THE HEATING OF INTRA(CLUSTER GAS BY THE JET ACTIVITIES OF ACTIVE GALACTIC NUCLEI: IS THE “PREHEATING” SCENARIO REALISTIC?

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ABSTRACT

We investigate the nongravitational heating of hot gas in clusters of galaxies (the intracluster medium [ICM]) on the assumption that the gas is heated well before cluster formation (“preheating”). We examine the jet activities of radio galaxies as the sources of excess energy in the ICM, and we examine the deformation of the cosmic microwave background (the Sunyaev-Zeldovich effect) by hot electrons produced at the jet terminal shocks. We show that the observed excess entropy of the ICM and the COBE/FIRAS upper limit for the Compton y-parameter are compatible with each other only when the heating by the jets occurs at relatively small redshifts (z ≤ 3). Since this result contradicts the assumption of preheating, it suggests that the heating occurred simultaneously with or after cluster formation.

Subject headings: cosmic microwave background — galaxies: clusters: general — galaxies: jets — intergalactic medium — X-rays: galaxies: clusters

1. INTRODUCTION

The departure of the properties of X-ray–emitting gas in galaxy clusters (the intracluster medium [ICM]) from simple scaling relations gives rise to arguments about their thermal history (Kaiser 1986, 1991; Evrard & Henry 1991; Fujita & Takahara 2000). Observed relations between X-ray luminosity and temperature show that from a rich cluster scale to a poor cluster scale, the exponent increases from (e.g.,23

\[ L \propto T^{\alpha} \]  

(\text{Kaiser} & Alexander 1997; Yamada et al. 1999). As this hot matter expands supersonically, a hot region surrounded by a shock surrounds the proto-ICM via thermalization at the shock at the hot spot. Thus, the gas temperature is determined not only by \( T_{\text{vir}} \) but also by \( T_{\text{vir}} \). Several authors have shown that preheating models can reproduce the observational results (e.g., Tozzi et al. 2000); however, the heat source itself and the input epoch have not been identified.

Some authors have investigated the heating by supernovae. However, Valageas & Silk (1999) show that the energy provided by supernovae cannot raise the entropy of the intergalactic medium (IGM) up to the level required by current observations. Moreover, Kravtsov & Yepes (2000) estimated the energy provided by supernovae from the observed metal abundance of the ICM and found that the heating by supernovae alone requires unrealistically high efficiency. On the other hand, active galactic nuclei (AGNs) may be much more powerful and therefore are plausible heating source candidates; thus, we focus on AGNs.

As for the input epoch, there have been few concrete arguments except for the ones inherent in models of individual sources. For AGNs, there have been no additional constraints like the metal abundance in the case of supernova heating (Kaiser & Alexander 1999). In this Letter, we propose a new approach to study this subject. Preheating sources that are so powerful as to influence the thermal properties of the ICM would also deform the spectra of the cosmic microwave background (CMB) via inverse Compton scattering (the Sunyaev-Zeldovich [SZ] effect). Indeed, it has been shown that the energy supplied by AGN jets could be a significant source of the SZ effect (Yamada, Sugiyama, & Silk 1999). If the preheating scenario is correct, then the ICM should have been heated before the collapse of poor clusters. This allows us to obtain a lower limit of the redshift of energy input. On the other hand, if a large amount of the hot IGM appears too early, the cumulative SZ effect would break the constraint made by Fixen et al. (1996) using COBE/FIRAS (\( y \leq 1.5 \times 10^{-3} \)). In this Letter, we compare the estimated SZ effect and the excess energy induced by cocoons formed by AGN jet activities with the observational constraints, and we discuss the validity of the simple preheating scenario.

2. MODELS

2.1. Cocoon Model and the Compton y-Parameter

We assume for simplicity that the heating of the proto-ICM by jet activities occurred well before cluster formation. The kinetic energy of the jet is transferred to the thermal energy of the proto-ICM via thermalization at the shock at the hot spot. The thermalized jet matter expands into the IGM (or the proto-ICM) surrounding the radio galaxy laterally as well as along the jet axis (Begelman & Cioffi 1989; Nath 1995; Kaiser & Alexander 1997; Yamada et al. 1999). As this hot matter expands supersonically, a hot region surrounded by a shock sur-
face around the radio galaxy is expected to form; hereafter, we refer to it as a "cocoon." We briefly summarize the evolution of the cocoon below (for details, see Yamada et al. 1999).

While the jet is active, the pressure inside the cocoon can be written as

\[
P_c = \left( \frac{5}{8} \frac{L_j(\gamma - 1)}{\epsilon \gamma^2} \frac{\rho_j^2 v_j}{c_s^2 \sin^2 \phi} \right)^{1/5}
\]

by balancing the shock thrust and ram pressure of the background matter and by using Rankine-Hugoniot conditions. In this equation, \( L_j \) represents the kinetic energy of the jet, \( \gamma = 5/3 \) is the adiabatic index, \( \epsilon \) is the "volume factor" that describes the shape of the cocoon (compared with a sphere), \( t \) is the time elapsed since the ignition of the jet, \( \phi \) is the opening angle of the bow shock ahead of the jet termination spot (see Fig. 1 of Yamada et al. 1999), \( c_s \) is the sound speed, \( \rho_j \) is the gas density, \( P_c \) is the pressure, and the suffix \( a \) denotes the ambient matter, respectively. In the derivation of the above equation, we assumed that \( L_j \) is independent of time and is given by the Eddington luminosity of the central black hole that activates the jet. We use the gas density of the background universe as \( \rho_c \). We adopt the black hole mass \( M_{\text{BH}} = 0.002 M_{\odot} \), where \( M_{\text{BH}} \) is the mass of the spheroidal component of the host galaxy (Magorrian et al. 1998). We can estimate the total thermal energy deposited during the jet active phase as

\[
P V = \epsilon_{\text{th}}(\gamma - 1) L_j \tau_{\text{life}}, \quad \text{where} \quad V = \text{the volume of the cocoon,} \quad \epsilon_{\text{th}} = \text{the thermalization efficiency,} \quad \text{and} \quad \tau_{\text{life}} = \text{the lifetime of the jet activity.}
\]

We adopt the standard value for \( \tau_{\text{life}} \) as \( 3 \times 10^7 \) yr and take the thermalization efficiency for a free parameter.

While the jet lifetime is short, the cocoon can stay hot for about its cooling time, even after the energy supply stops. This "residual" phase contributes much more strongly to the SZ effect (Yamada et al. 1999). We model the evolution of the cocoon by adopting the analogy of the evolution of a supernova remnant (SNR) in the interstellar medium. Thus, we define the effective lifetime of the cocoon as the time from the death of the jet to the epoch when the expansion time \( t_{\text{ex}} \) equals the cooling time behind the shock front, \( \tau_{\text{cool}}(R_e, v_e) \), where \( R_e \) is the shock radius and \( v_e \) is the velocity, respectively.

Finally, we write the evolution of the internal energy of a single cocoon as follows:

\[
P_v = \left\{ \begin{array}{ll}
\epsilon_{\text{th}} L_j(\gamma - 1)(t - t_{\text{begin}}), & t < t_{\text{life}}, \\
\epsilon_{\text{th}} L_j(\gamma - 1)t_{\text{life}} \exp \left[-(t - t_{\text{life}} - t_{\text{begin}})/\tau_{\text{cool}}(z)\right], & t > t_{\text{life}},
\end{array} \right.
\]

where \( t \) is the cosmological time, \( t_{\text{begin}} \) is the epoch of jet ignition, and \( t_{\text{cool}}(z) \) is the effective lifetime at redshift \( z \), respectively. Numerical simulations have shown that, although the thermal energy of an SNR rapidly decreases soon after the radiative phase begins, the cooling time increases as the SNR expands further, and about 10% of the initial thermal energy is left behind (Chevalier 1974; Thornton et al. 1998). Thus, we keep the total internal energy constant after it drops to 10% of its initial value.

The Compton \( v \)-parameter is calculated by integrating the product of the total internal energy within a single cocoon and the number of radio galaxies in the line of sight,

\[
y = \int \frac{P V}{m_e c^2} n_{\text{RG}}(M, z_{\text{coll}}) a^3 r^2 dr \frac{1}{R_4^2} dM,
\]

where \( m_e \) is the electron mass, \( \sigma_T \) is the Thomson scattering cross section, \( n_{\text{RG}} \) is the comoving number density of radio galaxies, \( z_{\text{coll}} \) is the typical collapse epoch of host galaxy halos, \( a \) is the cosmological scale factor, \( r \) is the comoving radial coordinate, and \( R_4 \) is the angular diameter distance, respectively (Yamada et al. 1999). We assume that radio galaxies reside in halos with the mass of \( M > 10^{10} M_{\odot} \). We also assume that a fraction of normal galaxies has jet activity, and we set the proportional constant to be a canonical value \( f_r = 0.01 \). We count the number of radio (or normal) galaxies using the Press-Schechter number density \( (n_{\text{ps}}) \), and we do not use the luminosity function of radio galaxies; this is because we intend to count up the residual cocoons, whose effective lifetime \( t_e \) is much longer than the synchrotron-decay time. We define the epoch of jet ignition \( t_{\text{begin}} \) separately from the "typical collapse time" \( t_{\text{coll}} \) of the dark halo of the host galaxy, at which the variance of density perturbation of scale \( M, (\delta \Delta M)^2 \), is equal to 1.69 \( \times 10^3 \phi \) when \( \Omega_{\text{m}} = 1 \). We take \( t_{\text{begin}} \equiv t_{\text{end}} - t_{\text{coll}} \) as a free parameter because of the uncertainty inherent in the jet activation mechanism. The value of \( t_{\text{begin}} \) varies between 0 (the jet ignition coeval with the collapse of the dark halo of its host galaxy) and \( \approx 10^3 \) yr (\( \approx H_0^{-1} \)).

2.2. Energy Input into the Proto-ICM

It is reasonable to assume that the density of the proto-ICM traces that of galaxies before the density perturbation corresponding to a protocluster \( \delta \) goes nonlinear. Thus, the local number density of radio galaxies and the gas density of the proto-ICM in a protocluster region are written as

\[
n_{\text{ps}}(M, z) = n_{\text{ps}} f_r \left( \frac{a_0}{a} \right)^3 (1 + \delta),
\]

\[
n_{\mu}(M, z) = \frac{\rho_{\text{gas}}}{\mu m_p} \Omega_{\gamma} f_r (1 + \delta),
\]

where \( a_0 \) is the present scale factor, \( \rho_{\text{gas}} \) is the critical density, \( \mu = 0.59 \) is the mean molecular weight for primordial gas, \( m_p \) is the proton mass, and \( f_r \) is the fraction of the gas compared with the baryon density \( \Omega_{\gamma} \), respectively.

According to equation (4), the energy density ejected by AGNs into a protocluster is given as

\[
\epsilon_{\text{tot}} = \int f_r n_{\text{ps}}(M, z) P V(M, z)(1 + \delta) dM.
\]

Hence, the energy input per nucleon \( E_{\text{input}} \) at present \( (z = 0) \) is

\[
E_{\text{input}} = \frac{\epsilon_{\text{tot}} V}{n_{\text{gas}} V_c} = \left( \frac{\rho_{\text{gas}}}{\mu m_p} \right)^{-1} \frac{1}{\Omega_{\gamma} f_r} \int f_r n_{\text{ps}}(M, 0) f_r P V(M, 0) dM.
\]

which measures the additional, nongravitational heating. Hereafter, we assume that \( f_r = 1 \), which is reasonable when the density contrast is in a linear regime.
3. RESULTS

We calculate equations (3) and (7) with various combinations of the two parameters $\epsilon_{\text{ff}}$ and $E_{\text{input}}$. We adopt the standard cold dark matter cosmology, with $\Omega_0 = 1$, $h = 0.8$, baryon density $\Omega_b h^2 = 0.0125$, and COMB normalization for the density perturbations. In Figure 1, the contours of the Compton $y$-parameter and $E_{\text{input}}$ are plotted. X-ray observations show that excess energy via nongravitational heating is $0.44 \pm 0.3$ keV per particle (Lloyd-Davies, Ponman, & Cannon 2000). The region where the parameter values are consistent with the $y$-parameter constraint obtained by Fixen et al. (1996) using COMB, $y \leq 1.5 \times 10^{-5}$, and the energy deduced by Lloyd-Davies et al. (2000) are represented as the shaded region. As is clearly seen, the almost horizontal contours from the $y$-parameter constraint severely limit the value of $t_{\text{gap}}$ to be $\geq 6.3 \times 10^8$ yr.

The result that the value of $y$ is almost independent of thermalization efficiency $\epsilon_{\text{ff}}$ comes from the weak dependence of the expansion speed on the internal energy in the “Sedov” phase ($v \propto E^{1/5}$; Shu 1992), which results in the weak dependence of the cooling time (the effective lifetime of a cocoon) on $\epsilon_{\text{ff}}$. On the other hand, contours of $E_{\text{input}}$ limit the thermalization efficiency to $\epsilon_{\text{ff}} \leq 0.4$. The fact that the contours of $E_{\text{input}}$ run vertically for small values of $t_{\text{gap}}$ reflects the rapid cooling of cocoons at high redshift. When $t_{\text{gap}}$ is small, the cooling time of a cocoon is so short that the cocoon energy rapidly reduces to $10\%$ of the energy supplied by the jet; thus, $E_{\text{input}}$ is simply given by $L_{\text{jet}} t_{\text{cool},\text{ff}} \times 0.1$ and is proportional to $\epsilon_{\text{ff}}$. For late input (large $t_{\text{gap}}$), the contours slightly curve to the left; this is due to the small number of cocoons that contribute to the heating, which means that a large value of $\epsilon_{\text{ff}}$ is needed to gain the same amount of energy.

In order to assign $t_{\text{gap}}$ and the jet ignition epoch, we plot the corresponding redshift $z_{\text{begin}}$ as the function of halo mass in Figure 2. Figure 1 shows that $t_{\text{gap}} \geq 6.3 \times 10^8$ yr, which means that the heating of the ICM occurred at $z_{\text{begin}} \leq 3$ (Fig. 2). Compared with the halo collapse epoch ($t_{\text{gap}} = 0$; solid line), the upper bound is very close to the formation epoch of poor clusters with masses of $M = 10^{15}$–$10^{14}$ $M_\odot$. This suggests that the heating of the ICM occurred simultaneously with or after the collapse of the poor clusters, which contradicts the assumption about the heating epoch inherent in the scenario. In other words, our results bring up a serious question about the genuine preheating model.

4. DISCUSSION AND CONCLUSIONS

We have proposed a new way to elucidate the thermal history of the ICM. We have calculated the Compton $y$-parameter and the energy ejected into the ICM through AGN jet activities assuming that the nongravitational heat input by the jets occurred well before cluster formation. Comparing them with observations, we have found that the heat input had not occurred at $z \geq 3$. Since $z \sim 3$ is the typical formation epoch of poor clusters, this is not consistent with the assumption of preheating and suggests that the heat input occurred simultaneously with or after the formation of poor clusters. Considering the wide range of dispersion in the formation epochs of poor clusters ($z \sim 3$; Lacey & Cole 1993; Kitayama & Suto 1996; Balogh, Babul, & Patton 1999), the scenario of the heating being coeval with the cluster formation may be more plausible and would be consistent with the dispersions of cluster properties (Fujita & Takahara 2000). Note that if the heating occurred in a dense environment like clusters, the lifetime and filling factor of the cocoons would decrease (Yamada et al. 1999), which might reduce the expected value of the $y$-parameter well below the observational limit. Valageas & Silk (1999) also estimated the $y$-parameter for QSO heating but found a smaller value than ours ($y \leq 10^{-5}$). This may be because in their model, the energy injected into the IGM by QSOs started to cool immediately after the energy injection, which leads to a smaller $y$-value. On the other hand, in our model, a cocoon remains hot for a long time until the cooling sets in (see § 2).

Below we discuss several points that are omitted in our simple model. First, a part of electrons may be accelerated at terminal shock to become nonthermal populations. The SZ effect concerning these populations was calculated by several authors (see, e.g., Birkinshaw 1999 and Ensslin & Kaiser 2000), and it is shown that the amplitude of the signal is reduced by only a small factor for a fixed total energy of the gas. Thus, we do not think that the results in our Letter change significantly. Second, although recent works show that jet matter is suggested to be electron-positron–dominated at least close to...
the core (e.g., Wardle et al. 1998), some authors proposed that protons constitute a part of the jet energy (e.g., Mannheim 1998). If this is the case, the \( y \)-value due to the jet matter is accordingly reduced, and the input energy epoch may not be constrained by the SZ effect.

Recently, Chandra observations found that there is no indication of shocks around several radio galaxies in the center of clusters (McNamara et al. 2000; Fabian et al. 2000). These sources reside in such high-pressure regions that the expansion speed of lobes is subsonic (e.g., Fujita 2001). We have considered radio galaxies in a proto-ICM that has not fully collapsed to have such high pressure, and we have then shown that this assumption is not compatible with observational constraints of \( y \) and \( E_{\text{input}} \). Thus, the Chandra findings do not alter our main conclusion.

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