ell \gtrsim 200 \) (Figure 4). Similar findings are also made by others, like the noticeable hemispherical power asymmetry in the WMAP1 analysis of Eriksen et al. (2004) and confirmed in the WMAP5 data by Hoftuft et al. (2009),
Figure 3. $V-W$ quadrupole of the $n_{side} = 64$ WMAP5 temperature difference maps, after ext-masking and point source subtraction. The mathematical procedure of extracting each multipole $\ell$ is given in Equations (3) and (4), and the software used to do these computations was from anafast of Healpix. (A color version of this figure is available in the online journal.)

or the large scale distribution investigated by Diego et al. (2009). Also because both (1) and (2) are not small effects, claims to precision cosmology are overstatements until they are properly accounted for and the cosmological model accordingly adjusted.

Concerning (1), unlike the dipole, there is no previous known CMB quadrupole of sufficient amplitude to justify its dismissal as a cross band calibration residual. In fact, our reported amplitude of $1 \mu K$ is about 7% of the $211 \mu K^2$ WMAP5 anisotropy in the unsubtracted maps of the individual bands at $\ell = 2$, which is far larger than the calibration uncertainty of $\approx 0.5\%$ (Hinshaw et al. 2009) for each band.

It will probably be more rewarding to search for remaining foreground contamination not yet removed by the standard data filtering and correction procedures of the WMAP5 team (Bennett et al. 2003b; Gold et al. 2009). Thermal dust emission might have a power-law spectrum with an index too close to that of the Rayleigh–Jeans tail in the $V$ and $W$ bands for an appreciable $V-W$ signal, although this is an interesting scenario worthy of further study (Diego et al. 2009). We consider here another possibility, viz., free–free emission from High Velocity Clouds (HVCs; Wakker et al. 2008 and references therein). The clouds are moving at velocities sufficiently large for any $H\alpha$ emission

Figure 4. Real and simulated (noise) power spectra of the WMAP5 $V-W$ map. These are $V-W$ cross power spectra computed by cross correlating the first three years of observations with the last two. The errors in the real data of the first two graphs represent the pixel noise power of the last graph; i.e., (c) is the average of 1000 simulated realizations of the $V-W$ WMAP5 pixel noise. Thus, if the noise power at harmonic $\ell$ is $(\delta T_{\ell})^2$ from (c), the upper error bar in (a) and (b) will extend from $T_{\ell}^2$ to $(T_{\ell} + \delta T_{\ell})^2$ where $T_{\ell}$ is the observed $V-W$ anisotropy of the real data point (given by the intersection of the error bars with the zig-zag line) in (a) and (b). The rising trend ($\sim \ell^2$) of all three curves toward higher $\ell$ simply reflects the relatively larger pixel noise for smaller angular areas. For $\ell > 200$ the real data of (a) and (b) rapidly become noise dominated.
Figure 5. Upper map shows 21 cm data of HVCs with H\textsubscript{i} column density ($N_{\text{H}i}$) larger than $7 \times 10^{18}$ cm\textsuperscript{-2} (i.e., the gray scale shows $N_{\text{H}i}$ with the outer contour at $7 \times 10^{18}$ cm\textsuperscript{-2}). Complex C is the cloud in the region $l = 90^\circ$–$130^\circ$, $b = 40^\circ$–$60^\circ$. Complex A is around $l = 150^\circ$, $b = 30^\circ$–$45^\circ$. The Magellanic Stream (MS) and Bridge are at $l = 280^\circ$–$310^\circ$, $b < -30^\circ$. The Leading Arm of the MS and some other bright HVCs are at $l = 240^\circ$–$300^\circ$, $b = 10^\circ$–$30^\circ$. Lower map gives our estimated $V - W$ temperature excess due to HVCs. Note that because the dynamic range of conversion from $N_{\text{H}i}$ to this excess (via free–free emission measure $EM$ of $N_{\text{H}ii}$) is not linear (e.g., Putman et al. 2003; Hill et al. 2009), our approach is to assign 0.5 and 1.0 units of $EM$, or $0.15$ and $0.3\, \mu K\, f$ of $V - W$ excess, to every direction with $N_{\text{H}i} \geq 2 \times 10^{19}$ cm\textsuperscript{-2} and $5 \times 10^{19}$ cm\textsuperscript{-2}, respectively.

from them to be outside the range\textsuperscript{9} of the WHAM survey, the database employed to estimate the free-free contribution to the WMAP foreground. HVC parameters for the larger and brighter clouds can reach $n_e \approx 0.2$ cm\textsuperscript{-3} and column density $\approx 3 \times 10^{19}$ cm\textsuperscript{-2} (Wakker et al. 2008). This corresponds to an emission measure of two units, or $6 \times 10^{18}$ cm\textsuperscript{-5}, or $\approx 0.6\, \mu K$ of $V - W$ temperature excess (Finkbeiner 2003), on par with the $1\, \mu K$ of our observed quadrupole. Moreover, as can be seen from the all-sky map of $N_{\text{H}i}$ and an estimate of the $V - W$ excess in Figure 5 when they are compared with Figures 3 and 4, the strength and distribution of HVCs do appear to be responsible for a non-negligible fraction of the observed anomaly on very large scales. Further work in this area is clearly necessary, and will be pursued in a future, separate paper.

We now turn to (2), the effect that occurs on the much smaller and cosmologically most significant angular scale of $1^\circ$. Calibration issues are again immediately excluded here, since the $8\, \mu K$
anomalous amplitude is on par with the pixel noise of WMAP5 for the scale in question (Table 1). Moreover, because the subtracted \( V - W \) dipole and the (unsubtracted) \( V - W \) quadrupole, the latter being (1), are both relatively feeble phenomena, of amplitudes \( \approx 0.2 \) and \( 1 \mu K \), respectively, as compared to the \( 7 \mu K \) amplitude of (2), the prospect of smaller scale fluctuations has been enhanced by a larger scale one can be ruled out here. CMB spectral distortion during the recombination era, or subsequently from the Sunyaev–Zeldovich (SZ) scattering, or from other foreground re-processing that were not properly compensated by the data cleaning procedure of WMAP5, could all be responsible for the observed anomaly. Although the first two interactions (Sunyaev & Chluba 2008; Birkinshaw & Gull 1983) exert much smaller influences than \( 7 \mu K \) (bearing in mind that the degree of SZ needs to be averaged over the scale of the whole sky), the foreground could potentially play a relevant role in a similar way as it did at very low \( \ell \). Thus, in respect of free–free emission by HVCs alone, until a full survey at high angular resolution is performed one cannot be certain that the emission measure from these clouds is too weak to account for our (2) anomaly. However, the action of the foreground is systematic in that it does not lead to random and symmetric temperature excitations (about zero) between two frequencies of \( V \) and \( W \). More precisely, because the sources or sinks involved have a characteristic spectrum that differs from blackbody in a specific way, any widening in Figure 2 of the data distribution with respect to the expected simulated Gaussian ought to be highly asymmetric. This obviously contradicts our findings, i.e., we note from Figure 2 that the widening of the data histogram is highly symmetric. As a result, the symptoms do not point to the foreground as responsible cause.

4. CONCLUSION

We performed a new way of testing the blackbody nature of the CMB degree scale anisotropy, by comparing the all-sky distribution of temperature difference between the WMAP5 cosmological bands of \( V \) and \( W \), with their expected pixel noise behavior taken fully into consideration by means of simulated data. In this way, a non-acoustic signal is found in the extracted \( V - W \) map at the \( \approx 1\sigma \) resolution of \( \text{side} = 64 \), with the following two properties. It has a quadrupole amplitude \( \approx 1 \mu K \) (Figures 2–4) which may in part be attributed to unsubtracted foreground emission. It also has excess anisotropy (or fluctuation) on all scales \( \ell > 2 \), including and especially the scales of 200 \( \lesssim \ell \lesssim 300 \) where most of the acoustic power resides, and about which the anomaly we reported is in the form of a symmetric random excursion about zero temperature with an rms \( \approx 8 \mu K \) (Figures 2 and 4, Table 1) which is \( \approx 10\% \) of the maximum acoustic amplitude found at \( \ell \approx 220 \). This type of excursion frustrates attempts to explain the effect as foreground residuals, i.e., it opens the question of whether the WMAP anisotropy on the \( 1^\circ \) scale is genuinely related to the seeds of structure formation.

In any case, it is clear that both anomalies have sufficiently large magnitudes to warrant their diagnoses through future, further investigations, if the status of precision cosmology is to be reinstated.

We are grateful to Jose Maria Diego for very valuable suggestions toward the improvement of this paper. Lyman Page, Priscilla Frisch, Gary Zank, and Barry Welsh are also acknowledged for helpful discussions. Some of the results were obtained by means of the HEALPix package (Górski et al. 2005).

Note added in Proof. Readers are alerted to the most recently available preprint by Sawangwit & Shanks (2009), which presented evidence for potentially very large systematic errors in the WMAP beam profile. Based on a stacking analysis of the WMAP radio source catalog and the temperature map, the authors reported significantly broader beam profile on scales on \( 10^\prime \)–30’’ than that used by the WMAP team, who did their calibration using measurements of Jupiter. If the wrong beams for the \( V \) and \( W \) band were employed by the standard software, this could account for the degree scale anomaly presented here. It could also be responsible for the near absence of the Sunyaev–Zel’dovich effect in the WMAP1 data (Lieu et al. 2006).

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