CLUSTERS IN PREHEATING SIMULATION AND ITS EFFECT ON CMB SPECTRUM

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We report an instantaneous heating scheme at $z = 2$ that can produce bound objects obeying the observed mass-temperature and luminosity-temperature relations. Such heating reduces the Sunyaev–Zeldovich (SZ) flux by a factor $3 - 2$ on scale of $4 - 6$ arcminutes. It exacerbates the need for the matter-fluctuation normalization σ_8 to assume an exceedingly high value (~ 1.2), if the several-arcminute excess anisotropy detected by the CBI experiment is entirely caused by the SZ effect of intergalactic hot gas. By contrast, we find that the several-arcminute excess detected by ACBAR can be consistent with the preheated SZ signals of $\sigma_8 = 1$.

Keywords: cosmology; theory; cosmic microwave background; intergalactic medium.

1. Introduction

In the hierarchical structure formation model of cold dark matter, gravitationally bound objects obey similarity scaling relations^{1 2}. However, the observed X-ray luminosity-temperature ($L-T$) relation shows that the cluster temperature appears considerably higher than the scaling $T \propto L^{1/2}$, indicates, more so for low-mass clusters than for high-mass clusters^{3 4 5}. Although the observed mass-temperature ($M-T$) relation roughly obeys $T \propto M^{2/3}$, the temperature is still found higher by 30% or so than expected from adiabatic structure formation processes⁶. These evidences suggest certain non-gravitational energy injection to be operative. One candidate of heat sources is the outflows from Active Galactic Nucleus (AGN)⁷⁸. Investigators have tested various schemes for heat injection at $z \geq 4$ ^{9 10 11 12}. Although the observed $L-T$ relation may be recovered, they failed in producing the observed $M-T$ relation.

Parallel to the developments in cluster physics, the CBI¹³ experiment the ACBAR¹⁴ experiment independently discovered a higher level of temperature anisotropy than anticipated by, around the harmonic mode number $2000 < l < 3000$, in cosmic-microwave-background (CMB) radiation. This feature was attributed to the Sunyaev–Zeldovich (SZ) effects^{15 16}. To account for the high level of SZ signals, the value of σ_8 was estimated, by a joint analysis, to be unity, though a slightly larger σ_8 fits the CBI data better. On the other hand, the cluster abundance study of

the Sloan Digital Sky Survey (SDSS) finds that $\sigma_8\Omega_m^{0.6} = 0.35 \pm 0.03$ ¹⁷, consistent with results of X-ray cluster abundance (See for example Ref. 18 and references therein). The extreme value $\sigma_8 = 1$ thus yields a low matter-density parameter, $\Omega_m = 0.175 \pm 0.025$. If the SZ effect indeed accounts for the high- l excess of CBI and ACBAR, preheating will exacerbate the awkward situation of the already large σ_8 . Past works have indicated that preheating reduces the SZ flux^{10 9 19}. These works were, however, unable to recover both observed $M - T$ and $L - T$, rendering the reduction of SZ flux not amenable to X-ray calibration. Motivated by the evidences of late preheating around $z = 2$ ^{20 21}, we study a local heating scheme, which recovers both observed $M - T$ and $L - T$ relations.

2. $M - T$ and $L - T$ Relations in Simulation

We ran cosmological hydrodynamic simulations with the GADGET code²² for both $\sigma_8 = 0.94$ and 1 cases in a periodic box of comoving size $100h^{-1}$ Mpc. The simulations contain 256^3 dark matter particles and 256^3 gas particles, with the gravitational softening length being $20h^{-1}$ kpc and the mass resolution $4.8 \times 10^9 h^{-1} M_\odot$ for the dark matter and $0.83 \times 10^9 h^{-1} M_\odot$ for the gas. All runs start at $z = 100$ with the same initial conditions for $(n_s, \sigma_8, \Omega_m, \Omega_b, \Omega_\Lambda, h) = (1, 0.94, 0.34, 0.05, 0.66, 0.66)$.

Heat injection occurs at $z = 2$ and assumes a density-dependent form,

$$\Delta u = u_0 \exp\left[-\frac{\rho_{b0}}{\rho_b}\right], \quad (1)$$

where ρ_b and ρ_{b0} are the local and background baryon densities respectively, and u is the specific internal energy. This form of heating ensures the highest-density region to receive a constant specific energy u_0 while the lowest density region no heat. We find the best value of $u_0 = 7$ keV/baryon, or equivalently 0.75 keV/baryon on average. Since our heating occurs late in time and since a present-day cluster of 10keV is still deficient in x-ray luminosity (c.f. Fig.1(b) below), we find this amount of local heat injection reasonable.

Throughout this work, emission-weighted temperature is used. Figure 1(a) compares both adiabatic and preheating $M_{500}-T_{500}$ relation from our $\sigma_8 = 0.94$ simulation with the fitting formula for adiabatic simulations given by Evrard, Metzler & Navarro (1996)²³ and with the fitting formula of HIFLUGCS data given by Finoguenov, Reiprich, & Böhringer (2001)⁶. The $M_{500} - T_{500}$ relation of the adiabatic simulation agrees fairly with that of Evrard *et al.*²³, but both yield too low a temperature in bound objects. On the other hand, our preheating simulation yields an $M_{500} - T_{500}$ relation agreeing very well with the observations.

A constant metallicity, 0.3 times the solar value, is adopted here to compute the X-ray bolometric luminosity. Figure 1(b) shows L_{500} against T_{500} . Also shown are the observed L_{500} and T_{500} compiled by Arnaud & Evrard (1999)²⁴, Helsdon & Ponman (2000)²⁵ and Markevitch (1998)²⁶. The preheating result for $\sigma_8 = 0.94$ case again shows good agreement with X-ray observations except for some excess luminosity at galaxy group scale with $T_{500} < 1$ keV.

Fig. 1. (a) $M_{500} - T_{500}$ relation: Adiabatic (circles) and preheating (squares) simulation data for $\sigma_8 = 0.94$, to be compared with the another adiabatic simulation (long-dashed line), and the observational data fit (solid line). (b) $L_{500} - T_{500}$ relation: Adiabatic (shaded lines) and preheating (dark lines) simulation results at 4 different redshifts. Observation results are represented as different points.

3. SZ and CMB Power Spectra

The agreement of our $M - T$ and $L - T$ relations with observations assures the proposed heating scheme to be well-constrained by observations. We thus proceed to construct one-deg² SZ maps up to $z = 2.5$, following the method described in da Silva et al.(2000)²⁷.

We employ the scaling formula in Komatsu & Seljak (2002)²⁸ and rescale the SZ power spectra of both $\sigma_8 = 1$ and 0.94 cases in Fig.2 from our original $\Omega_b h^2 = 0.018$ and 0.0218, respectively, to $\Omega_b h^2 = 0.022$ used in Bond *et al.*(2002)¹⁵ for detailed comparison. The CBI deep-field observations scanned a 9 deg² sky¹³. We hence compute the *preheated* SZ power spectrum averaged over 9 one-deg² SZ maps and add it to the (noise-free) primary CMB spectrum of $\Omega_b = 0.04, \Omega_m = 0.3, \Omega_\Lambda = 0.7$ used in Bond *et al.*(2002)¹⁵, to obtain one realization. A total of 40 realizations are constructed for checking the SZ cosmic variance. Both $\sigma_8 = 0.94$ and 1 runs show that preheating reduces the averaged SZ power spectra by a factor 2 – 3 over the angular scales $l = 2000 - 4000$. Clear in Fig.2 is that the preheated SZ+CMB power spectrum of $\sigma_8 = 1$ lies well below the 2 – σ error box of CBI data, but it is consistent with ACBAR data¹⁴.

Using the σ_8^7 scaling law of Komatsu & Seljak (2002)²⁸ to estimate the preheated SZ flux, we find that σ_8 must be raised to 1.2 for SZ effects to explain the CBI high- l data. But Ω_m is then pushed down to 0.13 ± 0.02 , constrained by $\sigma_8 \Omega_m^{0.6} = 0.35 \pm 0.03$ ¹⁷. Such an Ω_m is too low for the Big-Bang nuclear synthesis model to be consistent with the observed X-ray baryon fraction ($\leq 1/4$) in massive clusters^{29 30}. Various explanations, other than SZ effects, for the CBI high- l excess have also been proposed and they were discussed in Pearson *et al.*(2003)¹³.

Fig. 2. Comparison of CBI and ACBAR data with the averaged preheating and adiabatic SZ power spectra of $\sigma_8 = 0.94$ & 1, and with the CMB + preheated SZ spectrum of $\sigma_8 = 1$ where its $1\text{-}\sigma$ error bars arise from the cosmic variance over 40 fields of 9 deg^2 . While the $\sigma_8 = 1$ adiabatic SZ spectrum comfortably intersects the CBI $2\text{-}\sigma$ error box over the band $\ell=2000\text{--}4000$, the preheating spectrum lies well below the CBI data.

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