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Sunyaev–Zel'dovich polarization simulation

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Abstract

Compton scattering of cosmic microwave background (CMB) photons on galaxy cluster electrons produces a linear polarization, which contains some information on the local quadrupole at the cluster location. We use N-body simulations to create, for the first time, maps of this polarization signal. We then look at the different properties of the polarization with respect to the cluster position and redshift.

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1. Introduction

Photons from the last scattering surface (the cosmic microwave background; CMB) propagate toward us, interacting with the matter in between. These interactions cause a change in the temperature and polarization pattern of the CMB. For instance, Compton scattering can produce linear polarization if the interacting medium is illuminated by a quadrupolar radiation field.

Sunyaev and Zel'dovich (1980) first explored the different effects on CMB polarization that galaxy clusters, here the interacting medium, could produce and distinguished three sources: the primordial CMB quadrupole seen by the clusters, the quadrupole produced by a first interaction inside the cluster, and the transverse velocity of the cluster. Similar effects have been proposed more recently (Chluba and Mannheim, 2002; Diego et al., 2003). Though these are very small signals, it has been advocated that one can get interesting

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information on the CMB quadrupole (Kamionkowski and Loeb, 1997; Portsmouth, 2004) and the cluster transverse velocity (Sunyaev and Zel'dovich, 1980; Sazonov and Sunyaev, 1999; Audit and Simmons, 1999) through these effects. Cooray and Baumann (2003) have shown that the contribution from the primordial quadrupole dominates the signal, it will therefore be the focus of our work.

In this paper, we present the first map of the polarization arising from the primordial quadrupolar CMB anisotropies (though see Delabrouille et al. (2002) and Melin (2004) for simulations of other SZ effects) and look for the typical properties of the signal. We describe in the following our physical model of the induced polarization, we then show how we simulate the effect under reasonable assumptions, we finish by showing interesting properties of this simulation.

2. Model

The primordial CMB quadrupole is generated by two effects: the SW (Sachs–Wolfe) effect and the ISW (Integrated SW) effect which for adiabatic fluctuations in the cluster reference frame can be written as (Sachs and Wolfe, 1967):

$$\frac{\Delta T_{\mathrm{SW}}(\hat{n})}{T} = -\frac{1}{3}\Phi(\hat{n}, z_{\mathrm{CMB}}), \tag{1}$$

$$\frac{\Delta T_{\mathrm{ISW}}(\hat{n})}{T} = -2\int_{z_{\mathrm{CMB}}}^{z_{\mathrm{clus}}} \dot{\Phi}(\hat{n}, z)\,\mathrm{d}z, \tag{2}$$

where z_{clus} is the cluster redshift, $z_{\mathrm{CMB}} \simeq 10^3$ is the redshift of the last scattering surface, and $\hat{n}$ is the angular position of the cluster. The cross section for Compton scattering is:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{3\sigma_{\mathrm{T}}}{8\pi}|\hat{\epsilon}_{\mathrm{in}} \cdot \hat{\epsilon}_{\mathrm{out}}|^2, \tag{3}$$

where $\hat{\epsilon}_{\mathrm{in}}, \hat{\epsilon}_{\mathrm{out}}$ stand, respectively, for the input and output photon polarization vector, and σ_{T} for the Thomson cross-section. Using the stokes parameters Q and U, defining our coordinate system (centered on the cluster) with the axis $\hat{z}$ in the line of sight direction (x- and y-axes will define Q and U basis), and integrating on all incoming photon directions, we get:

$$Q(\hat{z}) = \frac{3\sigma_{\mathrm{T}}}{16\pi}\int \Delta T(\hat{n})\sin^2\theta\cos 2\phi\,\mathrm{d}\Omega, \tag{4}$$

$$U(\hat{z}) = \frac{3\sigma_{\mathrm{T}}}{16\pi}\int \Delta T(\hat{n})\sin^2\theta\sin 2\phi\,\mathrm{d}\Omega. \tag{5}$$

Substituting $\Delta T_{\mathrm{SW}}(\hat{n}) + \Delta T_{\mathrm{ISW}}(\hat{n})$ for $\Delta T(\hat{n})$ and τ_{clus} for σ_{T} in the above, we obtain the polarization created by clusters for a given potential Φ.

3. Simulations

In order to create a Φ field with which we compute the local quadrupole, we generated a cube of 256^3 points covering 30 Gpc in size at $z = 0$, which gave us enough space to trace back to the last scattering surface ($z \simeq 1100$) with sufficient resolution (around 100 Mpc/h) to compute the integrals in Section 2.

We used a simple Harrison–Zel'dovich, or scale-invariant, spectrum to model the potential fluctuations as we only look at very large scales. We then used an N-body simulation (see Vale et al. (2004), Amblard et al. (2004) for more details) to compute τ_{clus} in different z slices (35 from $z = 0$ to 2). The last step is to combine all of these ingredients:

$$Q(\hat{u}) = -\sum_i \frac{3\tau_{\mathrm{clus}}(z_i)}{16\pi}\sum_{\theta,\phi}\left\{\frac{\Phi(r_i\hat{u} + r_i^{\mathrm{CMB}}\hat{n}, z_{\mathrm{CMB}})}{3} + 2\sum_j \dot{\Phi}(r_i\hat{u} + r_j\hat{n}, z_j)\right\}\sin^2\theta\cos 2\phi\Delta z\Delta\Omega, \tag{6}$$

where $\tau_{\mathrm{clus}}(z_i)$ stands for the optical depth at redshift z_i (corresponding to one of our N-body simulation slices), r_i represents the distance to this redshift, $\hat{n}$ is the unit vector of direction (θ,ϕ) (we map the directions using the HEALPix[1] package), and r_i^{CMB} is the distance to the last scattering surface from the redshift z_i. We obtain $U(\hat{u})$ by substituting cos2ϕ by sin2ϕ.

From these Q and U maps we can compute the polarization fraction and angle or the E and B maps. In order to keep our algorithm simple and

[1] http://www.eso.org/science/healpix