Modeling Cosmic Microwave Background Distortions Through Particle-in-Cell Simulations of the Sunyaev-Zeldovich Effect

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The cosmic microwave background (CMB) is an astronomical phenomenon that serves as a direct snapshot of the early Universe and is imprinted with the interactions of galaxy clusters. The most significant interaction, the Sunyaev-Zeldovich (SZ) effect, results in spectral distortions of the CMB due to inverse Compton scattering. The SZ effect was modeled using a particle-in-cell simulation to predict CMB photon energy fluctuations across intergalactic and intracluster medium. This experiment acts as a foundation for correlating CMB observations with crucial physical properties. Particle-in-cell simulations that individually integrate the trajectory of charged particles in discrete time steps were constructed, modeling inverse Compton scattering from first principles. Photon energy changes in scattering collisions were verified with a derived equation and benchmarking simulation. The findings revealed that CMB deviations from the initial black body distribution are amplified proportional to the optical depth (probability of interaction). As optical depth was held constant, distortions of photon energy from the initial distribution varied linearly with electron temperature. Peak spectra position is solely correlated with electron temperature and independent of optical depth. The results suggest that galaxy cluster density and temperature distribution can be directly derived from CMB observational data, solidifying the importance of past missions like WMAP and COBE. Because the Sunyaev-Zelodvich effect is uniquely independent of redshift compared to other astronomical factors, these results also indicate promise in future work using CMB distortions to determine dark matter distribution and ultimately understand the formation and expansion of the universe.

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