Probing the Origin of the Large-angle CMB Anomalies

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Abstract

It has been argued that the large-angle cosmic microwave background anisotropy has anomalies at $\sim 3\sigma$ level. We review various proposed ideas to explain the origin of the anomalies and discuss how we can constrain the proposed models using future observational data.

1 Introduction

There has been mounting evidence that the large-angle cosmic microwave background (CMB) anisotropy has anomalies roughly at 3σ level. In addition to the anomalously low quadrupole reported by COBE-DMR (Smoot et al. 1992), various types of anomalies have been reported after the release the WMAP data (Bennett et al. 2003), namely, the octopole planarity and the alignment between the quadrupole and the octopole (Tegmark et al. 2004, de Oliveira-Costa et al. 2004); an anomalously cold spot on angular scales $\sim 10°$ (Vielva et al. 2004, Cruz et al. 2005); and an asymmetry in the large-angle power between opposite hemispheres (Eriksen et al. 2004, Hansen et al. 2004). Evidence for other forms of non-Gaussianity on large angular scales has also been reported (Chiang et al. 2004, Copi et al. 2004, Park 2004, Schwarz et al. 2004, Larson & Wandelt 2004).

As the origin of the anomalies, a variety of solutions have been suggested. To explain the low quadrupole, Luminet (2003) et al. proposed a non-trivial spherical topology and Gordon (2004) proposed isocurvature perturbations due to the dark energy. Jaffe (2005) et al. considered a locally anisotropic model based on the Bianchi type VII_h universe to explain the quadrupole/octopole planarity and the alignment. Other papers have studied the possibilities that the large-angle CMB is affected by local non-linear inhomogeneities (Moffat 2005; Tomita 2005a,b; Vale 2005; Cooray & Seto 2005; Rakic et al. 2006, Inoue & Silk 2006a,b). In this paper, we analyze the plausibility of these models and discuss what could be the most plausible scenario and how it will be probed by future observation.

2 Large angle anomalies

We summarize the feature of observed anomalies on large angular scales. Using the WMAP 1st year data (Bennett et al. 2003), noticeable deviations from the prediction of the fiducial ΛCDM cosmology (flat-FRW) are found in the angular power spectrum at $l = 2$, $l \sim 20$, and $l \sim 40$. These anomalies can be called the statistically isotropic anomalies (SIA). Other types of anomalies can be called statistically anisotropic anomalies (SAA), which include the octopole planarity and the alignment between the quadrupole and the octopole (Tegmark et al. 2003, de Oliveira-Costa et al. 2004), asymmetry in the large-angle power between opposite hemispheres (Eriksen et al. 2004, Hansen et al. 2004), an anomalously cold spot on angular scales $\sim 10°$ (Vielva et al. 2004, Cruz et al. 2005, 2006). A mysterious correlation between the quadrupole plus octopole and the ecliptic plane or equinox has also been found (Copi et al. 2004). These features are anomalous roughly at $3 - \sigma$ level if the fiducial standard LCDM model ($\Omega_0 = 0.24, \Omega_\Lambda = 0.76$) is assumed.

3 Feature on horizon scale in FRW models

The simplest way to suppress the large-angle fluctuation is to consider a specific feature on the present horizon scale. Such a suppression can be realized by introducing a cutoff on the primordial power spectrum. Then the ordinary Sachs-Wolfe (OSW) contribution at the last scattering would be significantly affected by such a cutoff while the integrated Sachs-Wolfe (ISW) contribution remains intact. A similar mechanism can work if one introduces an additional isocurvature mode that unticorrelates with the adiabatic mode. A certain class of the dark energy models that realize such a mechanism has been proposed (Gordon & Hue 2004). Modification of dynamics of the curvature perturbation due to non-trivial dynamics of the scalar field can also suppress the ISW contribution. Although the quadrupole can be lowered by these mechanism, planarity/alignment feature seems difficult to realize since the background metric is spatially homogeneous and isotropic.

4 Non-trivial topology with finite volume

After the discovery of the low quadrupole using the COBE data, suppression of the quadrupole for a toroidal topology T^3 has been studied (Starobinskly 1993, Stevens et al. 1993). Assuming the standard "slow-roll" inflationary scenario, the periodic boundary condition on the present horizon scale due to the toroidal topology naturally introduces a cut off scale on the primordial power spectrum. Furthermore, discreteness of the mode function yields an oscillating feature in the power spectrum. Although the fit to the observed angular power spectrum becomes better in comparison with the infinite flat FRW model, the fit to the observed fluctuations using full covariance matrix defined in pixels on the sky becomes worse when normalized over the orientation of the observer. However, for particular choices of orientation of the observer, better fits can be obtained in comparison with the corresponding infinite model (Inoue & Sugiyama 2003). In other words, almost all orientations of the observer are ruled out. A simple analysis using only the angular power spectrum can lead to a somewhat misleading result.

After the release of the WMAP data, Luminet et al. (2003) considered a globally homogeneous spherical model with a fundamental domain described by a dodecahedra. For a density parameter $\Omega_0 = 1.013$, the comoving volume of the space is just 83% of that within the last scattering surface. Therefore, the large scale fluctuations beyond the present horizon can be suppressed. The low quadrupole can be obtained by such a cut off beyond the present horizon. Unfortunately, this model has been ruled out by the "circle-in-the-sky" analysis using the WMAP data (Cornish et al. 2003). Furthermore, a subsequent analysis showed that the alignment/planarity feature in the $l = 2, 3$ modes cannot be naturally obtained (Weeks, 2006). Therefore, it seems reasonable to conclude that the non-trivial topology alone cannot explain all the features of the large-angle anomalies (SIA&SAA).

5 Homogeneous anisotropic models

Jaffe et al. (2005) considered a certain type of locally anisotropic model called Bianchi VII$_h$ model. In contrast to the FRW models, there is a shear and a vorticity which come from the anisotropic background metric. They can account for fluctuations with a particular "axis" and the "cold spot" in the sky.

The observational feature in Bianchi models has been studied (Barrow 1985) and their cosmological constraint using the COBE data has been explored (Bunn et al. 1996 and Kogut et al. 1997). The model has succeeded in explaining the planarity of the $l = 2, 3$ and $l = 5, 6$ modes and the large-scale "north-south" power asymmetry and the cold spot by introducing a particular spiral pattern on the background gaussian fluctuations. However, on smaller angular scales, the fit to the data becomes significantly worse because it needs a negatively curved universe with a density parameter $\Omega_0 = 0.5$ which is more than twice the "fiducial value" $\Omega_0 = 0.24$.

Because the Bianchi VII$_h$ model necessarily introduces "additive" contribution to the intrinsic anisotropy, the low quadruple can be only achieved by unusual cancellation between them. Although a quantitative

analysis has not been done, this might be another problem. Furthermore, it cannot explain the correlation with the ecliptic plane or the CMB dipole because there is no direct connection between the background geometry and the solar system.

Note that cosmological perturbation on this model has not been fully treated in this analysis as the three-dimensional vector and tensor modes generally couple to the three-dimensional scalar mode in anisotropic model. Simple addition of scalar perturbation on the FRW background and that from the anisotropic geometry may lead to a wrong result if coupling between the scalar type perturbation and the anisotropic metric perturbation on the present horizon scale is not negligible.

6   Local Inhomogeneity

As the origin of the anomalies, local inhomogeneities have been considered by several authors (Moffat 2005; Tomita 2005a,b; Vale 2005; Cooray & Seto 2005; Rakić et al. 2006). However, none of these explanations has succeeded in explaining the specific features of the anomalies, namely, the octopole planarity, the alignment between the quadrupole ($l = 2$) and the octopole ($l = 3$), and the alignment between the multipoles ($l = 2+3$) with the ecliptic plane. For instance, if one applies a model in which the local group is falling into the center of the Shapley supercluster (SSC), the discrepancy between the model prediction and the observed data becomes even worse (Rakić et al. 2006).

Inoue & Silk (2006a,b) firstly explored the possibility that the CMB is affected by a small number of compensated local dust-filled voids. It is found that a pair of voids with radius $(2 - 3) \times 10^2 \, h^{-1}$ Mpc and matter density contrast $\delta_m = -0.3$ separated by $60°$ can account for the alignment features in multipoles with $l = 2, 3, 4$ and the planar features in multipoles with $l = 2, 3, 6$. The Shapley supercluster (SCC) is near the tangential point of the two local large voids. The mysterious correlation with the ecliptic plane can be explained naturally because the ecliptic plane is by chance tangential to the CMB dipole that originates from a mass concentration around the SCC. The cold spot in the Galactic southern hemisphere, anomalous at roughly 3σ level, can be also explained by such a large void in the direction of the cold spot at $z < 1$.

If such dust-filled large voids exist, we would be able to observe dispersion in the locally measured Hubble constant as measured both in different directions and at different redshifts. For voids with a matter density contrast $\delta_m = -0.3$, the expected fluctuation in the Hubble constant is as large as $2 - 4\%$.

The inflow pattern in the void wall may induce a small polarization signal, as will the associated gravitational lensing of the CMB. These effects are small, amounting to an imprint on the ambient polarization pattern of order a percent, but the phase structure would be unique and correlated with both the temperature map and the large-scale galaxy distribution.

7   Future Prospects

In order to determine the origin of the anomalies, it is of great importance to compare the large-scale structure (LSS) with the CMB anisotropy. Although the current signal of the LSS-CMB cross correlation is $\sim 3\sigma$ level at most, the precision can be greatly improved by future wide and deep field galaxy surveys. Future observation of 21cm emission from neutral hydrogen gas will also provide us new information about the three-dimensional distribution of baryons. Much stringent constraints on the non-trivial topology or Bianchi models can be obtained from such data. Measurement of the Hubble anisotropy using the SNIa data will be a good test to assess to what extent the local inhomogeneities affects the large-angle CMB fluctuations.

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