

# Systematical effects in WMAP data

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Received \_\_\_\_\_; accepted \_\_\_\_\_

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## ABSTRACT

Previously, by re-analyzing the Wilkinson Microwave Anisotropy Probe (WMAP) raw data, we have seen significantly different cosmic microwave background (CMB) results to the WMAP official release, especially at the largest-scale structure detectable for the CMB anisotropy - the  $l = 2$  component, which is also called the CMB quadrupole. In this article, we first introduce the discovered differences, and then explain why the WMAP official release should be questioned. Since the differences are caused by complex systematical effects, we also manage to organize the involved systematical effects to show their inter relations, so that we can see clearly what we are doing in each work, and what we need to do in future works.

*Subject headings:* cosmic microwave background – cosmology: observations – methods: data analysis

## 1. INTRODUCTION

The CMB anisotropy map detected by the WMAP mission is of great importance in understanding the birth and evolution of the Universe (Bennett et al. 2003). In order to detect the CMB anisotropy, the WMAP spacecraft works on the L2 point of the Sun-Earth system in the shade of the Earth, receiving the CMB signal with two antennas A and B separated by  $141^\circ$ . The spacecraft is designed to provide full-sky image of the CMB anisotropy, thus the way it scans the sky is rather complex: The spacecraft spins while it moves around the Sun synchronously with the Earth, the spin axis is close to the Sun-to-Earth axis, but they don't overlap: The spin axis continuously moves around the Sun-to-Earth axis, otherwise the area near the north and south poles of the ecliptic system won't be observed. Although the scan pattern is complex, the recorded datum is simply the difference between the signals received by the two antennas, which looks like  $D^i = T_A^i - T_B^i + etc$  (See Equ. 1 for details) The raw data are accumulation of  $D^i$ s in time order, thus it's called the time-order data (TOD) (Limon et al. 2008). The TOD is transformed into a CMB anisotropy map by map-making processes (Hinshaw et al. 2003a), and it's right here that the difference between us and WMAP begins.

The spacecraft works in differential mode, thus detection to the CMB isotropy component, the 2.73 K blackbody emission, is made impossible. This component is the largest-scale structure of CMB, also called the monopole, or  $l = 0$  spherical harmonic component, because we often use spherical harmonics to decompose the CMB anisotropy map. The  $l = 1$  spherical harmonic component is called the dipole component, representing a smaller-scale structure than  $l = 0$ . This component is also undeterminable because it's impossible to distinguish the real CMB dipole from the Doppler dipole signal caused by the solar system's motion towards the CMB rest frame. Therefore the largest-scale structure determinable is the  $l = 2$  component, called the CMB quadrupole. However, it has been discovered by the WMAP mission ever since the first data release (WMAP1) that the detected CMB quadrupole is only  $1/5 \sim 1/10$  of the expected

value by the  $\Lambda$ CDM model - the standard cosmology theory (Hinshaw et al. 2003b; Bennett et al. 2003). This is called the low- $l$  anomaly. Considering the uncertainty due to cosmic variance, the detected quadrupole value is roughly within  $1 \sim 2\sigma$ , which looks not very abnormal; however, this is a common misconception, because the quadrupole power can never be negative. In ordinary cases, when we get a value that is right  $1\sigma$  lower than the expected value  $E$ , the convention is to use the probability for the value being in range  $-\infty \sim E - \sigma$  as the probability of "nothing is abnormal"; however, for the CMB quadrupole, all values below zero are forbidden, thus the range for the probability estimation is  $0 \sim E - \sigma$ , not  $-\infty \sim E - \sigma$ , which gives a substantially lower probability. Especially, if the true CMB quadrupole is  $1/10$  as we believe now, then the probability for the claim "nothing abnormal for the CMB quadrupole" will also be roughly 10% as before. Therefore, the lower is the true quadrupole, the more attention should be paid to the possibility that either the WMAP data or the standard cosmology is in trouble.

It seems that the WMAP team choose to preserve both, and they have changed their CMB power spectrum estimation method for low- $l$  in their later releases from WMAP3 to WMAP7, so that they can obtain a litter bit higher quadrupole estimation. (Hinshaw et al. 2007; Nolta et al. 2009; Jarosik et al. 2010) Although this only slightly mitigates the low- $l$  anomaly, the advantage is that they don't have to introduce substantial modification to their CMB anisotropy maps. However, we have found out that there could be a potential error in processing the WMAP TOD. If the error does exist, then the true CMB quadrupole component in the CMB anisotropy map could be not higher but even lower than released by WMAP. As explained above, a even lower quadrupole value is a strong implication for another way out for the problem: We should be careful in claiming success of the standard cosmology.

In map-making, the first and most important thing is to determine the antenna pointing vectors. This is easy to understand: If we don't know the antenna pointing vectors accurately, then we don't know where are we actually observing. We have found out that, with a difference

as small as  $7'$  in the antenna pointing vectors (about half pixel), the derived CMB product could be significantly different (Liu & Li 2009b), and the new map seem to be better consistent to the TOD than the released WMAP CMB anisotropy map (Liu & Li 2010a). With these results, it's necessary to study further to find out more evidences about which is correct. In later work (Liu et al. 2010), we have discovered that, given the  $\sim 7'$  pointing vector difference, estimation of the true Doppler dipole signal  $d$  will be consequently different. Since the true Doppler dipole signal  $d$  must be removed from the original time-order data before using them to make a CMB temperature map, difference in estimating  $d$  will certainly leave something on the final CMB temperature map: Let the estimated Doppler dipole signal be  $d' = d - \Delta d$ , then after removing  $d'$  from the TOD,  $\Delta d$  will be left in the TOD as an unwanted contamination. Since mapmaking from TOD is very well linear, we can make an output map from  $\Delta d$  to get the unwanted component on the final CMB temperature aroused by  $\Delta d$  (which looks very similar to Fig. 2 left). It's amazing that the unwanted component aroused by  $\Delta d$  closely resembles the CMB quadrupole component claimed by WMAP (Fig. 2 right); however, there is definitely no CMB signal in  $\Delta d$ ! Thus it's quite reasonable to believe that the WMAP CMB quadrupole is largely artificial, and by this way the WMAP CMB results are strongly questioned. The above fact is also confirmed by Moss et al. (2010); Roukema (2010a). In Liu et al. (2010), we have also found out that the WMAP spacecraft attitude information (which determines the antenna pointing vectors) is not recorded synchronously with the signal difference  $D^i$ , which casts doubt on the antenna pointing estimation in WMAP mission. Such asynchronism can be seen directly by checking the TOD files, and it has also been confirmed by independent authors with different methods (Roukema 2010b; Liu & Li 2010c). Moreover, we have discovered that, even if the antenna pointing vectors are correctly calculated, there are other effects that can create an “equivalent” pointing error, which can work together with real pointing error to amplify the overall effect. In fact, the equivalent pointing error has a very high upper limit, thus it can also produce the entire WMAP CMB quadrupole alone (Liu & Li 2010b).

Since there are several inducements involved in the problem of the difference between our result and WMAP, and each inducement can affect several different aspects of the data processing, we manage to organize the involved systematical effects in this article, and put them into a clear uniform frame, by which we will be able to see clearly what has been solved in each old work, and what is still unknown and need to be done in future work, so as to bring a possible solution to the problem.

## 2. THE DIFFERENCE BETWEEN OUR RESULTS AND WMAP

The most often seen results of the WMAP mission are the CMB anisotropy map and the CMB power spectrum, as shown in Fig. 1. The CMB anisotropy map produced in our work looks very similar to the one in the WMAP release, but we can find out the difference between them by subtracting our map from the WMAP one, and smooth the difference to a lower resolution (Fig. 2, left). It's interesting that, by doing so, we will obtain a map that is almost same to the quadrupole plot of the released WMAP CMB quadrupole (Fig. 2, right). Since all spherical harmonics are linearly independent, this indicates that for the quadrupole components  $Q_w$  of WMAP and  $Q_{ll}$  of us, we have  $Q_w - Q_{ll} \sim Q_w$ , with which we immediately get  $Q_{ll} \sim 0$  without having to compute the CMB power spectrum. By computing the CMB power spectrum from our new maps, this has been confirmed and  $Q_{ll}$  is only about 20% of  $Q_w$  (Liu & Li 2009b). With later works, it's discovered that  $Q_{ll}$  could be as low as 8% of  $Q_w$ .

Not only the large scale, but also the small scale CMB power spectrum has been computed for our new CMB anisotropy maps, which is also lower than WMAP, as shown in Fig. 3, In this figure, the power spectrum estimating process has also been validated by the good consistency between the CMB power spectra derived by us and by the WMAP team from the same WMAP released maps (solid and dotted lines).

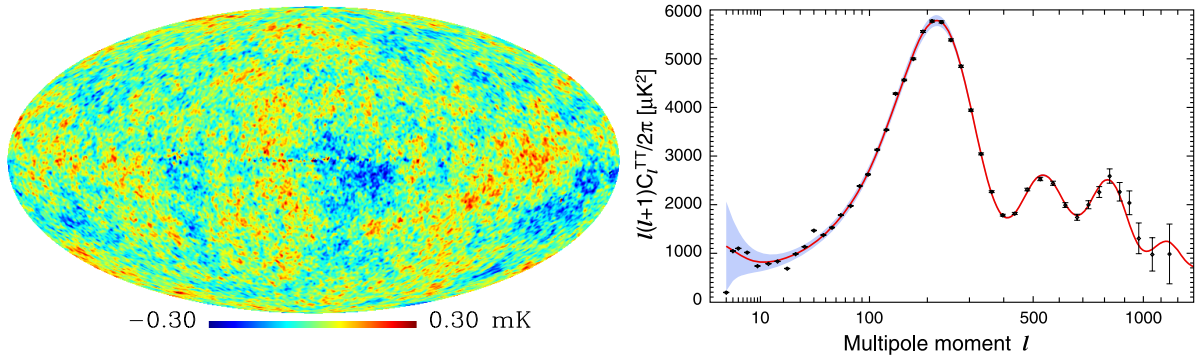


Fig. 1.— The CMB anisotropy map and power spectrum obtained by WMAP.

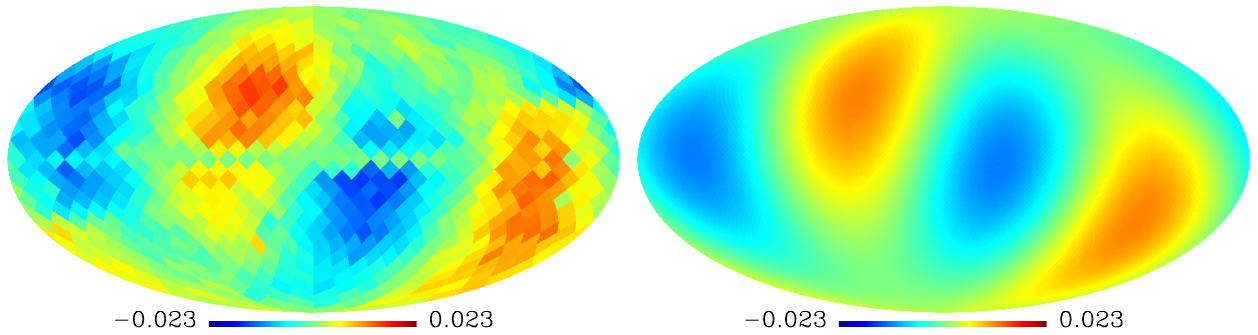


Fig. 2.— *Left panel:* The difference in CMB anisotropy maps, WMAP minus ours, smoothed to  $N_{side} = 8$ . *Right panel:* The quadrupole component of the WMAP CMB anisotropy map. Both in Galactic coordinate and units of mK.

With the new CMB power spectrum, we have derived new best-fit cosmological parameters, as shown in Table. 1. For example, the dark matter density  $\Omega_c$  is about 20% higher, and the dark energy density  $\Omega_\Lambda$  is about 10% lower.

### 3. WHY THE WMAP CMB RESULT SHOULD BE QUESTIONED

We have enough reason to question the WMAP result: Firstly, as presented in Fig. 2 of Liu et al. (2010) (looks very similar to Fig. 2 here), the released WMAP CMB quadrupole can be well reproduced without using any CMB data, which is very surprising. The correctness of this result has been confirmed by several authors (Roukema 2010a; Moss et al. 2010), and we have released the source code we used to accept worldwide verifications<sup>1</sup>. Moreover, in the same article, we have found evidence for an existing timing error by reading the WMAP TOD directly, which has later been independently confirmed (Roukema 2010b; Liu & Li 2010c). Another team from UK has also questioned the reliability of the WMAP beam profile, which can significantly affect the small scale CMB power spectrum (Sawangwit & Shanks 2010a,b). They have also provided a nice review about questioning our knowledge of the Universe (Sawangwit & Shanks 2010c). It's also suggested by Cover (2009) that the WMAP data calibration course should be more carefully checked in order to provide reliable CMB result: He tried to recalibrate the WMAP TOD and found out that, if the calibration parameters are allowed to change, then we can get a better fit even if there is no CMB anisotropy. In other words, the CMB anisotropy is too weak that it can

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<sup>1</sup>The source code is available at the web site of Tsinghua Center for Astrophysics:  
[http://dpc.aire.org.cn/data/wmap/09072731/release\\_v1/source\\_code/v1/](http://dpc.aire.org.cn/data/wmap/09072731/release_v1/source_code/v1/),  
and the CosmoCoffee forum: <http://cosmocoffee.info/viewtopic.php?p=4525#4525>



Table 1: The best-fit cosmological parameters

Description	Symbol	Value		
		WMAP5-only <sup>1</sup>	WMAP5+BAO+SN <sup>1</sup>	This work
Hubble constant (km/s/Mpc)	$H_0$	$71.9^{+2.6}_{-2.7}$	$70.1 \pm 1.3$	$71.0 \pm 2.7$
Baryon density	$\Omega_b$	$0.0441 \pm 0.0030$	$0.0462 \pm 0.0015$	$0.053 \pm 0.0030$
Dark matter density	$\Omega_c$	$0.214 \pm 0.027$	$0.233 \pm 0.013$	$0.270 \pm 0.027$
Dark energy density	$\Omega_\Lambda$	$0.742 \pm 0.030$	$0.721 \pm 0.015$	$0.677 \pm 0.030$
Fluc. Ampl. at $8h^{-1}$ Mpc	$\sigma_8$	$0.796 \pm 0.036$	$0.817 \pm 0.026$	$0.921 \pm 0.036$
Scalar spectral index	$n_s$	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$	$0.955 \pm 0.015$
Reionization optical depth	$\tau$	$0.087 \pm 0.017$	$0.084 \pm 0.016$	$0.109 \pm 0.017$

<sup>1</sup> from Hinshaw et al. (2009)

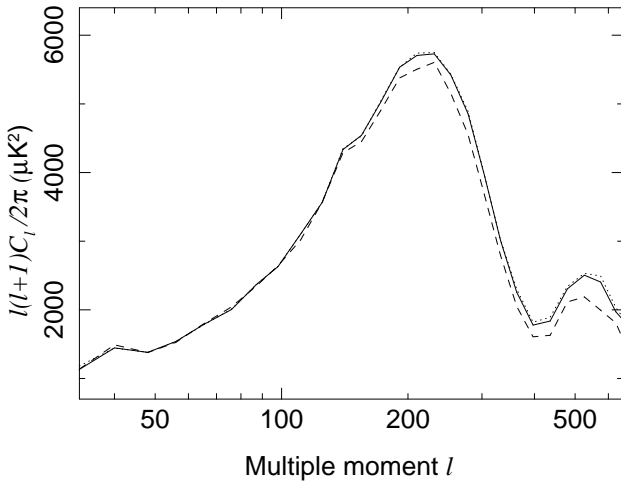


Fig. 3.— The CMB power spectra derived with our software from our new map (*dash line*), with our software but from the WMAP official maps (*dotted line*), and directly released by the WMAP team (*solid line*).

possibly be twisted by potential calibration uncertainties. This is probably the only publicly available 3rd-party work that has reached the very difficult WMAP data calibration course.

#### 4. ORGANIZING THE INVOLVED SYSTEMICAL EFFECTS

As a preparation, let's introduce some basic things about the TOD. The TOD consists of the CMB signal, the Doppler dipole signal  $d$ , the foreground  $F$ , the  $1/f$  noise, the observation noise  $n$ , and possible systematical deviation  $\delta$ , as shown here in sequence:

$$D = T_A - T_B + d + F + f^{-1} + n + \delta \quad (1)$$

The TOD are derived from uncalibrated TOD by a calibration process, in which the system gain  $G$  and baseline  $B$  are determined:

$$D_{uncal} = B + G \times D \quad (2)$$

Most work mentioned in this article is related to the antenna pointing error. What makes things confusing is that there are several inducements of the pointing error and several impacts produced by the pointing error. It's easy to confuse them three, thus we should keep in mind the logical relationship:

$$Inducements \rightarrow PointingError \rightarrow Impacts \quad (3)$$

There are at least three kinds of inducements: direct pointing error, something like, e.g., the antenna has been misplaced; pointing error caused by timing error (Liu et al. 2010); equivalent pointing error caused by the side-lobe response uncertainty (Liu & Li 2010b). As for the impacts, there are at least four: the Doppler dipole signal  $d$  and the map-making from TOD to sky map are both affected by pointing error, and both can occur in either calibration processes or post-calibration processes, thus the combinations are four. Although there are

several inducements and impacts, the connecting point is uniform: the pointing error. Thus we call the combination of each inducement with each impact an individual systematical effect:  $3(\text{Inducements}) \times 4(\text{Impacts}) = 12(\text{Sys.Err})$ , thus there are 12 different combinations. With each work, some of the combinations can be confirmed, whereas some of the combinations may be rejected. We give a list of the inducements and impacts in Table. 2, so as to refer to them by numbers hereafter.

## 5. OVERVIEW OF PREVIOUS WORKS

With the organized systematical effects, we can now start to summarize previous works and see what we have actually done in each work.

First of all, in Liu & Li (2009b), we have obtained different CMB results to the WMAP release in both large-scale and small-scale; however, the large-scale difference is determined by the systematical effect combination 1, 2, 3 with 1, 2, 3 (inducements first, then impacts, same henceforth), and the small-scale difference is determined by the combination 1, 2 with 1, 2, 4. However, in later work by Roukema (2010a), the combination 1, 2 with 4 for small-scale difference has been rejected. The combination 1, 2 with 1, 2 for the small scale difference is still possible, which need to be checked in the future.

Table 2: List of the inducements and impacts of the pointing error

	Inducements	Impacts
1	Direct	Doppler, in calibration
2	Timing	Mapmaking, in calibration
3	Equivalent	Doppler, post-calibration
4	–	Mapmaking, post-calibration

Several months later, in Liu et al. (2010), the inducement 2 is discovered with a suggested timing error amplitude of 25.6 ms, and this was soon confirmed by the following works of Roukema (2010b) and Liu & Li (2010c). Also in Liu et al. (2010), we have discovered that the WMAP CMB quadrupole can be reproduced without using any CMB data, which strongly suggests something wrong in the data processing, especially when the fact has later been confirmed by Roukema (2010b) and Moss et al. (2010). In other words, given this fact, at least one of the 12 combinations should be true, and the true CMB quadrupole is likely to be nearly zero. As explained in § 1, this strongly implicates that the standard cosmology is violated.

Then, in Liu & Li (2010b), we have discovered inducement 3, and this is the first time for us to realize that, even if the antenna pointing vectors are absolutely accurate, there is still effect that can produce equivalent pointing error, which can even produce the entire WMAP quadrupole component alone. Thus we have developed a method of model fitting, trying to ignore the sources and remove all similar effects together on the large-scale.

Recently, the existence of the timing error has been confirmed by Roukema (2010b) in temperature map space and by Liu & Li (2010c) in TOD space. The most important difference between these two works is that, they are done in the TOD and CMB map respectively, which are two different spaces: The mapping from TOD to CMB map is multi-to-one<sup>2</sup>, but the inverse mapping is one-to-one. By working purely in the TOD space, we can completely ignore the mapping attribute between the two spaces and obtain a straightforward evidence. Although the two works are essentially different, they have come to very well consistent results: the WMAP TOD timing is rejected at  $> 8\sigma$  by both, and both found out that the suggested 25.6 ms timing error is within  $1.7\sigma$ . Thus inducement 2 stands a good chance to be true, as well as the possibility

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<sup>2</sup>Theoretically speaking, this mapping is one-to-multi, because the monopole in the CMB map can be any value. However, in practice, significantly different TOD can bring to nearly same CMB map, especially for the large-scale, thus it's more useful to regard the mapping as multi-to-one.

of combination 1, 2, 3 with 1, 2, 3: As mentioned above, the large scale difference between WMAP and us is determined by such a combination.

## 6. DISCUSSION

As discussed in Sec. 3, we have enough reason to question the current WMAP result for the quadrupole of the CMB anisotropy, especially with the discovered fact that the WMAP quadrupole can be reproduced without using any CMB data. As for the small scale, some of the systematical effect combinations responsible for the CMB small-scale power spectrum difference has been rejected, but not all, thus we should still be careful, especially when there are works suggesting extra uncertainty for the small-scale coming from the beam profile issue (Sawangwit & Shanks 2010a,b,c).

An apparent advantage of our new map is that the axis-of-evil will disappear. It has been discovered since the first WMAP release that the WMAP CMB quadrupole and Octupole are aligned (de Oliveira-Costa et al. 2004; Eriksen et al. 2004; Jaffe et al. 2005; Schwarz et al. 2004), which is called the axis-of-evil problem; however, in our work, the quadrupole has almost disappeared, thus they are no longer aligned (Liu & Li 2009b) and the problem of axis-of-evil has been softened.

However, even with our new maps, there are still unexplained anomalies. In previous works, we have discovered that the pixels that are  $141^\circ$  away from hot galactic pixels are systematically cooled (Liu & Li 2009a), which is called a  $141^\circ$  ring cooling effect. This work has been independently confirmed by Aurich et al. (2009) and they have also discovered that, by removing the pixels affected by the cooling effect, the large-scale CMB two-point correlation function seem to be better consistent to the  $\Lambda$ CDM expectation (their Fig. 6). In another work (Li et al. 2009), we have discovered that the WMAP CMB temperatures are correlated with the number of

observations, which is apparently abnormal. In our new maps, it's true that these two anomalies become weaker, but they still exist, remind us that there might be even more undiscovered imperfections in the WMAP data.

There are several works involving the pointing error in the calibrated TOD, but few work has been done to the uncalibrated TOD like Cover (2009). Study in this area could possibly give an answer, or at least more helpful evidences to the problem.

This work is Supported by the National Natural Science Foundation of China (Grant No. 11033003), the National Basic Research Program of China (Grant No. 2009CB824800) and the CAS Project KJCX2-YW-T03. The data analysis made use of the WMAP data archive and the HEALPix software package (Gorski et al. 2005).

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