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The Weird Side of the Universe: Preferred Axis

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In both WMAP and Planck observations on the temperature anisotropy of cosmic microwave background (CMB) radiation a number of large-scale anomalies were discovered in the past years, including the CMB parity asymmetry in the low multipoles. By defining a directional statistics, we find that the CMB parity asymmetry is directional dependent, and the preferred axis is stable, which means that it is independent of the chosen CMB map, the definition of the statistic, or the CMB masks. Meanwhile, we find that this preferred axis strongly aligns with those of the CMB quadrupole, octopole, as well as those of other large-scale observations. In addition, all of them aligns with the CMB kinematic dipole, which hints to the non-cosmological origin of these directional anomalies in cosmological observations.

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1. Introduction

In the past twenty years, based on various cosmological observation, including the temperature and polarization anisotropies of the cosmic microwave background (CMB) radiation, the distribution of the galaxies, Type Ia supernovas, the weak lensing, and so on, the so-called standard cosmological model, i.e. inflation+ΛCDM model,[1] has been built. In this model, the universe is completely described by six parameters, i.e. the energy density of baryon Ω_b and dark matter Ω_{CDM}, the Hubble constant H_0, the optical depth of re-ionization τ, the amplitude of primordial density perturbations A_s, and the spectral index n_s. This successful model is based on the following assumptions: (1) On large scales, the Universe is isotropic and homogeneous, known as the cosmological principle; (2) Einstein's General Relativity is the correct theory that describes gravity on all the macroscopic scales; (3) The

main components of the Universe are baryons, cold dark matter and dark energy (or cosmological constant Λ); (4) Primordial fluctuations were created as quantum fluctuations, which gave rise to structure formation.

At the same time, with the release of various precise observed data, a number of large-scale "anomalies" have also been reported recently. In particular, it was noticed that some of them are directional dependent, e.g. the alignment of CMB low multipoles, the large-scale velocity flows, the alignment of the polarization of QSOs, the directional dependence of CMB parity asymmetry, the anisotropy of cosmic acceleration, the anisotropy of the fine structure constant α and so on.[2] If this kind of directional anomaly has a cosmological origin, they will challenge the standard cosmological model, and change the base of modern cosmology. In this paper, we shall first focus on the directional dependence of the CMB parity asymmetry by searching for the preferred axis stored in it, and compare this axis with the other ones in the other observations. In addition, we shall also introduce the possible physical origins of these anomalies.

2. The Parity Asymmetry in the CMB Temperature Anisotropy

By the observations of WMAP and Planck satellites, people found that in the high multipole range, i.e. in the small scales, the observed data excellently fit the theoretical prediction. However, in the low multipole range $\ell < 100$, the data are quite problematic. Some non-gaussian anomalies are reported in this scale, which includes the low quadrupole problem, the lack of large-scale correlation, the cold spot, the CMB power asymmetry, the mirror asymmetry, the large-scale quadrant asymmetry, the alignment of low multipoles, the parity asymmetry and so on.[3,4] Based on these facts, the Planck collaboration claimed that "the Universe is still weird and interesting". Here, let us focus on the CMB parity asymmetry.

We can decompose the two-dimensional CMB temperature anisotropy field in the sphere as follows,

$$\Delta T(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi), \tag{1}$$

where $a_{\ell m}$ are coefficients which satisfy the Gaussian distribution in the standard inflationary scenario. The power spectrum is defined as

$$C_\ell = \langle a_{\ell m} a_{\ell m}^* \rangle,$$

where the bracket denotes the ensemble average. In order to estimate the power spectrum, one can define the unbiased estimator as

$$\hat{C}_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} a_{\ell m} a_{\ell m}^*,$$

which satisfies the χ^2-distribution with the expectation value $\langle \hat{C}_\ell \rangle = C_\ell$. This means that, in principle, the data $\hat{C}_\ell$ should randomly oscillate around theoretical power spectra C_ℓ.

However, in the real data, it was noticed that in the low-multipole range $\ell \lesssim 30$, the even-multipole data are systematical smaller than the theoretical curve, while the odd ones are systematically larger than the model predictions, which is the so-called CMB parity asymmetry. By defining the statistic as the ratio between the sum of all the even multipoles and that of the odd ones, people found that the anomalies maximize at about $\ell_{\max} = 22$ (see Ref.[5]).

3. Directional Properties of CMB Parity Violation

In order to study the direction properties of the CMB parity asymmetry, we define the new unbiased estimator for C_ℓ as follows ,[6]

$$D_\ell = \frac{1}{2\ell} \sum_{m=-\ell}^{\ell} a_{\ell m} a_{\ell m}^* (1 - \delta_{m0}).$$ (2)

Comparing with the standard one, $\hat{C}_\ell$, this new estimator is rotationally variant, its value depends on the choice of the coordinate system, and the preferred axis is exactly the z-axis of the coordinate system. For any given coordinate system with the z-direction labelled as $\hat{q}$ (which can also be treated as the coordinate of this direction in the Galactic coordinate system), we denote the corresponding estimator as $D_\ell(\hat{q})$.

Now, we can define the rotationally variable parity parameter $G_1(\ell; \hat{q})$ by using $D_\ell(\hat{q})$ as follows:

$$G_1(\ell; \hat{q}) \equiv \frac{\sum_{\ell'=2}^{\ell_{\max}} (2\ell' + 1) D_{\ell'}(\hat{q}) \Gamma^+(\ell')}{\sum_{\ell'=2}^{\ell_{\max}} (2\ell' + 1) D_{\ell'}(\hat{q}) \Gamma^-(\ell')} ,$$ (3)

where $\Gamma^+(\ell) = \cos^2(\ell\pi/2)$ and $\Gamma^-(\ell) = \sin^2(\ell\pi/2)$. By considering all the possible $\hat{q}$, we can construct the 2-dimensional G_1-map for any given maximum multipole ℓ, in which the smaller G_1 value denotes the larger parity asymmetry. In this paper, we define the direction in which the G_1 value is minimized as the preferred axis.

In order to search for the preferred axis in the CMB parity asymmetry, we consider the WMAP ILC7 map, and construct the corresponding G_1-map for each maximum ℓ. We find that for any given ℓ, the morphologies of these G_1-maps are similar to each other, and their preferred axes are all around ($\theta = 45°$, $\phi = 280°$) (see Ref.[6]). The angles between the axes of different maximum are smaller than 15° as long as $3 < \ell < 22$.

To study the stability of our conclusion, we apply the directional analysis to the Planck observations, including the Commander, NILC, SMICA and SEVEM maps. From the results of Commander, NILC and SMICA maps, we find quite similar results, which are all consistent with the ones derived from the WMAP ILC7 map.[7] The results of SEVEM map are quite different. This is caused by the extremely dirty region of the Galactic plane region on this map.

The results derived above are all based on the definition of G_1 statistic. However, an important problem arises: Whether or not the preferred axis of CMB parity

asymmetry depends on the definition of statistic or estimator? In order to cross-check the results, we define the following directional statistics G_i $(i = 2, 3, 4, 5, 6)$ (see Ref.[7]), which are quite different from G_1.

$$G_2(\ell; \hat{q}) \equiv \frac{\sum_{\ell'=2}^{\ell_{\max}} \ell'(\ell'+1)D_{\ell'}(\hat{q})\Gamma^+(\ell')}{\sum_{\ell'=2}^{\ell_{\max}} \ell'(\ell'+1)D_{\ell'}(\hat{q})\Gamma^-(\ell')}, \quad G_3(\ell; \hat{q}) \equiv \frac{2}{\ell-1} \sum_{\ell'=3}^{\ell} \frac{(\ell'-1)\ell'D_{\ell'-1}(\hat{q})}{\ell'(\ell'+1)D_{\ell'}(\hat{q})}.$$

$$(4)$$

G_i $(i = 4, 5, 6)$ are same with G_i $(i = 1, 2, 3)$ but the estimators D_ℓ are replaced by

$$\tilde{D}_\ell = \frac{1}{2\ell+1} \sum_m m^2 |a_{\ell m}|^2.$$

Then, we repeat our analysis by adopting the new statistics. Interesting enough, we find that the morphologies of the G_i-maps are completely different for different statistics. However, their preferred axes are nearly same for all the used statistics and all the maximum multipole ℓ, as long as $\ell < 10$ (see Ref.[7]). So, we conclude that the preferred axis of the CMB parity asymmetry is independent of the definition of the directional statistic.

In the CMB observations, various foreground residuals are always unavoidable, especially in the Galactic region. It is worthy to investigate the cases in which these contaminated data are excluded. The simplest way to exclude the polluted region is to apply the top-hat mask to the data. In order to study the effect of CMB mask on the preferred axis. We consider the Planck data and taking into account the corresponding mask suggested by Planck team. For each CMB map and the mask, we define the pseudo-estimator of CMB power spectra as follows,[8]

$$\tilde{D}_\ell = \frac{1}{2\ell} \sum_{m=-\ell}^{\ell} \tilde{a}_{\ell m} \tilde{a}_{\ell m}^* (1 - \delta_{m0}),$$

where $\tilde{a}_{\ell m}$ are the pseudo-coefficients of the masked CMB map. The unbiased estimator is defined as

$$\mathcal{D}_\ell = \sum_{\ell'} N_{\ell\ell'}^{-1} \tilde{D}_{\ell'},$$

where

$$N_{\ell\ell'} = M_{\ell\ell'} - \frac{2\ell'+1}{2\ell} \sum_{\ell_2 \ell_2' m_1} \frac{\sqrt{(2\ell_2+1)(2\ell_2'+1)}}{4\pi} \times$$

$$\begin{pmatrix} \ell' & \ell_2 & \ell \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell' & \ell_2' & \ell \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell' & \ell_2 & \ell \\ m_1 & -m_1 & 0 \end{pmatrix} \begin{pmatrix} \ell' & \ell_2 & \ell \\ m_1 & -m_1 & 0 \end{pmatrix} w_{\ell_2 m_1} w_{\ell_2' m_1}, \quad (5)$$

and

$$M_{\ell\ell'} = (2\ell'+1) \sum_{\ell_2} \frac{2\ell_2+1}{4\pi} \begin{pmatrix} \ell' & \ell_2 & \ell \\ 0 & 0 & 0 \end{pmatrix}^2 \tilde{w}_{\ell_2}. \quad (6)$$

Table 1.   Preferred axis in various large-scale observations.

observations	θ [degree]	ϕ [degree]
CMB parity asymmetry	45.82	279.73
CMB kinematic dipole	42	264
CMB quadrupole	13.4	238.5
CMB octopole	25.7	239.0
Polarization of QSOs	69	267
Large-scale velocity flows	84	282
Handedness of spiral galaxies	158.5	232
Anisotropy of cosmic acceleration	23.4	247.5
Distribution of fine-structure constant	104	331

We define the directional statistic by a similar way as $G_1(\ell; \hat{q})$, but the estimator D_ℓ is replaced by $\mathcal{D}_\ell$. Applying the described method to the masked Planck maps, we find nearly the same preferred axis as that in the full-sky map.[8]

4. Comparison with the Other Direction-Dependent Anomalies

As well known, the lowest anisotropy of CMB is the dipole component with an amplitude of 3.35 mK, and it is caused by the peculiar velocity of the Solar System relative to the comoving cosmic rest frame.[9] Relative to the observers, the dipole anisotropy defines a peculiar axis in the Universe, which is at ($\theta = 42°$, $\phi = 264°$) in the Galactic coordinate system. By comparing it with the preferred axis discovered above, we find the strong alignment between them. The angle between them is smaller than $10°$.

The lowest cosmological anisotropic modes of the CMB fluctuations are the quadrupole and octopole. By defining the proper directional statistics, people discovered their preferred axes[10] (see Table 1). In addition, they are strongly correlated, and very close to the direction defined by the CMB kinematic dipole. In order to study the relation between these axes and the one discovered here, we define the average angle between these four axes (CMB dipole, quadrupole, octopole, and the CMB parity asymmetry). Comparing with the random simulations, we find that the alignment between them are confirmed at more than 3σ (see Ref. [7]).

Besides the peculiar axes in the CMB, several other preferred axes are also reported in various large-scale cosmological observations, including the alignment of quasar polarization vectors, large-scale velocity flows of the cosmic matter in the CMB rest frame, the distribution of handedness of spiral galaxies, the anisotropy of the cosmic acceleration, the anisotropic distribution of fine-structure constant.[2] We list the direction of these axes in Table 1, in which we find that all the large-scale observations point to the nearly same preferred direction. And also, this direction is exactly the same direction defined by CMB kinematic dipole. So, it is also called the *evil axis* in cosmology.

5. Possible Explanations

The standard cosmological model is based on two assumptions: One is that Einstein's general relativity correctly describes gravity, the other assumes the universe as homogeneous and isotropic on large scales. If we believe that the anomalies have a cosmological origin, at least one of these two assumptions will be broken.[2] One possibility relies on the Bianchi models. The Bianchi classification provides a complete characterization of all the known homogeneous but anisotropic exact solution to general relativity. So, in general, Bianchi models can provide preferred directions in the universe. Another way is to revise the gravitation theory. For instance, some authors considered that the universe is influenced by large-scale wind, and the cosmic matter is drifted by this wind, which is described by the Finsler geometry.[2]

On the contrary, some other people believe that these anomalies are due to some non-cosmological reasons: Unsolved systematical errors, calibration errors or foreground contaminations (CMB dipole-related). One possible reason is related to the contaminations generated by the collective emission of Kuiper Belt objects. Another explanation may relate it to a deviation measured in the CMB kinematic dipole. It is also possible that the preferred direction is caused by the tidal field originated from the anisotropy of our local halo.[2,6]

6. Discussions and Conclusions

In the recent observations of the large-scale structure, several directional anomalies have been reported, including anomalies in the CMB low multipoles, and the CMB parity asymmetry. Although the confidence level for each individual anomaly is not too high, the directional alignment of all these anomalies is quite significant, which strongly suggests a common origin of these anomalies.

If these anomalies are due to cosmological effects, e.g. an alternative theory of gravity or geometry, they indicate the violation of the cosmological principle. So, one should consider building a new cosmological model to explain the large-scale data. However, if these directional anomalies arise from non-cosmological reasons, e.g. the unsolved systematical errors or contaminations, we should carefully treat the current data, and exclude the errors in the future analysis to avoid the misleading explanations of the data. Although the physical origins are still unclear, from the alignment between preferred axes of cosmological observations and the motion of the Solar System in the CMB rest frame, we are lead to believe the non-cosmological origin of the large-scale anomalies. We expect that the future measurements on the CMB polarization fields, the cosmic weak lensing, or the distribution of 21-cm line can help us to solve the puzzles.

References

1. Planck Collab. (P. A. R. Ade *et al.*), *Astron. Astrophys.* **571**, A1 (2014).
2. see for instance, W. Zhao and L. Santos, *The Universe* **3**, 9 (2015).
3. WMAP Collab. (C. L. Bennett *et al.*), *Astrophys. J. Suppl.* **192**, 17 (2011).
4. Planck Collab. (P. A. R. Ade *et al.*), *Advances in Astronomy* **571**, A23 (2014).
5. J. Kim, P. Naselsky, and M. Hansen, *Advances in Astronomy* **2012**, 960509 (2012).
6. P. Naselsky, W. Zhao, J. Kim, and S. Chen, *Astrophys. J.* **748**, 31 (2012).
7. W. Zhao, *Phys. Rev. D* **89**, 023010 (2014).
8. C. Cheng, W. Zhao, Q. Huang, and L. Santos, *Phys. Lett. B* **757**, 445 (2016).
9. WMAP Collab. (N. Jarosik *et al.*), *Astrophys. J. Suppl.* **192**, 14 (2011).
10. M. Tegmark, A. de Oliveira-Costa, and A. Hamilton, *Phys. Rev. D* **68**, 123523 (2003).