AGN HEATING, THERMAL CONDUCTION AND SUNYAEV-ZELDOVICH EFFECT IN GALAXY GROUPS AND CLUSTERS

S. ROYCHOWDHURY
Raman Research Institute, Bangalore 560080, India;
suparna@rri.res.in

M. RUSZKOWSKI 1 AND B.B. NATH 2
JILA, Campus Box 440, University of Colorado at Boulder, CO 80309-0440;
mr.biman@quixote.colorado.edu
accepted for publication in ApJ

ABSTRACT

We investigate in detail the role of active galactic nuclei (AGN) on the physical state of the gas in galaxy groups and clusters, and the implications for anisotropy in the cosmic microwave background (CMB) from Sunyaev-Zeldovich (SZ) effect. We have recently showed that AGNs can significantly change the entropy of the intracluster medium (ICM) and explain the observations of excess entropy in groups and clusters. AGNs are assumed to deposit energy via buoyant bubbles which expand as they rise in the cluster atmosphere and do $PdV$ work on the ICM. Here, we include the effect of thermal conduction, and find that the resulting profiles of temperature and entropy are consistent with observations. Unlike previously proposed models, our model predicts that isentropic cores are not an inevitable consequence of preheating. The model also reproduces the observational trend for the density profiles to flatten in lower mass systems.

We deduce the energy $E_{\text{agn}}$ required to explain the entropy observations as a function of mass of groups and clusters $M_{\text{cluster}}$ and show that $E_{\text{agn}} \propto M_{\text{cluster}}^{\alpha}$ with $\alpha \sim 1.5$. We demonstrate that the entropy measurements, in conjunction with our model, can be translated into constraints on the cluster—black hole mass relation. The inferred relation is nonlinear and has the form $M_{\text{bh}} \propto M_{\text{cluster}}^{\beta}$. This scaling is an analog and extension of a similar relation between the black hole mass and the galactic halo mass that holds on smaller scales.

In addition, we study the implications of these results for thermal SZ effect. We show that the central decrement of the CMB temperature is reduced due to the enhanced entropy of the ICM, and that the decrement predicted from the plausible range of energy input from the AGN is consistent with available data of SZ decrement. We also estimate the Poisson contribution to the angular power spectrum of the CMB from the SZ effect due to AGN heating. We show that AGN heating, combined with the observational constraints on entropy, leads to suppression of higher multipole moments in the power spectrum and we find that this effect is stronger than previously thought. The suppression in the power spectrum in our model is due to depletion of gas from the central regions that is more efficient in low mass clusters and groups than in massive clusters.

Subject headings: cosmology: theory — galaxies: clusters: general — cosmic microwave background — X-rays: galaxies: clusters

1. INTRODUCTION

The formation of structures in the Universe is believed to be hierarchical, as primordial density fluctuations, amplified by gravity, collapse and merge to form progressively larger systems. This hierarchical development leads to the prediction of self-similar scaling relations between systems of different masses and at different epochs (Peebles, 1980). These structures contain two components — the gravitationally dominant dark matter and the baryons contained in these potential wells whose response to processes other than gravitational interactions bring about deviations from the self-similar scaling relations.

Clusters and groups of galaxies contain dark matter and hot, diffuse gas called the intracluster medium. It was believed that this intracluster gas follows a self-similar scaling relations. However, recent observations of clusters and groups of galaxies have shown that the scaling relations are not self-similar. The observed relations of different physical parameters of the ICM such as density, temperature, X-ray luminosity and entropy have mostly confirmed the requirement for non-gravitational processes like AGN heating and radiative cooling (Lloyd-Davies et al. 2000, Ponman et al. 2003, Sanderson et al. 2003, Pratt & Arnaud 2003, Pratt & Arnaud 2005). Simulations and theoretical models of clusters with gravitational processes alone also point to the fact that the entropy or X-ray luminosity observations can be matched only with non-gravitational heating (Roychowdhury & Nath 2003). Many theoretical models have been proposed to explain these X-ray observations by heating from supernovae (Valageas & Silk 1999; Wu, Fabian & Nulsen 2000), radiative cooling (Bryan 2000; Voit & Bryan 2001; Muanwong et al. 2002; Wu & Xue 2002a; Davé, Katz & Weinberg 2002, Tornatore et al. 2003), accretion shocks (Tozzi & Norman 2001; Babul et
The extrapolation of the cluster L-T relation onto Figure 2 of Croston et al. (2004) would fall above all the points. Slightly smaller deviation in the radio quiet AGN could be due to the fact that they are not active now but were active in the past. (We thank the referee for pointing out this possibility, see also Donahue (2005))
profile (Komatsu & Seljak 2001) with a softened core (Zakamska & Narayan, 2003)

\[
\rho_{\text{dm}} = \frac{\rho_s}{(r + r_s)(r + r_s)^2},
\]

where \(r_s\) is the standard characteristic radius of the NFW profile, \(r_c\) is a core radius inside which the density profile is a constant and \(\rho_s\) is the standard characteristic density of the usual NFW profile. The mass profile is given by

\[
M_{\text{dm}}(\leq r) = 4\pi\rho_sr_s^3 m(x),
\]

where \(m(x)\) is a non-dimensional mass profile

\[
m(x) = \frac{x^2}{(1 - x_c)^2} \ln(1 + x/x_c)
+ \frac{(1 - 2x_c)}{(1 - x_c)^2} \ln(1 + x) - \frac{1}{1 - x_c} \frac{x}{1 + x},
\]

where \(x = r/r_s\) and \(x_c = r/r_c\). If \(r_c = 0\), the usual mass distribution is recovered as in Komatsu & Seljak (2001). We follow Zakamska & Narayan (2003) and assume \(r_c = r_s/20\). This is a reasonable choice as cluster lensing studies suggest that the core radius can be \(\sim\) tens of kilo-parsecs (Tyson et al., 1998; Shapiro & Iliev, 2000). We investigate the effect of the smoothing of the dark matter profile on our results.

We do not model the effects of magnetic fields explicitly. However, magnetic fields are likely to be below the equipartition value and thereby dynamically unimportant (Fabian et al. 2002). Polarization measurements suggest that the magnetic fields in the vicinity of bubbles have subequipartition values (Blanton et al. 2003). Nevertheless, they may still be important for suppressing instabilities on bubble-ICM interfaces. Such effects may implicitly be included in the bubble heating model.

### 2.2. Heating, cooling and thermal conduction

#### 2.2.1. Effervescent heating and radiative cooling

The effervescent heating mechanism is a gentle heating mechanism in which the cluster gas is heated by buoyant bubbles of relativistic plasma produced by central AGN (Begelman 2000, Ruszkowski & Begelman 2002). The average volume heating rate is a function of the ICM pressure gradient and is given by

\[
H = -h(r) P_{\text{gas}}^{(\gamma - 1)/\gamma_b} \frac{1}{r} \frac{d}{dr} P_{\text{gas}},
\]

where \(P_{\text{gas}}\) is the ICM pressure, \(\gamma_b\) is the adiabatic index of buoyant gas in the bubbles and \(h(r)\) is the normalization function

\[
h(r) = \frac{(L)}{4\pi r^2} [1 - e^{-r/r_0}] q^{-1}.
\]

In equation (6), \((L)\) is the time averaged energy injection rate and \(r_0\) is the inner heating cut-off radius. The normalization factor \(q\) is defined by

\[
q = \int_{r_{\text{min}}}^{r_{\text{max}}} P^{(\gamma - 1)/\gamma_b} \frac{1}{r} \frac{d}{dr} P [1 - e^{-r/r_0}] dr,
\]

where \(r_{\text{max}} = r_{200}\). The inner heating cut-off radius is the transition region between the bubble formation region and the buoyant (effervescent) phase. It can be determined self-consistently by taking into account energy losses due to bubble creation,

\[
\int_0^{r_0} 4\pi r^2 H dr = \frac{(\gamma_b - 1)}{\gamma_b} (L) = \frac{1}{4} (L)
\]

This comes from the fact that the energy lost within the radius \(r_0\) due to bubble creation is \(P_0 V_0\) where \(V_0\) is the volume of the bubble at the creation region or transition region, \(r_0\), and \(P_0\) is the pressure at that region. However, the energy lost due to bubble expansion, i.e. in the effervescent phase is

\[
\int_{P_0}^{P_{\text{bubble}}} P_{\text{bubble}} dV.
\]

Assuming adiabatic evolution of the gas inside the bubbles (low density, low radiative losses) and mass conservation in the bubble one has \(dV = (1/\gamma_b)(P_0/P_{\text{bubble}})^{1/\gamma_b} V_0 dP/P\). On integrating, one gets effervescent energy as \(3P_0 V_0\) for \(\gamma_b = 4/3\). It can be easily seen from above that the energy loss due to bubble creation is approximately 25% of the total energy available for heating. Thus this condition sets the inner cut-off radius, \(r_0\), since this 25% of the total energy or, equivalently, \(1/4(L)\) will be lost for bubble creation and injection within this radius. We find that \(r_0\) roughly turns out to be around \(\sim 20 – 45\) kpc depending on the cluster mass \(M_{\text{cl}}(\equiv M_{\text{vir}})\) and temporal profiles of pressure and density. Higher mass clusters have greater \(r_0\).

The volume cooling rate is calculated using a fit (Nath 2003) to the normalized cooling function \(\Lambda_n(T)\) for a metallicity of \(Z/Z_\odot = 0.3\), as calculated by Sutherland & Dopita (1993). This cooling function incorporates the effects of free-free emission and line cooling. Thus, the volume cooling rate is \(\Gamma = n_e^2 \Lambda_n(T)\), where \(n_e = 0.875(\rho/m_p)\) is the electron density.

#### 2.2.2. Thermal Conduction

A potential difficulty in raising the entropy of the intracluster medium at large radii \((r > 0.1r_{200})\) by means of a central heating source is that the energy required is fairly large \((\gtrsim 10^{62} \text{ erg})\) over a period of the age of the cluster. This sets up a negative entropy gradient in the central regions of clusters (see Figure 2 in RRNB04) and a rising temperature profile (see right panel of Figure 3 in RRNB04) which are somewhat different from the observed temperature and entropy profiles. Our previous analysis, however, did not include the effect of thermal conduction which would have decreased the temperature gradient in the inner region and made it consistent with observations. We, therefore, include the effect of thermal conduction here to address these issues.

Thermal conduction has been suggested to be an important process in galaxy clusters for quite some time (Bertschinger & Melas 1986; Malyskin 2001; Bridgmai & Mathews 2002; Voigt et al. 2002; Fabian, Voigt & Morris 2002). However, it is not clear as to how dominant it would be since magnetic fields would suppress the conduction co-efficient by a large amount from the classical Spitzer value. However, recent theoretical works by
Narayan & Medvedev (2001), Chandran & Maron (2004), Loeb (2002) and several others suggests that conduction could be as high as 10% to 20% of the Spitzer value in the presence of a tangled and turbulent magnetic field. Motivated by these results we adopt the suppression factor $f = 0.1$.

The flux due to thermal conduction $F_{\text{cond}}$ is given by

$$F_{\text{cond}} = -f \kappa \nabla T,$$

where $\kappa$ is the Spitzer conductivity

$$\kappa = \frac{1.84 \times 10^{-5} T^{5/2}}{\ln \lambda},$$

with the Coulomb logarithm $\ln \lambda = 37$, appropriate for ICM temperature and density.

2.3. Evolution of the ICM

The intracluster gas is assumed to be in quasi-hydrostatic equilibrium at all times since cooling is not precipitous at these radii and the heating is mild. The gas entropy per particle is

$$S = \text{const} + \frac{1}{\gamma - 1} k_b \ln (\sigma),$$

where $\sigma \equiv P_{\text{gas}}/\rho_{\text{gas}}^\gamma$ is the “entropy index” and $\gamma$ is the adiabatic index. The particle number density of the gas, $n$, is given by $n = \rho_{\text{gas}}/m_n$.

During each timestep $\Delta t$, the entropy of a given mass shell changes by an amount

$$\Delta S = \frac{1}{\gamma - 1} k_b \frac{\Delta \sigma}{\sigma} = \frac{1}{n T}(\mathcal{H} - \Gamma - \nabla \cdot F_{\text{cond}}) \Delta t.$$

After evaluating the change in the entropy index of each mass shell of gas due to heating, cooling and conduction after a time $\Delta t$ using equation (13), the new entropy index of each shell is calculated using

$$\sigma_{\text{new}}(M) = \sigma_0(M) + \Delta \sigma(M)$$

where $\sigma_0(M) = P_{\text{gas}}/\rho_{\text{gas}}^\gamma$ is the default entropy index. The system relaxes to a new state of hydrostatic equilibrium with a new density and temperature profile. After updating the function $\sigma(M)$ for each mass shell, we solve the equations

$$\frac{dP_{\text{gas}}}{dM} = \frac{GM(< r)}{4\pi r^2}$$

and

$$\frac{dM}{dr} = \frac{1}{4\pi r^2} \left( \frac{P_{\text{gas}}(M)}{\sigma(M)} \right)^{(1/\gamma)}$$

to determine the new density and temperature profiles at time $t + \Delta t$. The boundary conditions imposed on these equations are that (1) the pressure at the boundary of the cluster, $r_{\text{out}}$, is constant and is equal to the initial pressure at $r_{200}$, i.e., $P(r_{\text{out}}) = \text{constant} = P_{\text{gas}}(r_{200})$, and (2) the gas mass within $r_{\text{out}}$ at all times is the mass contained within $r_{200}$ for the default profile at the initial time, i.e., $M_{\text{g}}(r_{\text{out}}) = M_{\text{g}}(r_{200}) = 0.1333 M_{\text{lim}}(r_{200})$. It is important to note here that $r_{\text{out}}$ increases as the cluster gas gets heated and spreads out.

The observed gas entropy $S(r)$ at $0.1r_{200}$ and at $r_{500}$ is then calculated using

$$S(r) \equiv T(r)/n_e^{2/3}(r).$$

The updated values of $\sigma(M)$ and pressure of the ICM $P_{\text{gas}}(r)$ are used to calculate the heating and cooling rates and the conduction flux for the next time step. This is continued for a duration of $t_{\text{heat}}$. After that the heating source is switched off, putting $\mathcal{H} = 0$. The cooling rate and conduction flux continue to be calculated to update the function $\sigma(M)$ at subsequent timesteps and the hydrostatic structure is correspondingly evolved for a duration of $t_{\text{H}} - t_{\text{heat}}$, where $t_{\text{H}}$ is the Hubble time. Note that $r_{\text{out}}$ decreases during this time since the intracluster gas loses entropy and shrinks. The only free parameters in our calculation are the energy injection rate $\langle L \rangle$ and the time $t_{\text{heat}}$ from which the “effervescent heating” of the ICM takes place. After evolving the gas for the total available time, $t_{\text{H}} \sim 1.35 \times 10^{10}$ years, we check whether the entropy at $0.1r_{200}$ and $r_{500}$ matches the observed values, and adjust parameters accordingly. In this way, we explore the parameter space of $\langle L \rangle$ and $t_{\text{heat}}$ or rather a single free parameter, i.e. the total energy, $E_{\text{agn}} = \langle L \rangle t_{\text{heat}}$ for different cluster masses so that the entropy (after $1.35 \times 10^{10}$ years) at $0.1r_{200}$ and $r_{500}$ matches the observed values.

For numerical stability of the code, the conduction term is integrated using timesteps that satisfy the appropriate Courant condition. The Courant condition for conduction is

$$\Delta t_{\text{cond}} \leq 0.5 (\Delta r)^2 n_k b / \kappa (\gamma - 1).$$

The timesteps, $\Delta t$, used in equation (12) to update the entropy of the gas and calculate its pressure, temperature and density profiles always obey the above Courant condition (Ruszkowski & Begelman 2001; Stone, Pringle & Begelman 1990).

3. THERMAL SUNYAEV-ZELDOVICH EFFECT

The temperature decrement of CMB due to the SZ effect is directly proportional to the Compton parameter ($y$). For a spherically symmetric cluster, the Compton parameter is given by

$$y = \frac{2 \sigma_T}{m_e c^2} \int_0^R p_e(r) dr$$

where $\sigma_T$ is the Thomson cross-section, and $p_e(r) = n_e(r) k_b T_e(r)$ is the electron pressure of the ICM, where $n_e(r) = 0.875 (\rho_{\text{gas}}/m_p)$ is the electron number density, $k_b$ is the Boltzmann constant, and $T_e(r)$ is the electron temperature. The integral is performed along the line–of–sight ($l$) through the cluster and the upper limit of the integral ($+R$) is the extent of the cluster along any particular line–of–sight. We do not include the effects of beam size in calculating the $y$ parameter. This approximation is justified by the fact that the pressure profiles are relatively flat in the inner region. The variation of pressure integrated along the line–of–sight as a function of the projected radius is even flatter thus providing more justification for the above approximation.

The angular temperature profile projected on the sky due to SZ effect, $\Delta T(\theta)/T_{\text{CMB}}$ is given in terms of the Compton parameter in equation (19)
\[ \frac{\Delta T(\theta)}{T_{\text{CMB}}} = g(x)y(\theta), \]  
(20)

where \( g(x) = \tanh(x/2) - 4, x = h\nu/k_B T_{\text{CMB}}, T_{\text{CMB}} = 2.728 \) (Fixsen et al. 1996). In the Rayleigh-Jeans approximation, \( g(x) \approx -2 \). We only evaluate “central” SZ decrement from the pressure profiles of our models. In this case, the integral in equation (19) reduces to

\[ y_0 = 2 \frac{\sigma_T}{m_e c^2} \int_0^R p_e(r) dr \]  
(21)

In the Rayleigh-Jeans part of the CMB spectrum, the deviation from the black-body spectrum results in a decrement of the CMB temperature,

\[ \Delta T_{\nu_0} \approx -5.5 y K \]  
(22)

We use the pressure profiles resulting from our model to calculate the central SZ decrement in the temperature of the CMB.

4. ANGULAR POWER SPECTRUM

The angular two-point correlation function of the SZ temperature distribution in the sky is conventionally expanded into the Legendre polynomials:

\[ \left\langle \frac{\Delta T}{T_{\text{CMB}}} \left( \hat{n} \right) \frac{\Delta T}{T_{\text{CMB}}} \left( \hat{n} + \theta \right) \right\rangle = \frac{1}{4\pi} \sum_l (2l+1) C_l P_l(\cos \theta) \]  
(23)

Since we consider discrete sources, we can write \( C_l = C_l^{(P)} + C_l^{(C)} \), where \( C_l^{(P)} \) is the contribution from the Poisson noise and \( C_l^{(C)} \) is the correlation among clusters (Peebles 1980, § 41). We define the frequency independent part in the power spectrum as \( C_l^{(P)} = C_l / g^2(x) \). The integral expression of \( C_l^{(P)} \) can be derived following Cole & Kaiser (1988) as

\[ C_l^{(P)} = \int_0^{z_{\text{dec}}} \frac{dV}{dz} \int_{M_{\text{min}}}^{M_{\text{max}}} \frac{dM}{dM} \frac{dn(M,z)}{dM} |y_l(M,z)|^2, \]  
(24)

where \( V(z) \) is the co-moving volume and \( y_l \) is the angular Fourier transform of \( y(\theta) \) given by

\[ y_l = 2\pi \int y(\theta) J_0([(l+1/2)\theta]) d\theta, \]  
(25)

where \( J_0 \) is the Bessel function of the first kind of the integral order 0. In equation (24), \( z_{\text{dec}} \) is the redshift of photon decoupling and \( dn/dM \) is the mass function of clusters which is computed in the Press-Schechter formalism (Press & Schechter 1974). The mass function has been computed using the power spectrum for a ΛCDM model with normalization of \( \sigma_8 = 0.9 \). We choose \( M_{\text{min}} = 5 \times 10^{13} M_\odot \) and \( M_{\text{max}} = 2 \times 10^{15} M_\odot \) and integrate till redshift of \( z = 5 \) instead of \( z_{\text{dec}} \). This is done because the integral in equation (24) is found to be insensitive to the upper limit in redshift beyond \( z = 4 \), the reason being that the mass function is exponentially suppressed beyond that redshift in this mass range.

5. RESULTS

In this section, we discuss our results for cluster evolution due to heating, cooling and conduction. We also discuss our results for the central SZ decrement for clusters with masses ranging from \( M_{\text{cl}} = 5 \times 10^{13} - 2 \times 10^{15} M_\odot \).

The gas is heated for a time \( t_{\text{heat}} = 1.35 \times 10^{10} \) years has elapsed. The final entropy values at \( 0.1 r_{200} \) and \( r_{500} \) are compared with the observed ones.

In Figure (1), the evolution of the density and temperature profiles of the ICM are shown for a cluster of mass \( 6 \times 10^{14} M_\odot \) and for a luminosity of \( L = 5.25 \times 10^{45} \) ergs s\(^{-1}\). The gas density decreases with time during the heating epoch, and increases due to radiative cooling and conduction after the heating source is switched off. It is interesting to note that the changes in density are minimal beyond \( 0.5 r_{200} \), as compared to \( 0.2 r_{200} \) in Figure (3) in RRBN04, and that conduction plays a very important role in regulating the density profiles after the heating source is switched off. It is seen that conduction actually decreases the density of the gas at larger radii (beyond \( 0.5 r_{200} \)) by conducting heat out from the central regions. This is seen more clearly if one studies the evolution of the temperature profiles. After the heating source is switched off, it is seen that the temperature of the central regions fall very rapidly since conduction pumps out heat from the central regions and redistributes it in the outer regions of the cluster. Thus the temperature profiles do not rise towards the centre as compared to what is seen in Figure (3) in RRBN04. On the other hand, their evolution shows a rise in the outer regions (beyond \( 0.5 r_{200} \)) due to thermal conduction even after the heat source has been switched off. Thus conduction acts like a heating source for larger radii.

Figure (2) shows the time evolution of scaled entropy profiles of a cluster of mass \( M_{\text{cl}} = 6 \times 10^{14} M_\odot \) for \( L = 5.25 \times 10^{45} \) erg s\(^{-1}\). We use the same method of emissivity weighting as in Roychowdhury & Nath (2003) to calculate the average quantities. The entropy profiles are plotted in time-steps of \( 5 \times 10^{7} \) years. They are seen to rise with time as the ICM is heated. Then, after the heating is switched off (after \( t_{\text{heat}} = 5 \times 10^{9} \) years), the gas loses entropy due to cooling and the profiles are seen to fall progressively. The inclusion of conduction removes the negative gradient in the scaled entropy profiles in the central regions of the cluster (within \( 0.5 r_{200} \)). These entropy profiles do not show any flat entropy core unlike in RRBN04 (left panel in their Figure 2). Thus, this probably indicates that thermal conduction is a more plausible process in ICM than convection for such gentle AGN heating.

The model is constrained by entropy-temperature relation. At fixed cluster temperature this corresponds to a given density (at both radii for which the entropy data is provided). Now, since at a given density we have an additional constraint from the L-T relation (that our model fits reasonably well; see below), we implicitly satisfy the constraints on the slope of the density profile. Thus, as the model fits both the entropy data and the observed L-T relation that specify the slopes of the density profiles, these slopes must also be consistent with observations that show flattening in low mass systems. Indeed, this flattening is
Fig. 1.— Gas density (left panel) and temperature (right panel) profiles as a function of scaled radius \((r/r_{200})\), for the cluster model described in the text. Dashed lines represent density profiles when heating is active and the dot-dashed line represents density profiles after the heating source has been switched off (i.e. after \(t_{\text{heat}} > 5 \times 10^9\) years). The profiles are plotted after every \(5 \times 10^8\) years till Hubble time. It is seen here that conduction removes temperature gradients in the central regions (within \(0.2r_{200}\)) and flattens the temperature profile. This is the reason thermal conduction was included in the cluster model as compared to RRNB04, wherein left panel of Figure (3) shows rising temperatures in the centre. The density profiles are seen to rise after the heating source is switched off and thermal conduction and radiative cooling are the only two processes which are active. Initial density and temperature profiles correspond to the solid curves in both plots.

Fig. 2.— Scaled entropy profiles as a function of scaled radius for a cluster of mass \(6 \times 10^{14} \, M_{\odot}\) heated by an AGN with \(\langle L \rangle = 3 \times 10^{45} \, \text{erg s}^{-1}\). The scaled entropy profiles are plotted at intervals of \(5 \times 10^8\) years. The dashed lines correspond to times when heating is on and the dot-dashed lines correspond to times when heating has been switched off. They are seen to rise as the gas is heated and then fall as the gas cools. It is seen here that the final entropy profiles (after hubble time) has neither negative entropy gradient nor any entropy core in the central regions, as compared to Figure (2) in RRNB04. Initial states correspond to the solid curves.
**Fig. 3.**—Final density profiles for objects of mass $4.5 \times 10^{13} \, M_\odot$ (solid line), $2.0 \times 10^{14} \, M_\odot$ (short dashed line), $9.0 \times 10^{14} \, M_\odot$ (long dashed line). The assumed heating time $t_{\text{heat}}$ in this example was $5 \times 10^9$ years. Note the flattening in the density profile as the mass of the system is decreased.

**Fig. 4.**—This figure shows the permitted total injected energy range as a function of the cluster mass for ICM heating times between $t_{\text{heat}} = 5 \times 10^8$ yr (upper envelope) and $t_{\text{heat}} = 5 \times 10^9$ yr (lower envelope). The shaded region corresponds to values of $E_{\text{agn}}$ that are able to match the entropy observations at both 0.1$r_{200}$ and $r_{500}$. The thin solid line represents a non-linear relation between the total energy injected into the cluster by AGN and the mass of the cluster with an exponent of 1.5. The thick long-dashed line represents a non-linear relation between the total energy injected into the cluster by AGN and the mass of the cluster with an exponent of 5/3. The permitted parameter space comes from the sum of permitted regions that satisfy the entropy constraints at both radii for fixed $t_{\text{heat}}$. 

apparent in Figure 3 that shows final density profiles for different masses.

We now discuss the permitted range in the total energy injected into the cluster, $E_{\text{inj}} = \langle L \rangle \times t_{\text{heat}}$, required to match the observed entropy as a function of the cluster mass.

Figure (4) shows the permitted total injected energy range as a function of the mass of cluster for heating times between $t_{\text{heat}} = 5 \times 10^8$ years and $t_{\text{heat}} = 5 \times 10^9$ years. Here the entropy is required to match observations at both $0.1r_{200}$ and $r_{500}$. The thick solid line represents a relation between the total energy injected to the cluster by AGN and the mass of the cluster (see next section for more details).

Figure (5) shows the X-ray luminosity ($L_X$) versus emission-weighted temperature ($T_X$) relation in clusters. The data points have been compiled from Arnaud & Evrard (1999) (represented by stars), Markevitch et al. 1998 (represented by open squares) and Helsdon & Ponman 2000 (with error bars). The X-ray luminosity has been calculated within the cluster volume of $0.3r_{200}$, as done for the data. It is also seen that the X-ray luminosity does not change much (within 1%) if the volume increased from $0.3r_{200}$ to $r_{200}$. The shaded region in the plot corresponds to the predicted X-ray luminosity when the cluster is heated by an AGN for $5 \times 10^8 \leq t_{\text{heat}} \leq 5 \times 10^9$ years with luminosities which correspond to the two bounding lines of the shaded region in Figure (3). It is seen that the predicted luminosities of the heating model satisfy the data points in the low mass end as well as the high mass end. The solid line in the plot shows the predicted luminosity due to the universal temperature profile and the default density profile. We note that the X-ray luminosity is over-predicted by the universal temperature profile which indicates that the addition of non-gravitational heating is required to lower the X-ray luminosity to satisfy the data points (see Roychowdhury & Nath 2003, for more details).

In Figure (6), the central SZ temperature decrement $\Delta T_{w0}$ is plotted as a function of the emission-weighted temperature of the cluster ($T$). The data points are a compilation of data sets from Zhang & Wu (2000) and McCarthy et al. (2003b). The solid line shows the predicted $\Delta T_{w0}$ from the default temperature profile and NFW potential. The dot-dashed line shows the predicted $\Delta T_{w0}$ for the same temperature profile but for smoothed NFW potential with $r_c = r_{500}/20$. The dashed line shows the prediction from the self-similar profile (Wu & Xue, 2002b; Bryan 2000).

It has been shown by Roychowdhury & Nath (2003) that the density profile of gas is much flatter in comparison to the self-similar profile when it assumes the “universal temperature profile” and the standard NFW profile is assumed. As a result, the predicted central temperature decrement ($\Delta T_{w0}$) is lower than that predicted by the self-similar model. The normalization of $\Delta T_{w0}$ for a smoothed NFW profile with a core radius $r_c = r_{500}/20$ is even lower. This happens because the introduction of a core radius in the dark matter profile makes the ICM density profile shallower in the central regions as compared to the ICM density with a standard NFW profile. These decrements are closer to the data than predicted by earlier self-similar models for rich clusters.

Next we examine the effects of the effervescent heating, radiative cooling and conduction on the central SZ decrement. We evaluate $\Delta T_{w0}$ for clusters in our sample after they have been evolved for a Hubble time $t_H$. The heating source was active for $t_{\text{heat}} \ll t_H$. The values of $\langle L \rangle$ and $t_{\text{heat}}$ have been chosen so as to satisfy observational constraints on ICM entropy after $t_H$ at $0.1r_{200}$ and $r_{500}$ (Ponman et al. 2003; see Figure 4 and 5 in RRNB04). In other words, there is a range of $\langle L \rangle$ that satisfies the entropy observations at a 1-$\sigma$ uncertainty level that we used in our calculations. We used smoothed NFW profile with the core radius $r_c = r_{500}/20$.

In Figure 7, the shaded region is the expectation for the SZ central decrement when the gas is heated by the central AGN. The shaded region represents the spread in $\langle L \rangle$ which satisfies the entropy requirements at both radii, $0.1r_{200}$ and $r_{500}$ for $5 \times 10^8 < t_{\text{heat}} < 5 \times 10^9$ years. The solid line shows the prediction from self-similar profile (Wu & Xue, 2002b; Bryan 2000).

In Figure 8, the evolution of the central SZ decrement $\Delta T_{w0}$ is shown as a result of heating, cooling and conduction for a cluster of mass $M_{\text{cl}} = 6 \times 10^{14} M_\odot$. The dashed line is the result of heating for $t_{\text{heat}} = 5 \times 10^8$ years and the solid line is the result of heating the ICM for $t_{\text{heat}} = 5 \times 10^9$ years. It can be seen that, as long as the heating source is active, $\Delta T_{w0}$ decreases. When the source is switched off, $\Delta T_{w0}$ starts to increase as the gas evolves only due to radiative cooling and conduction. This happens because the density, or equivalently the electron pressure, decreases when the gas is heated but becomes larger when it is allowed to cool. In addition, we have also plotted the default $\Delta T_{w0}$ for the same cluster with a point denoted with an open circle. The central SZ decrement corresponding to our heating model is always lower than the default value.

Finally, we evaluate the Poisson contribution to the angular power spectrum of the SZ and compare our model predictions with earlier ones from self-similar models. In Figure (9), the thin solid line represents the angular power spectrum (Poisson) for the universal temperature profile and the corresponding density profile (Roychowdhury & Nath, 2003). The dashed line is for self-similar model (Komatsu & Kitayama, 1999). The shaded regions represent the angular power spectra from heating model. The region shaded with gray represents the result due to heating for $t_{\text{heat}} = 5 \times 10^9$ years and the region shaded with dashed lines represents the result due to heating for $t_{\text{heat}} = 5 \times 10^8$ years. The spread reflects the fact that there is a range of $\langle L \rangle$ for a given $t_{\text{heat}}$ that satisfies the observational entropy data at $0.1r_{200}$ and $r_{500}$.

6. THE HALO-BLACK HOLE MASS RELATION

The relation between the mass of the group or cluster halo and the total injected energy (Figure 4) can be translated to the halo-black hole mass relation. We follow the arguments in Wyithe & Loeb (2003) to derive this relation.

Mass of a virialized halo can be expressed in terms of its circular velocity $v_c$ (Barkana & Loeb 2001)

$$M_{\text{halo}} = 4.7 \times 10^{14} \left( \frac{v_c}{100 \text{ km s}^{-1}} \right)^3 M_\odot$$

(26)

We can combine the above relation with the self-regulation
Fig. 5.— Relation between bolometric X-ray luminosity $L_X$ and emission-weighted temperature $\langle T \rangle$. The data points represented by 'stars' show measurements of clusters with insignificant cooling flows compiled by Arnaud & Evrard (1999). Open squares show cooling flow-corrected measurements by Markevitch et al. (1998). The data points with error bars show group data from Helsdon & Ponman (2000). The shaded region represents X-ray luminosity calculated for the region of $E_{\text{agn}}$ shown in Figure (4) which satisfies the observed entropy requirements at both radii for $5 \times 10^8 < t_{\text{heat}} < 5 \times 10^9$ years. The solid line represents the X-ray luminosity calculated using the default model of the ICM i.e. the universal temperature profile. The models assume a $\Lambda$CDM cosmology with $\Omega_M = 0.29$, $\Omega_\Lambda = 0.71$, and $\Omega_b = 0.047$, and a Hubble parameter of $h = 0.71$ has been applied to the models and the data.

Fig. 6.— Observed and predicted $\Delta T_{\mu w_0} - \langle T \rangle$ relation of clusters. The solid line represents the predicted $\Delta T_{\mu w_0}$ with “universal” temperature profile (Loken et al. 2002), dark matter density profile given by NFW with $r_c = 0$ and the resulting density profile (Roychowdhury & Nath 2003). The dash-dotted line is the result of the dark matter profile given by NFW with $r_c = r_s/20$ and the ICM temperature profile as before. The dashed line is the result of self-similar profile (Wu & Xue 2002b). The data points are from Zhang & Wu (2000) and McCarthy et al. (2003b).
Fig. 7.— Observed and predicted $\Delta T_{\mu w0} - (T)$ relation of clusters. The solid line shows $\Delta T_{\mu w0}$ for self-similar profile (Wu & Xue 2002b). The shaded regions are the SZ decrement due to heating of the ICM, the region shaded with dashed line representing the spread in $\langle L \rangle$ which satisfy the entropy observations at both radii, $0.1r_{200}$ and $r_{500}$ for $t_{\text{heat}} = 5 \times 10^8$ years and the gray region representing the spread in $\langle L \rangle$ for $t_{\text{heat}} = 5 \times 10^8$ years. The data points are from Zhang & Wu (2000) and McCarthy et al. (2003b).

Fig. 8.— The evolution of the central SZ temperature decrement, $\Delta T_{\mu w0}$, is shown for two different $L_{\text{agn}}$ corresponding to the two values of $t_{\text{heat}}$ for $M_{\text{cl}} = 6 \times 10^{14} M_{\odot}$. The point denoted by an open circle is the value of $\Delta T_{\mu w0}$ for the default profile with smoothed NFW ie. with a core for the same mass cluster.
As a result of the "universal temperature profile" of the cluster ICM, the dashed line is the expectation from a $\beta$-profile and isothermal temperature profile. The dotted and the dot-dashed line represent the heated ICM models. The dot-dashed line being for $t_{\text{heat}} = 5 \times 10^8$ years and the dotted line is for $t_{\text{heat}} = 5 \times 10^9$ years.

In this paper, we have examined the effects of effervescent heating by AGN in clusters with thermal conduction and cooling in the context of the excess entropy requirements at large radii. We have also examined the consequences of this heating, cooling and conduction on SZ temperature decrement.

As is clear from Figure (4), it is possible to heat the ICM with a single central AGN to match the entropy requirements at both $0.1r_{200}$ and $r_{500}$. However, in order to match the entropy at both radii, the total injected energy $E_{\text{agn}}$, for a given value of $t_{\text{heat}} \ll t_{\text{fit}}$, must be tightly constrained. In fact, our calculations have shown that for any value of $t_{\text{heat}} < t_{\text{fit}}$, i.e., for any heating time (or AGN lifetime), it is always possible to satisfy the entropy observations at both radii with a single value of the luminosity $\langle L \rangle$. This is different from the cooling flow problem, where $\langle L \rangle$ must be finely tuned to match the cooling rate (Ruszkowski &
Begelman 2002), because cooling effects on large scales are rather mild and, thus, the results depend mostly on the total injected energy \( E_{\text{agn}} = \langle L \rangle \times t_{\text{heat}} \). Thus, if we can fit the observed entropy values for just one pair \( \langle L \rangle \) and \( t_{\text{heat}} \), we can do so for a wide range of such pairs.

We note here that the inclusion of thermal conduction brings down the energy which has to be provided by the AGN over its life-time to satisfy the entropy observations at both radii for all heating times as compared to our model in RRNB04. In addition, for shorter heating times, the \( E_{\text{agn}} \) is less or comparable to the energy pumped in for longer heating times. This is in contradiction to our findings in RRNB04. This happens here because thermal conduction acts as a heating source after the AGN is switched off (for \( t_H - t_{\text{heat}} \)) and raises the entropy at large radii (at \( r = r_{500} \)). The results are mostly sensitive to the total energy input from the black hole, rather than to \( \langle L \rangle \) and \( t_{\text{heat}} \) separately. As a consequence, satisfactory fits can be obtained as long as the total injected energy falls within a relatively narrow range of values, which depends on the cluster mass (Figure (3)).

Finally, we note that cooling and thermal conduction play important roles in controlling the heating mechanism so that the entropy profiles broadly match the observed entropy profiles in clusters (Ponman et al. 2003). Notably, in the later stages of evolution of the gas, after the heating source is switched off, conduction removes negative entropy gradients in the central regions of the cluster. Moreover, there is no entropy core seen in the final stages of the evolution of the ICM. Instead we see positive entropy gradients as observed in the entropy profiles of galaxy groups (Mushtozky et al. 2003, Ponman et al. 2003). Unlike previously proposed models, our model predicts that isentropic cores are not an inevitable consequence of preheating. However, the clusters that show isentropic core have also been observed (Ponman et al. 2003). We note that our entropy profiles show a core while the source of heating is active. It is conceivable that the clusters which show entropy cores are being observed during the active phase of the AGN duty cycle.

As seen in Figure (6), the central SZ decrement for individual clusters is diminished if the “universal temperature profile” corresponding to the gravitational interactions of the ICM with the background dark matter is used. This reduces the discrepancy between the predicted central SZ signal and the observations compared to the predictions based on the standard self-similar profiles. The solid line in Figure (6) matches the observed points for rich clusters \((\langle T \rangle \leq 5 \text{ keV})\) better than the dashed line, indicating that the requirement of non-gravitational heating for rich clusters is lower than previously thought. It is important to note here that the introduction of a core radius in the dark matter profile brings the SZ temperature decrements down further to match the observed points. This happens because the pressure profile of the intracluster medium becomes shallower in the central regions than for the NFW dark matter profile without smoothing.

We also find that the inclusion of effervescent heating, cooling and conduction have a significant effect on the SZ signal. The gas in the central region is depleted as a result of effervescent heating and thus we see a diminution in the SZ signal as a result of AGN heating. Similar conclusion was reached by McCarthy et al. (2003a, 2003b) and Cavaliere & Menci (2001). However, in our case, there is a spread in the SZ signal. The spread reflects the fact that there is a range of energies required to satisfy the observed entropy at 0.1\( R_{200} \) and \( R_{500} \) for a particular \( t_{\text{heat}} \). Shaded regions in Figure 2 are based on fits of the heating model to the observational entropy data. The region shaded with dashed lines corresponds to the predicted SZ signal for the range in \( E_{\text{agn}} \) that satisfies the entropy requirements at both radii for \( t_{\text{heat}} = 5 \times 10^7 \) years and the region shaded gray corresponds to the range in \( E_{\text{agn}} \) that satisfies the entropy requirements at both radii for \( t_{\text{heat}} = 5 \times 10^8 \) years. As seen in Figure 7 the data for SZ are still not good enough to constrain heating models at present. We hope that future SZ observations of low temperature clusters will constrain the models better in the regime where discrepancies between self-similar and heating models are more pronounced. The capabilities of future experiments like SZA are such that a decrement in the CMB temperature of 10 \( \mu \text{K} \) could be detected (S. Majumdar, private communication). This would mean that the lowest mass systems that SZA could observe would have \( T \sim 2 \text{ keV} \). It should be noted here that the parameter \( L_{\text{agn}} \) and thus \( E_{\text{agn}} \) estimated in this paper are slightly different from those in RRNB04. This is due to differences in the effervescent heating mechanism and the dark matter profile. The inclusion of a self-consistent method for estimating the inner heating cut-off radius, \( r_0 \) and a smoothed NFW profile with a core radius have changed the range in \( E_{\text{agn}} \) that satisfies the entropy requirements at two different radii, 0.1\( R_{200} \) and \( R_{500} \), for the two values of \( t_{\text{heat}} \) stated above.

We have also studied the time evolution of the SZ temperature decrement due to AGN heating, cooling and conduction. It is seen in Figure (8) that the SZ signal is diminished as a result of AGN heating at all times in comparison to the default SZ signal. This is in contrast to the transient phases with enhancement of SZ signals predicted by Lapi et al. (2003) owing to strong feedback mechanisms that they assumed. Also, in the case of effervescent heating, the SZ decrement is lower than the default case even after the gas has evolved for a time \( t_H - t_{\text{heat}} \) after the heating has been switched off. We note here that the values of \( \langle L \rangle \) and \( t_{\text{heat}} \) have been chosen so as to satisfy the entropy requirements after evolving for \( t_H \).

Finally, we examine the effect of the universal temperature profile and AGN heating on the Poisson part of the angular power spectrum. We note that the peak of the SZ power spectrum is somewhat sensitive to the amount of heating that is added to the cluster gas. The peak of \( C_\ell \) is at a lower \( \ell \) for a larger \( t_{\text{heat}} \) and at a higher \( \ell \) for a smaller \( t_{\text{heat}} \). Also, the effect due to heating is larger for higher values of \( \ell \). In our case the suppression takes place because the gas depletion from the central regions is more efficient in low mass groups than in rich clusters. Therefore, the SZ signal is suppressed more efficiently at smaller scales and, thus, larger \( \ell \). We note that the general trend for the Poisson contribution to the spectrum to be suppressed at higher \( \ell \) has been noted by others (Holder & Carlstrom, 1999; Kitayama & Komatsu 1999; Springel, White & Hernquist, 2001; Holder & Carlstrom 2001, Zhang & Wu 2003). This effect leads to a mismatch between the observed and the-
eral spectra (Dawson et al. 2001, Mason et al. 2003) when preheating required to account for the entropy floor is considered. In our physically motivated effervescent AGN heating model, that fits the X-ray observations of entropy of the ICM, the power spectrum at small scales is even lower than previously thought. This suggests that other sources, such as, e.g., “dead” radio galaxy cocoons at higher redshifts (Yamada, Sugiyama & Silk 1999), should significantly contribute to anisotropies in the cosmic microwave background at large $\ell$. We emphasize that our model deals only with global, average effect of heating on clusters and neglects small scale fluctuations in the gas distribution that are associated with heating.

8. CONCLUSION

The primary aim of this work was to study the implications AGN heating and thermal conduction on the global properties of groups and clusters of galaxies including the Sunyaev-Zeldovich effect.

We have demonstrated that the available entropy data, in conjunction with our feedback model, put constraints on the relation between the total energy injected by the AGN and the mass of the cluster ($E_{\text{AGN}} \propto M_{\text{cluster}}^\alpha$). The inferred black hole-halo mass scaling ($M_{\text{bh}} \propto M_{\text{cluster}}^\alpha$, $\alpha \sim 1.5$) is an analog and extension of the similar relation between the black hole mass and the mass of the galaxy halo that holds on smaller scales.

The “effervescent heating” mechanism heats the gas in the central regions of clusters and makes the gas density profile shallower. This reduces the electron pressure of the gas and, thus, reduces the SZ temperature decrement. This is in accordance with the findings of other authors (Cavaliere & Menci 2001, McCarthy et al. 2003b, Lapi et al. 2003). Here we have also shown how the SZ decrement would evolve as heating, cooling and conduction regulate the physical state of the ICM. Our heating model is consistent with the available entropy data at 0.1$r_{200}$ and $r_{500}$. We give specific predictions of our model for the SZ decrement for low mass (low temperature) clusters. Future observations performed with, e.g., Sunyaev-Zeldovich Array (SZA) or Combined Array for Research in Millimeter-wave Astronomy (CARMA) will be able to test these predictions.

We also point out that the “universal temperature profile”, that takes into account pure gravitational interactions, leads to lower SZ decrement than that calculated assuming that the ICM has a self-similar profile and is in better agreement with data for high $\langle T \rangle$ clusters. This implies that the discrepancy between observations and models without heating is reduced.

Unlike in the case of previously proposed models, we found that isentropic cores are not an inevitable consequence of preheating. This is consistent with observations of groups that do not show large isentropic cores (Ponman et al. 2003, Mushotzky 2003). Clusters that show isentropic core have also been observed (e.g., Ponman et al. 2003). We note that our entropy profiles show a core while the source of heating is active which may explain such cases as well. It is conceivable that the clusters which show entropy cores are being observed during the active phase of the AGN duty cycle. This suggests that there may exist an observationally testable correlation between the presence of isentropic cores and radio emission from the central galaxy. However, we note that such a correlation may not be strong as the radio emission may quickly fade away while the mechanical effects of feedback may still be present.

We have also demonstrated that the model reproduces the observed trend for the density profiles to flatten in low mass systems.

Finally, we also estimated the angular power spectrum of the CMB due to the SZ effect from Poisson distributed clusters. We showed that the average effect of heating is to reduce the SZ signal and thus the angular power spectrum. The finding that the power spectrum at large $l$ is suppressed is consistent with previous results (e.g., Komatsu & Kitayama 1999, Holder & Carlstrom 2001). However, our results indicate that the contribution to the power spectrum that results from AGN heating, that is consistent with entropy measurements, is lower than previously thought. This suggests that other sources, such as, e.g., dead radio galaxy cocoons at higher redshifts (Yamada, Sugiyama & Silk 1999), should significantly contribute to small scale anisotropies of the cosmic microwave background.

9. ACKNOWLEDGMENTS

We would like to thank Mark Voit for discussions and many insightful comments that helped to improve the paper. We would also like to thank Mitch Begelman, Tetsu Kitayama, Eiichiro Komatsu and Subhabrata Majumdar, Shiv Sethi as well as the referee for their helpful comments, suggestions and clarifications. MR acknowledges the support from NSF grant AST-0307502 and NASA through Chandra Fellowship Award Number PF3-40029 issued by the Chandra X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-39073.

REFERENCES

Barkana, R., Loeb, A., 2001, Physics Reports, 349, 125
Loeb, A. 2002, New Astronomy, 7, 279