PROCEEDINGS OF SCIENCE

Ray-tracing through N-body simulations and CMB anisotropy estimations

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The fully nonlinear evolution of galaxy clusters and substructures –given by N-body simulations– is used to simulate maps of the Rees-Sciama (RS) effect. The universe is covered by simulation boxes and photons move across them. A recent technique for ray-tracing through N-body simulations is described in detail and implemented. It is based on the existence of preferred directions (to move photons through the boxes), and also on the use of an appropriate cutoff. By the moment, only small RS maps (around $2^\circ \times 2^\circ$) have been obtained with this technique. We justify that our ray-tracing procedure is also appropriate in the case of large simulation cubes (~ 1000 Mpc per edge), where high enough resolutions can be obtained with appropriate N-body codes and modern computers.

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1. Introduction

This paper is devoted to the study of the so-called Rees-Sciama (RS) effect [1] – [4]. It is an integrated gravitational effect produced by nonlinear cosmological structutres at low redshifts. Fully nonlinear evolution is simulated by using a Perticle-Mesh (PM) N-body code. Cosmic Microwave Background (CMB) photons move in a periodic universe covered by simulation boxes. Periodicity magnifies the RS and lens effects [5], but an appropriate ray-tracing procedure [5] makes negligible this magnification. Here, our procedure is described in detail with the essential aim of facilitating its implementation. Our ray-tracing is designed in such a way that: *while the RS effect is being produced, the CMB photons cross successive boxes through statistically independent regions separated by a certain distance D*, in this way, the potential of a given cluster (or structure) does not contribute various times to the RS effect and, consequently, periodicity magnification becomes very small. This idea is implemented as follows: (i) photons move along special directions (hereafter: *preferred directions*) and (ii) the contribution of the spatial scales greater than D is substracted (cutoff), from the N-body output potential, before using it to estimate the RS effect. Both the preferred directions and the cutoff are to be appropriately chosen after fixing the size of the simulation box.

Our simulations are based on the concordance model with the following choice of parameters: the reduced Hubble constant is $h = 10^{-2}H_0 = 0.71$ (where H_0 is the Hubble constant in units of $Km\ s^{-1}Mpc^{-1}$), the density parameters associated to dark matter, baryonic matter, and vacuum energy are $\Omega_d = 0.23$, $\Omega_b = 0.04$, and $\Omega_\Lambda = 0.73$, respectively. There are no tensor modes and the spectrum of the adiabatic scalar modes is first calculated with CMBFAST [6] and, then, it is normalizaed by the condition $\sigma_8 = 0.9$; this σ_8 value is marginally compatible with the analysis of the first year WMAP (Wilkinson Microwave Anisotropy Probe) data, ([7]), but it is greater than the value (~ 0.76) obtained in the analysis of three year WMAP data recently published ([8]) (after our calculations were performed).

2. Numerical methods and results

Our PM code simulate dark matter evolution in a 256 Mpc cube. The number of particles is 512^3 and the cell size is 0.5 Mpc. It is assumed that the RS effect is produced in the redshift interval (0,5.2) and, consequently, the resulting RS maps are small ($1.83^\circ \times 1.83^\circ$). Greater simulation cubes are necessary to get more extended maps, but the greater the cube, the smaller the resolution (for a similar computational cost). From $z = 5.2$ to $z = 0$, the distance travelled by a photon is ~ 8000 Mpc and ~ 30 simulation boxes cover all the trajectory. For appropriate preferred directions, CMB photons cross these 30 boxes through different statistically independent regions, reaching the initial positions just inside the 31th cube; that is illustrated in Figs. (1) and (2), where the preferred directions 1 and 2 (hereafter P.D.1 and P.D.2) are, respectively, considered. In each of these figures, the reader can find all the quantities necessary to obtain the unit vector of the represented direction (either P.D.1 or P.D.2) and the distance D between the regions crossed in neighbouring boxes (Euclidean geometry). This distance is $D = 51.9$ Mpc ($D = 66.7$ Mpc) for P.D.1 (P.D.2); therefore, a cutoff eliminating scales greater 60 Mpc is good enough in both cases. The right panels of Figs. (1) and (2) show the the crossing points of the preferred directions P.D.1 and P.D.2 with successive horizontal cube faces, in both cases, 30 of these faces are crossed;

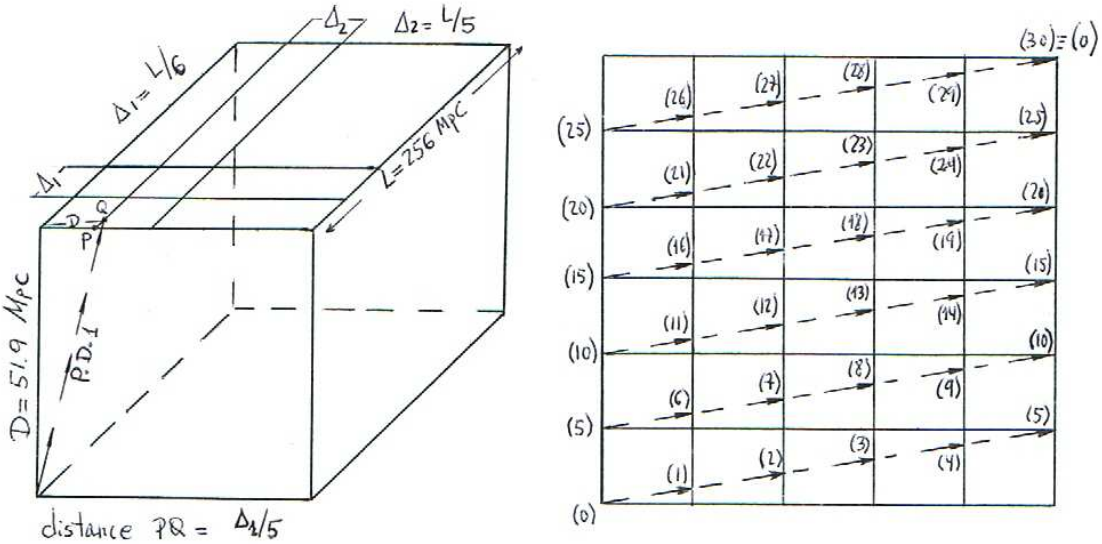

Figure 1: Left: sketch of the photon motion along the preferred direction 1 (P.D.1) inside the first box. Right: representation of the point (i) where a photon moving along P.D.1 crosses the upper face of the (i)-th box. Arrows connect pairs of successive crossing points (i) and (i+1) separated by the distance *D* (see text).

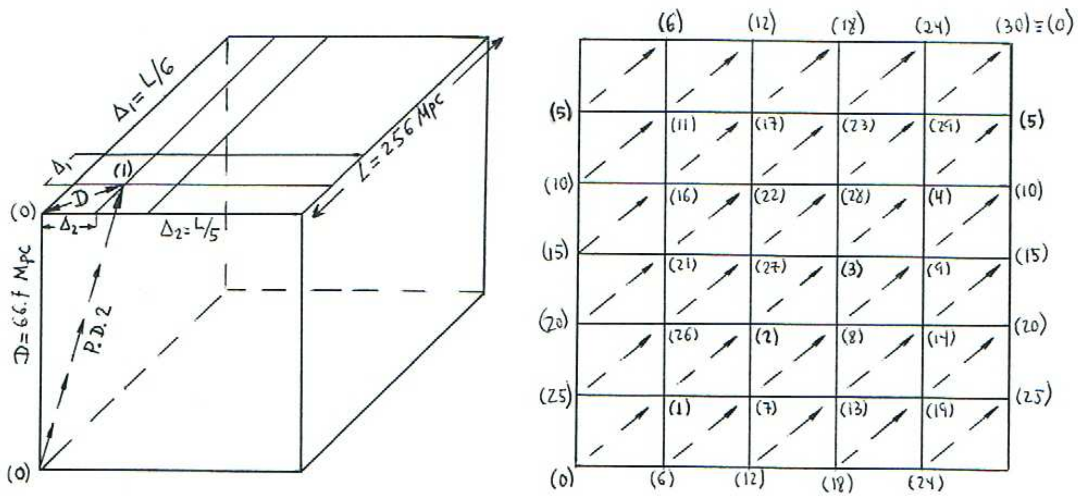

Figure 2: Same as in Fig. (1) for the preferred direction 2 (P.D.2)

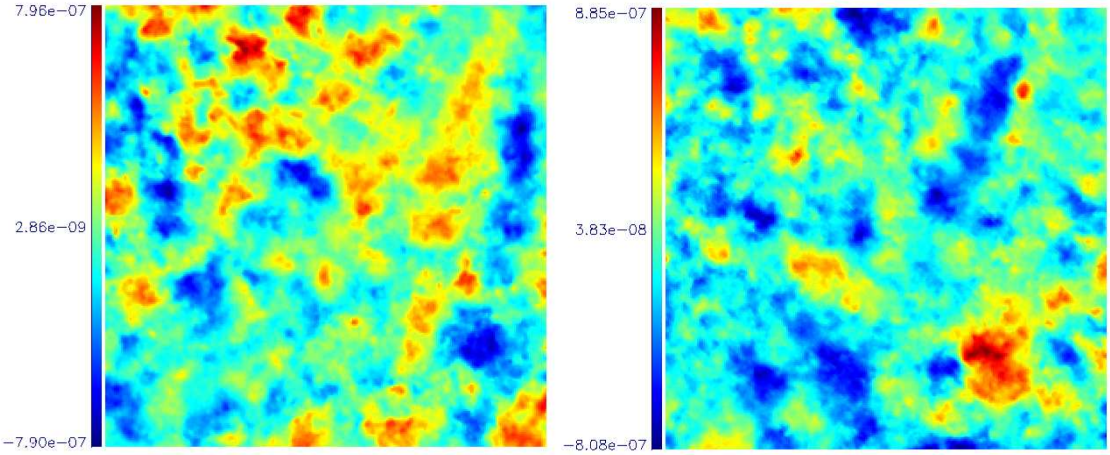

Figure 3: $1.83^\circ \times 1.83^\circ$ RS simulated maps obtained as it is described in the text

however, for P.D.1, the number of crossed vertical faces is smaller than in the case P.D.2. Although periodic boundary conditions ensure that there are not discontinuities at crossing points, regions close to faces, edges, and vertices are the worst simulated ones and, in practice, numerical problems can appear at crossing points (where photons pass from box to box); by this reason, the number of crossing points must be minimized and, consequently, we ever use P.D.1 in our calculations. Figure 3 shows two RS maps obtained with P.D.1 and a cutoff at 60 Mpc.

The use of P3M and AP3M codes would lead to higher resolutions in larger boxes, from which, more extended RS maps could be obtained. Even in the case of simulations in 1000 Mpc boxes, our ray-tracing procedure is appropriate because the photon trajectories crosses ~ 8 of these boxes and, consequently, periodicity magnification must be taken into account.

Acknowledgments

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