Effects of Preheated Clusters on the CMB Spectrum

Kai-Yang Lin$^1$, Lihwai Lin$^1$, Tak-Pong Woo$^1$, Yao-Huan Tseng$^1$ & Tzihong Chiueh$^{1,2}$

$^1$ Department of Physics, National Taiwan University, Taipei, Taiwan
$^2$ Institute of Astronomy and Astrophysics, Academia Sinica, Taipei, Taiwan

ABSTRACT

Mounting evidence from x-ray observations reveals that bound objects should receive some form of energy in the past injected from non-gravitational sources. We report that an instantaneous heating scheme, for which gases in dense regions were subjected to a temperature jump of 1keV at $z = 2$ whereas those in rarified regions remained intact, can produce bound objects obeying the observed mass-temperature and luminosity-temperature relations. Such preheating lowers the peak Sunyaev-Zeldovich (SZ) power by a factor of 2 and exacerbates the need for the normalization of matter fluctuations $\sigma_8$ to assume an extreme high value ($\sim 1.1$) for the SZ signals to account for the excess anisotropy on 5-arcminute scale detected by the Cosmic Background Imager in the cosmic microwave background radiation.

Subject headings: cosmology: theory – cosmic microwave background – intergalactic medium

1. Introduction

In the hierarchical structure formation model of cold dark matter, gravitationally bound objects ought to obey self-similar scaling relations. That is, at any cosmic epoch the mass of a collapse object scales as the third power of its size, and the squared velocity dispersion or temperature scales as the second power of the size. These scaling relations follow from a straightforward dimensional analysis, given that gravitational collapse occurs much faster than Hubble expansion and depends on only two dimensional (quasi-)constants: the gravitational constant $G$ and the background matter density $\rho_{mb}$. Although $\rho_{mb}$ varies on the Hubble time scale, such dependence on long time scale affects only the interior profiles of bound objects (Navarro et al. 1996; Shapiro & Iliev 2002; Chiueh & He 2002).

However, x-ray observations in the past years have consistently indicated that gases in bound objects violate the self-similar scaling relations. The observed x-ray luminosity-temperature ($L - T$) relation shows that at a given luminosity the cluster temperature appears considerably higher than the scaling relation ($L \propto T^2$), more so for low-mass clusters than for high-mass clusters (Ponman et al. 1996; Allen & Fabian 1998; Xue & Wu 2000). The observed mass-temperature (M-T) relation also follows the same trend in violating the $M \propto T^{3/2}$ scaling law (Finoguenov et al. 2001). More remarkably, recent XMM observations of metal lines that directly probe the core temperatures of cooling-flow clusters find that gases of temperature below some fraction of bulk temperature are unexpectedly rare (Peterson et al. 2002), suggestive of an entropy floor at the cluster core (Ponman, Cannon & Navarro 1999; Loewenstein 2000) thus requiring some form of non-gravitational energy injection to compensate for Bremsstrahlung cooling.

One candidate for the quested heat sources in clusters and groups is the outflow from Active Galactic Nucleus (AGN). (Tabor & Binney, 1993; David et al. 2001). If this is correct, such a mechanism should be more pronounced in the far past when quasars were highly active than the present. For this and other reasons, investigators have tested various schemes for heat injection at $z \geq 4$ (da Silva et al. 2001; Bialek et al. 2001; Muanwong et al. 2002). However, recent combined analyses of the ASCA data on the entropy profiles in galaxy groups and the structure forma-
tion model indicate that preheating should occur impulsively around $z = 2 - 2.5$ (Finoguenov et al. 2002). A similar conclusion has also been reached from a different perspective, using the constraint on Compton $y$ ($< 1.5 \times 10^{-5}$) provided by the COBE/FIRAS data in testing the SZ effect at the hot spots of AGN jets (Yamada & Fujita 2001). The present work has been so motivated to consider impulsive heating around $z \sim 2$.

On the other hand, the recent Cosmic Background Imager (CBI) experiment discovered that the temperature anisotropy of cosmic-microwave-background radiation (CMB) exhibits a 3σ higher level of anisotropy, around the harmonic mode number 2000 $< l < 3500$, than anticipated with Silk damping (Pearson et al. 2002). This feature has been attributed to the large SZ flux (Bond et al. 2002). In order to account for such a large SZ flux, the value of $\sigma_8$ needs to be at least as large as unity, though from Figs. 10 and 11 of Bond et al. (2002), a slightly larger $\sigma_8$ fits the CBI data even better.

The SZ flux has been known to depend very sensitively on $\sigma_8$ (Fan & Chiuhe 2001; Komatsu & Seljak 2002), due to the sensitive dependence of cluster number density on the amplitude of matter fluctuations at the high end of mass function. Hence the SZ effect can serve as a unique probe to fix $\sigma_8$ to high precision. As of today, the large-scale galaxy distribution combined with distant supernova and CMB data have constrained $\sigma_8$ within a narrow window $0.75 < \sigma_8 < 1$ (Bond et al. 2002). From the perspective of cluster abundance explored by the Sloan Digital Sky Survey (SDSS) (Bahcall et al. 2002), the extreme value $\sigma_8 = 1$ has, however, placed a considerably low ceiling for the matter density $\Omega_m = 0.175 \pm 0.025$.

If the SZ effect indeed accounts for the CBI deep-field excess, preheating can actually exacerbate the awkward situation pertinent to a high value of $\sigma_8$. Past works have indicated that preheating generally reduces the SZ flux (Bialeck et al. 2001; da Silve et al. 2001). However, these works were not able to reproduce both observed $L - T$ and $M - T$ relations and hence the reduction factor for SZ flux cannot be reliably gauged. The present paper reports that impulsive heating around $z = 2$ can reproduce the observed $L - T$ and $M - T$ relations and yields a modified SZ power spectrum lower than that without preheating by a factor 2. It therefore pushes $\sigma_8$ upward by a factor 1.1 for SZ effects to explain the CBI high-$l$ result, and $\Omega_m$ downward by 1.2 constrained by local cluster abundance.

2. Simulations, M-T and L-T Relations

Cosmological hydrodynamical simulations with the GADGET code (Springel, Yoshida & White 2001) were run for both $\sigma_8 = 0.94$ and 1 cases in a periodic box of comoving size $100 h^{-1}$ Mpc on our 32-node, dual-cpu Athlon cluster. The simulations contain $256^3/2$ dark matter particles and $256^3/2$ gas particles, and the gravitational softening length is chosen to be $20 h^{-1}$ kpc. Both adiabatic and preheating runs start at $z = 100$ with the same initial conditions of $n_s = 1$ and $(\sigma_8, \Omega_m, \Omega_b, \Omega_{\Lambda}, h) = (0.94, 0.34, 0.05, 0.66, 0.66)$ and $(1, 0.3, 0.044, 0.7, 0.64)$ separately.

Preheating takes place at $z = 2$ with a density-dependent injection energy per mass,

$$\Delta u = u_0 \exp[-\beta \rho_{m0}/\rho_m],$$

where $\rho_{m0}$ is the background matter density. Both $u_0$ and $\beta$ are parameters to be tuned to fit the observed $M - T$ and $L - T$ relations described below. This form of energy injection ensures that the low-density regions receive no heat, giving rooms for some cool gases to survive and the high density regions receive a constant energy per mass $u_0$. The injected entropy has minima at the cores of bound objects and maxima at the outskirts around $\rho_m \sim \beta \rho_{m0}$. This heating scheme is similar, though not in detail, to the entropy injection of Borgani et al. (2001 & 2002). The best parameters are found to be $\beta = 1$ and $u_0 = (500 \text{ km/sec})^2$. Such a value of $u_0$ corresponds to 1 keV temperature, and the amount of injected heat is equivalent to giving every baryon a 0.5 keV temperature jump. This amount is roughly consistent with those suggested by recent studies on heat injection from the bound-object interiors (Loewenstein 2000; Wu, Fabian & Nulsen 2000; Bower et al. 2001; Borgani et al. 2001 & 2002; Xue & Wu 2002).

Standard FOF algorithm with a 0.2 linking length is employed to locate halos. The mass centers may considerably deviate from the peaks of spherical over-density, such as in the case of major mergers. In these cases, the over-density so
obtained is not useful for testing the $L - T$ and $M - T$ relations. They are avoided by selecting only those haloes with nonzero $M_{2500}$, where $M_n$ represents the mass within a sphere of over-density $n$ times that of the critical density. The temperature $T$ of an ionized plasma is related to the internal energy per mass $u$ of the neutral-fluid in hydrodynamic simulations by $k_B T = (2/3) \mu m_p u$, where $\mu$ is the mean "molecular" weight of $e^-$, $p^+$ and $He^{2+}$ and equal to 0.588. In addition, we define the Bremsstrahlung emission-weighted temperature $\langle n_e^2 T^{3/2} \rangle / \langle n_e^2 T^{1/2} \rangle$, to be compared with the measured temperature of x-ray continuum.

Figure 1 compares both adiabatic and preheating $M_{500} - T_{500}$ relations from our $\sigma_8 = 0.94$ and 1 simulations with the fitting formula given by Evrard, Metzler & Navarro (1996) from their adiabatic simulations, and with the fitting formula of Finoguenov, Reiprich, & Böhringer (2001) derived from the observational data re-scaled to $z = 0$. Only data with luminosity higher than $10^{41}$ erg/sec are plotted here. The $M_{500} - T_{500}$ relation of the adiabatic simulation agrees fairly with that of Evrard et al., but both predict too low a temperature in bound objects. On the other hand, our preheating simulations yield $M_{500} - T_{500}$ relations of $\sigma_8 = 0.94$ and 1 agreeing quite well with the observations.

The x-ray luminosity requires somewhat sophisticated treatments (Mathiesen & Evrard 2001), since line emission below 0.5 keV can vastly dominate the Bremsstrahlung continuum. A constant metalicity, 0.3 times the solar value, is adopted and the bolometric luminosity reads

$$L_{500} = 1.4 \times 10^{-27} \int T^{1/2} g(T) n_e(\sum_i n_i Z_i^2) dV$$

in unit of erg/sec, where the volume integration is up to $R_{500}$, the summation is over different ion species, $Z$ is the atomic number, and $g(T)$ the Gaunt factor. Figure 2 shows $L_{500}$ against the emission weighted $T_{500}$. Also shown are the observed $L_{500}$ and $T_{500}$ compiled from Arnaud & Evrard (1999), Helsdon & Ponman (2000) and Markevitch (1998). The preheating results for both $\sigma_8 = 0.94$ and 1 cases again show excellent agreement with x-ray observations. Interestingly, Novicki, Sornig & Henry (2002) pointed out that the $L - T$ relation is consistent with no evolution in a low-density universe. Our preheating result does display this tendency within $0 < z < 1$. This behavior also suggests that after initial transients, the heated clusters quickly assume certain relaxed states since $z = 1$.

3. **SZ and CMB Power Spectra**

The agreement of our $M - T$ and $L - T$ relations with observations confirms the proposed heating scheme to be quantitatively viable. We thus proceed to construct the 1 deg$^2$ SZ map by projecting the electron pressure through the randomly displaced and oriented simulation boxes, separated by $100h^{-1}$Mpc, along a viewing cone to the redshift direction up to $z = 2.5$. The average power spectra of 40 such SZ maps for each adiabatic and preheating simulation of $\sigma_8 = 0.94$ and 1 cases are shown in Fig.3. The adiabatic results are consistent with earlier GADGET results (Springel et al. 2001), where small-scale structures are more abundant than those in grid-based hydrodynamic simulations (Zhang et al. 2002). Both $\sigma_8 = 0.94$ and 1 runs show that preheating lowers the averaged SZ power spectrum by a factor 2 on few-arcminute
Fig. 2.— \(L_{500} - T_{500}\) relation: square, circle, and diamond symbols are the observed x-ray luminosities and temperatures given by different groups as described in the text. The solid, dashed, dotted and long-dashed lines are the simulation results for \(\sigma_8 = 0.94\) at \(z = 0, 0.5\) and 1, and for \(\sigma_8 = 1\) at \(z = 0\), respectively. The upper band is for the adiabatic simulations, and the lower band for the preheating simulations. Both display little evolution within \(0 < z < 1\).

In Fig. 3 we have rescaled the power spectra of the \(\sigma_8 = 1\) case from original \(\Omega_b h^2 = 0.018\) to \(\Omega_b h^2 = 0.022\) so as to be compared with those analyzed in Bond et al. (2002). The CBI deep-field observations scanned a 9 deg\(^2\) sky (Pearson et al. 2002). We hence compute the preheated SZ power spectrum averaged over 9 one-deg\(^2\) SZ maps, which is then added to the (error-free) primary CMB spectrum of \(\Omega_b = 0.04, \Omega_m = 0.3, \Omega_{\Lambda} = 0.7, n_s = 0.975, h = 0.68\), parameters used in Fig.11 of Bond et al. (2002), to obtain one realization. A total of 40 realizations are constructed.

The preheated SZ power spectrum of \(\sigma_8 = 1\) looks very much like the adiabatic power spectrum of \(\sigma_8 = 0.9\), according to the scaling law given by Komatsu & Seljak (2001) that the peak SZ power approximately scales as \(\sigma_8^7\). The 1\(\sigma\) error bars for the \(\sigma_8 = 1\) preheated SZ+CMB power arise from the cosmic variance of SZ clusters and are seen to be within a factor 1.3 from the mean. Also clear in Fig. 3 is that the preheated SZ+CMB power spectrum nearly misses the 2-\(\sigma\) error box of band-averaged power in CBI deep data by 1\(\sigma\). Such reduction of SZ power by preheating makes it implausible for the SZ effect to explain the excess flux detected by CBI around 2000 < \(l\) < 4000 under the framework of concordance model with \(\sigma_8 = 1\). Employing the \(\sigma_8^7\) scaling law, we estimate that the required \(\sigma_8\) needs to be raised to 1.1 in order to be consistent with the CBI high-\(l\) excess.

4. Conclusions

The agreement of our preheating cosmological simulations with the observed \(M - T\) and \(L - T\) relations demonstrates that the impulsive heating scheme described by Eq.(1) is a plausible prescription, though it is probably not the unique one and its physical origin is unclear. Contrary to our results, recent simulations of Borgani et al. (2002) adopting entropy injection failed in producing the observed \(M - T\) relation despite their successful reproduction of the \(L - T\) relation. Various preheating schemes so far reported tend to yield reduced SZ flux, which in our case can be attributed to that gases impulsively blown away from the gravita-
tional potential well form an extended halo, which can subsequently not fall into, therefore compressionally heated by, the ever-growing potential well. The agreement of our results with the observed $M-T$ and $L-T$ relations encourages us to believe that our quantitative prediction of the preheated SZ flux reduced by a factor 2 is founded on an empirically sound base.

This reduction of SZ flux has a significant implication to the interpretation of the CBI deep-field results, in that the measured $3\sigma$ enhancement of CMB high-$l$ anisotropy is unlikely to be caused by the SZ effect of intra-cluster gases in a $\sigma_8 = 1$ universe of concordance model proposed in the original CBI paper (Bond et al. 2002). We estimate that $\sigma_8$ needs to assume a value 1.1 for this mechanism to work. The unfortunate consequence of it is that $\Omega_m$ is then pushed to lie about 0.15 ± 0.02, constrained by $\sigma_8 \Omega_m^{0.6} = 0.35 \pm 0.03$ of recent SDSS cluster abundance studies (Bahcall et al. 2002). Such an $\Omega_m$ can be just too low to be consistent with the observed x-ray baryon fraction ($\leq 1/4$) in massive clusters (Ettori & Fabian 1999; Mohr et al. 1999).

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