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Modeling integrated properties and the polarization of the Sunyaev–Zeldovich effect

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Abstract

Two little explored aspects of Compton scattering of the CMB in clusters are discussed: the statistical properties of the Sunyaev–Zeldovich (S–Z) effect in the context of a non-Gaussian density fluctuation field, and the polarization patterns in a hydrodynamically-simulated cluster. We have calculated and compared the power spectrum and cluster number counts predicted within the framework of two density fields that yield different cluster mass functions at high redshifts. This is done for the usual Press and Schechter mass function, which is based on a Gaussian density fluctuation field, and for a mass function based on a χ^2-distributed density field. We quantify the significant differences in the respective integrated S–Z observables in these two models.

S–Z polarization levels and patterns strongly depend on the non-uniform distributions of intracluster gas and on peculiar and internal velocities. We have therefore calculated the patterns of two polarization components that are produced when the CMB is doubly scattered in a simulated cluster. These are found to be very different than the patterns calculated based on spherical clusters with uniform structure and simplified gas distribution.

Keywords: Clusters of galaxies; Cosmic microwave background; Large-scale structure

Contents

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1. Introduction

The pioneering experimental and observational CMB work of our esteemed colleague Francesco Melchiorri has paved the way for generations of students and colleagues in Italy and elsewhere, who are continuing the mission he helped define and lead for more than 30 years. Francesco worked hard to advance experimental and observational capabilities to measure the Sunyaev–Zeldovich (S–Z) effect in nearby clusters. His expertise and leadership resulted in the successful development of MITO, the measurement of the effect in the Coma cluster (De Petris et al., 2002), and the upgrading of MITO to a bolometer array (Lamagna et al., 2005). As noted by Rephaeli (2005) in Francesco's obituary, his passing marks the end of the founder's era in the growth of the thriving Italian CMB community.

In light of current and future capabilities of the many upcoming S–Z experiments, we have calculated the power spectrum and cluster number counts in the context of a specific non-Gaussian density fluctuation field. As we discuss in the following section, certain observational results point to the possible need for excess power on cluster scales. The enhanced interest in non-Gaussian models motivates contrasting the integrated S–Z observables of one such viable model with those of the standard Gaussian model whose parameters are well determined.

Future sensitive mapping of the S–Z effect in individual clusters will allow measuring its polarization level. A basic description of some of the S–Z polarization patterns in clusters has already been given by Sazonov and Sunyaev (1999). In Section 3, we briefly summarize some of the features of two of the polarization components that are induced when the CMB is doubly scattered in a (non-idealized) cluster whose dynamical state and gas properties are deduced directly from hydrodynamical simulations.

2. Integrated S–Z observables in a non-Gaussian model

It has been suggested (Mathis et al., 2004) that some observational results possibly point to an appreciable deviation from a Gaussian probability distribution function (PDF) of the primordial density fluctuation field. These are the relatively high CMB power at high multipoles measured by the *CBI* (Mason et al., 2003) and *ACBAR* (Kuo et al., 2004) experiments, the detection of structures with high velocity dispersions at redshifts $z = 4.1$ (Miley et al., 2004) and $z = 2.1$ (Kurk et al., 2004), and the apparent slow evolution of the X-ray luminosity function (as deduced from catalogs compiled by Vikhlinin et al. (1998), Mullis et al. (2003)).

Analyses of *WMAP* all-sky maps (Komatsu and Seljak, 2002; McEwen et al., 2006) do not rule out an appreciable non-Gaussian PDF tail on clusters scales. Enhanced power on the scales of clusters may lead to detectable differences in S–Z power levels and cluster number counts as compared with those predicted from the standard Gaussian PDF. It is of interest, therefore, to explore the consequences of a non-Gaussian PDF, especially in light of the large S–Z surveys that will be conducted by ground-based telescopes and the Planck satellite. These will measure the effect in thousands of clusters and map the anisotropy it induces in the CMB spatial structure.

The non-Gaussian model we consider here has its origin in isocurvature fluctuations produced by massive scalar fields that are thought to have been present during inflation. The model is characterized by a PDF that has a χ^2_m distribution of m CDM fields which are added in quadratures (Peebles, 1999; Koyama et al., 1999).

We have carried out detailed calculations of the S–Z power spectrum and cluster number counts predicted in the standard Gaussian and a non-Gaussian model with $m = 1,2$. Below we briefly describe the principal aspects of our work and its main results; a more comprehensive description can be found in Sadeh et al. (2006, hereafter, SRS).

2.1. Calculations

The integrated statistical properties of the population of clusters involve the basic cosmological and large-scale quantities, and essential properties of intracluster (IC) gas. For Gaussian models these properties have been quantitatively determined by semi-analytic calculations (e.g., Colafrancesco et al., 1994, 1997; Molnar and Birkinshaw, 2000; Sadeh and Rephaeli, 2004) and from hydrodynamical simulations (e.g., Springel et al., 2001).

The Press and Schechter (1974) mass function is

$$n(M,z) = -F(\mu)\frac{\rho_b}{M\sigma}\frac{d\sigma}{dM}dM, \quad (1)$$

where $\mu \equiv \delta_c/\sigma$ and ρ_b is the background density. The critical overdensity for spherical collapse (which is only weakly dependent on redshift) is assumed to be constant, $\delta_c = 1.69$, and the density field variance, smoothed over a top-hat window function of radius R, is

$$\sigma^2(R) = \int_0^\infty P(k)\widetilde{W}^2(kR)k^2\,dk, \quad (2)$$

where $P(k) \equiv Ak^nT^2(k)$. Evolution of the mass variance is given in

$$\sigma(M,z) = \frac{g[\Omega_m(z)]}{g[\Omega_m(0)]}\frac{\sigma(M,0)}{1+z}, \quad (3)$$

where

$$\Omega_m(z) = \frac{\Omega_m(0)(1+z)^3}{(1+z)^2[1+\Omega_m(0)z-\Omega_\Lambda(0)]}; \quad (4)$$

$$\Omega_\Lambda(z) = 1 - \Omega_m(z),$$

and (Carroll et al., 1992)

$$g[\Omega_m(z)] = \frac{2.5\Omega_m(z)}{[\Omega_m(z)^{4/7} - \Omega_\Lambda + (1+\Omega_m(z)/2)(1+\Omega_\Lambda/70)]}. \quad (5)$$