CMB Maximum Temperature Asymmetry Axis: Alignment with Other Cosmic Asymmetries

Antonio Mariano†

Department of Mathematics and Physics, University of Salento & INFN, Via Arnesano, 73100 Lecce, Italy

Leandros Perivolaropoulos‡

Department of Physics, University of Ioannina, Greece

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We use a global pixel based estimator to identify the axis of the residual Maximum Temperature Asymmetry (MTA) (after the dipole subtraction) of the WMAP 7 year Internal Linear Combination (ILC) CMB temperature sky map. The estimator is based on considering the temperature differences between opposite pixels in the sky at various angular resolutions (4° − 15°) and selecting the axis that maximizes this difference. We consider three large scale Healpix resolutions (N_{side} = 16 (3.7°), N_{side} = 8 (7.3°) and N_{side} = 4 (14.7°)). We compare the direction and magnitude of this asymmetry with three other cosmic asymmetry axes (α dipole, Dark Energy Dipole and Dark Flow) and find that the four asymmetry axes are abnormally close to each other. We compare the observed MTA axis with the corresponding MTA axes of 10^4 gaussian isotropic simulated ILC maps (based on ΛCDM). The fraction of simulated ILC maps that reproduces the observed magnitude of the MTA asymmetry and alignment with the observed α dipole is in the range of 0.1% − 0.5% (depending on the resolution chosen for the CMB map). The corresponding magnitude+alignment probabilities with the other two asymmetry axes (Dark Energy Dipole and Dark Flow) are at the level of about 1%. We propose Extended Topological Quintessence as a physical model qualitatively consistent with this coincidence of directions.

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1. INTRODUCTION

There is observational evidence coming mainly from the isotropy of the Cosmic Microwave Background (CMB) that the Universe is isotropic on Hubble scales. Any anisotropy on these scales is bound to be smaller than about 1 part in 10^3. This constraint combined with the Copernican principle (supported by kSZ data [1]) leads to strong support of the cosmological principle: the Universe is homogeneous and isotropic on Hubble scales.

The violation of the cosmological principle is expected to occur at a small level even on Hubble scales due to small statistical fluctuations of the cosmic energy density (matter, radiation, dark energy). Precise cosmological observations are in principle able to detect this deviation from the cosmological principle on Hubble scales and compare the expected magnitude with the one anticipated based on the standard isotropic cosmological model.

The lowest order deviation from isotropy, which is also easiest to detect, is the anisotropy that distinguishes a preferred cosmological axis. Such an axis is usually reasonably described by a dipole deviation from isotropy. An exception consists of the CMB temperature perturbations where the dipole term is dominated by our motion with respect to the CMB frame and therefore it has been removed completely from the CMB maps. This removal has also swept away any subdominant cosmological contribution to the dipole. However any axial cosmological anisotropy that is not perfectly described by a dipole could have left a trace after the removal of the dipole. The detection of this trace may be possible by using specially designed statistical tests.

Early hints for deviations from isotropy on Hubble scales have been accumulating during the last decade. Some of these hints may be summarized as follows [2, 3]:

1. Large Scale Velocity Flows (Dark Flow):
There are recent indications that there is a large scale peculiar velocity flow with amplitude larger than 400km/sec on scales up to 100h^{-1}Mpc (z ≤ 0.03) [4] with direction l ≃ 282° ± 11°, b ≃ 6° ± 6°. Other independent studies have also found large bulk velocity flows with similar direction [5] on scales of about 100h^{-1}Mpc or larger than 300h^{-1}Mpc [6]. This large scale peculiar velocity flow is known as Dark Flow. The standard homogeneous-isotropic cosmology (ΛCDM), predicts significantly smaller amplitude and scale of flows than what these observations indicate. The deviation of these observations from ΛCDM predictions is more than 3σ. Other studies [7] using Type Ia supernovae find a flow of a somewhat smaller magnitude, consistent with ΛCDM. Even in these studies however the direction of the flow is similar to the direction found by Refs. [4] and [6]. Thus, even though there is some controversy about the magnitude of the Dark Flow it appears that its di-
2. **Fine Structure Constant Dipole:** Quasar absorber spectra obtained using UVES (the Ultraviolet and Visual Echelle Spectrograph) on the VLT (Very Large Telescope) in Chile and also previous observations at the Keck Observatory in Hawaii [9] have indicated that the value of the fine structure constant at high redshifts \(z \in [0.2, 4.2]\) is not distributed isotropically. Its anisotropy is well described by a dipole with axis directed towards \(l \simeq 320^\circ \pm 11^\circ, b \simeq -15^\circ \pm 7^\circ\). The deviation of these observations from isotropy is \(4.1\sigma\) [4, 10].

3. **Dark energy Dipole:** A recent fit of the Type Ia distance moduli residuals (from the best fit \(\Lambda\)CDM) to a dipole anisotropic distribution has indicated [10] that the angular distribution of these residuals is well described by a dipole analogous to the Fine Structure Constant dipole. Its axis is towards \(l \simeq 309^\circ \pm 18^\circ, b \simeq -15^\circ \pm 11^\circ\) and deviates by only about \(11^\circ\) from the fine structure constant dipole. The deviation of these observations from isotropy is at the \(2\sigma\) level.

Each one of the above observed deviations from isotropy is between \(2\sigma\) and \(4\sigma\). The angular proximity of the corresponding anisotropy axes makes their combination even more unlikely in an isotropic universe where there is no correlation between them. In Ref. [10] it was shown that the combined magnitude-\(l\)-alignment of the fine structure constant \(\alpha\) and dark energy dipoles has a probability less than one part in \(10^6\) to occur in an isotropic universe where the two dipoles are uncorrelated.

A physical model was proposed in Refs. [10, 11] that has the potential to explain the existence and the alignment of the above three dipoles. The model is based on the existence of a topological defect (e.g. a global monopole) with Hubble scale core formed during a recent phase transition by an \(O(3)\) symmetric scalar field *non-minimally coupled to electromagnetism*. An off-center observer with respect to the monopole center would observe faster accelerating expansion towards the core where the vacuum energy density is larger and also varying \(\alpha\) along the same direction due to the variation of the scalar field magnitude. This model is a generalization of ‘Topological Inflation’ [12] and has been called **Extended Topological Quintessence** [10] due to its non-minimal coupling to electromagnetism. The model also has some similarities with texture models which have been considered as a physical origin of the observed Cold Spots on CMB maps [31].

In contrast to Extended Topological Quintessence however, texture models have not been considered as a physical origin for cosmic accelerated expansion of for spatial variation of \(\alpha\).

Extended Topological Quintessence makes the following qualitative predictions [10]:

1. **Large Scale Velocity Flows:** Due to the stronger repulsive gravity in the defect core a large scale peculiar velocity flow is predicted along the axis that connects the off center observer and the monopole core. The direction of the flow is predicted to be away from the repelling core (‘Great Repulser’) and its scale is predicted to be the Hubble scale (the defect core scale). A reversal of the velocity flow direction is predicted for observations that go beyond the defect core. As discussed in the following section, the direction of the observed Dark Flow is consistent with the directions of the fine structure and dark energy dipoles in accordance with the above prediction.

2. **Correlation between values of \(\alpha\) and presence of strong magnetic fields:** As discussed in Ref. [10], the scalar field magnitude is expected to depend weakly of the presence of local strong magnetic fields. This magnitude variation is in turn expected to lead to local variations of \(\alpha\) in cosmological regions with large magnetic fields.

3. **Maximal large scale CMB variation towards the defect core:** Due to the recent formation of the global defect, the ISW effect is expected to lead to large temperature differences between opposite directions in the sky along the direction towards the defect core. A large part of this temperature asymmetry would have been subtracted from CMB maps along with the dipole moment which is mainly due to our motion with respect to the CMB. However, smaller traces of this asymmetry could have survived the dipole subtraction and may be detectable in large scale CMB maps.

A wide range of *large scale anomalies* have been detected on CMB maps [13, 14]. The anomalies include an abnormal alignment and planarity of the octopole and quadrupole moments [15, 16], the existence of two large and deep cold spots [17–19], the lack of large scale power [20–23], the even excess of the CMB power spectrum [24], the hemispherical power asymmetry [25] and quadrupolar dependence of the two point function (see Ref. [14] for a detailed review). Recent evidence for mirror symmetry and antisymmetry (along different directions) has also been obtained [26, 27] using the ILC WMAP7 CMB map [28]. Finally evidence for the existence of statistically significant giant rings in the CMB sky has also been reported [29]. Some of these anomalies appear to be related to a large scale bipolar asymmetry of the CMB even though there is no current quantitative study of a physical model than can give rise to all these anomalies simultaneously (see however [30, 32]). Due to the lack of such a model these anomalies are usually assumed to be a posteriori manifestations of expected large statistical fluctuations.
Having at our disposal a well defined physical model which makes specific predictions allows us to focus on specific aspects of CMB maps and search for signatures of our model. Thus, in what follows we focus on the predicted large scale CMB anisotropy and search for the axis of maximal temperature asymmetry in the WMAP7 ILC map. In particular we consider three large scale Healpix pixelizations of the WMAP7 ILC map and identify those pairs of opposite pixels in the sky that correspond to Maximum Temperature Difference. We compare the magnitude of this Maximum Temperature Asymmetry (MTA) with that expected from an isotropic model using Gaussian simulated CMB maps. We also compare the direction of the MTA with the direction of the other observed cosmic asymmetry axes (Dark Flow, Dark Energy Dipole and $\alpha$ Dipole). We find the likelihood that the observed magnitude and alignment would occur by chance in an isotropic model with no correlation between the CMB and the other observables.

The structure of this paper is the following: In the next section we describe in some detail the method for identifying the MTA magnitude and direction in the WMAP7 ILC map. We also show the resulting magnitude and direction and also its alignment with the other observed axes. We then compare the observed magnitude and alignment with those obtained by $10^4$ Gaussian simulated ILC maps based on $\Lambda$CDM. In section III we discuss the implications of our results and point out the next steps of this research program.

2. METHOD-RESULTS

The subtraction of the dipole moment from the CMB maps removes along with the dominant Doppler component any cosmological signal that may happen to have a dipole anisotropy. Such a signal is expected to emerge in the context of extended topological quintessence as discussed in the Introduction (see also Refs. [10, 11]). In addition to the dipole however, an off center observer will also experience axial anisotropies corresponding to higher moments although at a smaller magnitude [35, 36]. Depending on the dynamics and the geometry of the forming defect these higher moment asymmetries may have detectable magnitude. Such asymmetry could manifest itself as maximized temperature difference between opposite pixels in the CMB sky. In order to obtain the direction and magnitude of such residual MTA we use the following steps applied on the WMAP foreground reduced ILC map pixelized according to Healpix. In order to minimize foreground contamination we focus on large angular scales ($N_{\text{side}} = 4$ (pixel size about $14.7^\circ$), $N_{\text{side}} = 8$ (pixel size about $7.3^\circ$), $N_{\text{side}} = 16$ (pixel size about $3.7^\circ$))

1. Construct a Temperature Difference Map (TDM) obtained by assigning to each pixel a number equal to the difference between its temperature value and the value of the temperature of the opposite pixel in the sky. Thus we have

$$D^-(\hat{n}_i) = (T(\hat{n}_i) - T(-\hat{n}_i)),$$  \hspace{1cm} (2.1)

where $\hat{n}_i$ is the direction of the $i^{th}$ Healpix pixel. A similar estimator was considered in Ref. [37] in an effort to test statistical isotropy of CMB maps. In the context of the Healpix pixellization the opposite pixel is always simply defined and identified. By construction, opposite pixels of the TDM are assigned to opposite values.

2. In the TDM we select the pixel $D^\text{max}_-(\hat{n}_k)$ with the maximum absolute value. This pixel along with the pixel located opposite to it defines the axis of MTA. If the dipole had not been subtracted the MTA axis would be almost identical to the dipole axis. Thus the MTA axis is the residual asymmetry axis after the subtraction of the dipole.

3. The direction of the MTA is then compared with the directions of other cosmic asymmetry axes ($\alpha$ dipole, Dark Energy dipole and Dark Flow) and the corresponding angular differences are identified.

4. The magnitude and direction of the MTA are compared with a large number of $\Lambda$CDM simulated ILC maps [38] and we evaluate the likelihood to obtain the observed MTA magnitude (or larger) in the context of $\Lambda$CDM. The likelihood of obtaining the angular differences (or smaller) with the other cosmic asymmetry axes in the context of $\Lambda$CDM is also evaluated.

The WMAP7 ILC maps using Healpix pixellizations with $N_{\text{side}} = 4, 8, 16$ (corresponding to a pixel size of $\sqrt{4\pi/(12N_{\text{side}}^2)}$ rad i.e. about $14.7^\circ$, $7.3^\circ$ and $3.7^\circ$ respectively) are shown in Figure 1 along with the MTA pixels. The original map has $N_{\text{side}} = 512$. The proximity of the MTA axis with one of the Cold Spots center is evident.

In Table I we show the directions in galactic coordinates of the four cosmic asymmetry axes. In Figure 2 we show these directions in a Mollweide projection. The filled contours around each direction correspond to the $1\sigma$ error regions. In Table I we show the corresponding angular separations for each pair.

The cumulative probability for obtaining a given value of MTA or larger, may be obtained using $10^4$ simulated statistically isotropic $\Lambda$CDM ILC maps [38]. The result is shown in Figure 3 for each one of the three angular resolutions (pixel sizes) considered. We used the publicly available $\Lambda$CDM simulated ILC maps of Ref. [38]. The observed value of the MTA magnitude is indicated by an arrow. The probability to obtain the observed magnitude of MTA (or larger) in the context of $\Lambda$CDM varies between $16\%$ and $7\%$ depending on the ILC map angular resolution. This result by itself does not indicate
any statistically significant deviation from ΛCDM predictions. Perhaps, this is the main reason that this simple statistic has been largely ignored by previous studies (see however Ref. [37]). However, the statistic becomes more interesting when the proximity of the direction of the MTA to other cosmic asymmetry axes is considered.

In Fig. 4 we plot the percentage of the MTA directions obtained from the simulated maps that form an angle with the observed $\alpha$ dipole direction smaller than a given angle (shown on the horizontal axis). The cases of map resolutions corresponding to $N_{side} = 4, 8, 16$ are shown. The angle between the observed MTA and the observed $\alpha$
FIG. 2: Directions in galactic coordinates for the $\alpha$ (blue) and Dark Energy (green) dipoles, for the Dark Flow direction (red) and for the direction of MTA in the 7 years ILC CMB map degraded to $N_{\text{side}} = 8$ (yellow). The opposite corresponding directions are also shown.

FIG. 3: Percentage of the maximum temperature difference values obtained from the simulated maps bigger than the observed maximum temperature difference obtained from the degraded maps with $N_{\text{side}} = 4, 8, 16$.

| $N_{\text{side}}$ | $l$ (°) | $b$ (°) |
|-------------------|---------|---------|
| $N_{\text{side}} = 4$ | 337.5 ± 14.7 | -9.6 ± 14.7 |
| $N_{\text{side}} = 8$ | 331.9 ± 7.3 | -9.6 ± 7.3 |
| $N_{\text{side}} = 16$ | 331.9 ± 3.7 | -7.2 ± 3.7 |
| $\alpha$ dipole | 320.5 ± 11.8 | -11.7 ± 7.5 |
| Dark Energy dipole | 309.4 ± 18.0 | -15.1 ± 11.5 |
| Dark Flow direction | 282 ± 11 | 6 ± 6 |

| MTA ($N_{\text{side}} = 8$) | $l$ (°) | $b$ (°) |
|---------------------------|---------|---------|
| 0.0 | 11.4 ± 12 | 22.6 ± 18 |
| 11.4 ± 12 | 0.0 | 11.3 ± 18 |
| 22.6 ± 18 | 11.3 ± 18 | 0.0 |
| 52.1 ± 11 | 42.2 ± 11 | 34.4 ± 18 |

TABLE I: Directions in galactic coordinates for the $\alpha$ and Dark Energy dipoles [10], the Dark Flow and the maximum CMB temperature difference (MTA). For the Dark Flow direction we have used Ref. [4]. The larger scale direction of Ref. [6] is consistent with that of Ref. [4] but it has significantly larger errorbars. The error on the MTA direction has been taken to be equal to the side of the pixel, $\sqrt{4\pi / (12N_{\text{side}}^2)}$ rad.

TABLE II: Angular distances in degrees between the Alpha and Dark Energy dipoles, the Dark Flow and the MTA directions. For the MTA direction we have chosen the result obtained in the $N_{\text{side}} = 8$ case.

of the $\alpha$ dipole direction we have used the Dark Energy dipole and Dark Flow directions respectively.

The probability that the $\Lambda$CDM simulated maps reproduce the observed alignment of cosmic asymmetries varies between 1.37% (alignment with $\alpha$ dipole), and 22.77% (alignment with Dark Flow). The combined probability to obtain both a large enough magnitude and angular proximity of MTA to the $\alpha$ dipole direction is...
FIG. 4: Percentage of the maximum temperature difference directions obtained from the simulated maps closer to the α dipole than the observed maximum MTA obtained from the degraded maps with $N_{\text{side}} = 4, 8, 16$.

FIG. 5: Percentage of the MTA directions obtained from the simulated maps closer to the Dark Energy dipole than the observed MTA directions obtained from the degraded maps with $N_{\text{side}} = 4, 8, 16$.

shown in Table III. In particular, the probability to obtain the observed MTA magnitude (or larger) and the observed angular proximity to the α dipole direction in the context of ΛCDM varies between 0.5% and 0.1% depending on the angular resolution of the WMAP7 ILC map. If the probability of obtaining the α dipole magnitude in the context of ΛCDM is also factored in, the probability reduces to about one part in $10^7$ which is similar to the probability for obtaining simultaneously the Dark Energy and the α dipoles in the observed directions [10].

The last column of Table III is also shown in Table IV along with the corresponding results for the other two anisotropy directions corresponding to the Dark energy Dipole and the Dark Flow.

We stress that the above abnormally low probabilities assume that the corresponding datasets (Keck+VLT quasar absorbers [9], Dark Flow data [4, 6], Union2 data [39] and ILC maps [28]) are free of systematic errors. The potential validity of these datasets combined with the generic nature of the statistical tests applied, assigns a particularly low likelihood to the statistical isotropy feature of ΛCDM.

Nevertheless, the existence of a physical model where the alignment of the above axes will appear with a significantly larger probability is a prerequisite before putting ΛCDM to disfavor. Even though the qualitative predictions of Extended Topological Quintessence appear to be significantly more consistent with the observed cosmic asymmetries than ΛCDM, a quantitative analysis is required before any valid conclusion in favor of Extended Topological Quintessence is drawn. Such an analysis is currently in progress.

3. CONCLUSION-OUTLOOK

We have identified a direction on Maximum Temperature Asymmetry (MTA) of the WMAP7 foreground reduced ILC map. Even though the magnitude of this asymmetry is consistent with ΛCDM at the 2$\sigma$ level, its direction is abnormally close to other observed cosmic asymmetry axes. The direction of the MTA is close to the direction of one of the Cold Spots. This angular proximity may imply that this Cold Spot (or the opposite located Hot Region) is physically related to the existence of other cosmic asymmetry axes. In the context of Extended Topological Quintessence, the existence of such a feature (Hot or Cold spot) is expected to exist at the core of the ‘Great Repulser’ global defect while in the opposite direction an opposite temperature behavior is expected.

The planarity and alignment of the CMB octupole and quadrupole moments may be partly due to a combination of two or more features on the preferred plane of these moments. Indeed, MTA axis we have identified lies on this preferred plane and therefore the MTA may be related to the observed quadrupole-octupole alignment [13].

An interesting extension of this project is the derivation of the detailed CMB signature predicted by Extended Topological Quintessence. Such a derivation
FIG. 6: Percentage of the MTA directions obtained from the simulated maps closer to the Dark Flow direction than the observed MTA directions obtained from the degraded maps with \( N_{\text{side}} = 4, 8, 16 \).

| \( N_{\text{side}} \) | \( MTA_{\text{sims}} > MTA_{\text{obs}} \) | \( \theta_{MTA-\alpha;\text{sims}} < \theta_{MTA-\alpha;\text{obs}} \) | both | \%
| --- | --- | --- | --- | ---
| 4 | 16.25 | 2.58 | 0.48 | 19.62
| 8 | 10.86 | 1.37 | 0.19 | 19.06
| 16 | 7.12 | 1.9 | 0.12 | 7.93

TABLE III: Probabilities of obtaining a simulated CMB map with a maximum temperature difference bigger than the observed one and with a MTA direction closer to the \( \alpha \) dipole direction than the observed one.

| \( N_{\text{side}} \) | DE(\%) | DF(\%) | both(\%) | \%
| --- | --- | --- | --- | ---
| 4 | 0.48 | 0.95 | 3.37 | 4.7
| 8 | 0.19 | 0.52 | 2.06 | 0.0
| 16 | 0.12 | 0.28 | 1.28 | 0.0

TABLE IV: Probabilities of obtaining a simulated CMB map with both a maximum temperature difference bigger than the observed one and a MTA direction closer to the \( \alpha \) dipole direction and Dark Energy dipole and Dark Flow directions than the observed one.

Numerical Analysis Files: The data, Mathematica and Healpix program files used for the numerical analysis files may be downloaded from [http://leandros.physics.uoi.gr/mta](http://leandros.physics.uoi.gr/mta).

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