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# Heating of Cluster Cores by Acoustic Waves

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Using an analytical model, we show that acoustic waves generated by turbulent motion in intracluster medium effectively heat the central region of a so-called "cooling flow" cluster. We assume that the turbulence is generated by substructure motion in a cluster or cluster mergers. Our analytical model can reproduce observed density and temperature profiles of a few clusters. We also show that waves can transfer more energy from the outer region of a cluster than thermal conduction alone.

## 1. **Introduction**

For many years, it was thought that radiative losses via X-ray emission in clusters of galaxies leads to a substantial gas inflow, which was called a "cooling flow" (Fabian 1994, and references therein). However, X-ray spectra taken with *ASCA* and *XMM-Newton* fail to show line emission from ions having intermediate or low temperatures, implying that the cooling rate is at least 5 or 10 times less than that previously assumed (e.g., Ikebe et al. 1997; Makishima et al. 2001; Peterson et al. 2001; Tamura et al. 2001; Kaastra et al. 2001; Matsushita et al. 2002). *Chandra* observations have also confirmed the small cooling rates (e.g., McNamara et al. 2000; Johnstone et al. 2002; Ettori et al. 2002; Blanton, Sarazin, & McNamara 2003).

These observations suggest that a gas inflow is prevented by some heat sources that balance the radiative losses. There are two popular ideas about the heating sources. One is energy injection from a central AGN of a cluster (Tucker & Rosner 1983; Böhringer & Morfill 1988; Rephaeli 1987; Binney & Tabor 1995; Soker et al. 2001; Ciotti & Ostriker 2001; Böhringer et al. 2002; Churazov et al. 2002; Soker, Blanton, & Sarazin 2002; Reynolds, Heinz, & Begelman 2002; Kaiser & Binney 2003). Recent *Chandra* observations show that AGNs at cluster centers actually disturb the intracluster medium (ICM) around them (Fabian et al. 2000; McNamara et al. 2000; Blanton et al. 2001; McNamara et al. 2001; Mazzotta et al. 2002; Fujita et al. 2002; Johnstone et al. 2002; Kempner, Sarazin, & Ricker 2002), although some of them were already discovered by *ROSAT* (Böhringer et al. 1993; Huang & Sarazin 1998). Numerical simulations suggest that buoyant bubbles created by the AGNs mix and heat the ambient ICM to some extent (Churazov et al. 2001; Quilis, Bower, & Balogh 2001; Saxton, Sutherland, & Bicknell 2001; Brüggen & Kaiser 2002; Basson & Alexander 2003). The other possible heat source is thermal conduction from the hot outer layers of clusters (Takahara & Takahara 1979, 1981; Tucker & Rosner 1983; Friaca 1986; Gaetz 1989; Böhringer & Fabian 1989; Sparks 1992; Saito & Shigeyama 1999; Narayan & Medvedev 2001).

However, it has already been known that the ICM heating by AGNs or thermal conduction has problems. For the AGN heating, the efficiency of the heating must be quite high (Fabian, Voigt, & Morris 2002). Moreover, the intermittent activity of an AGN makes the temperature profile of the host cluster irregular, which is inconsistent with observations (Brighenti & Mathews 2003). For the thermal conduction, stability is the most serious problem; either the observed temperature gradient disappears or the conduction has a negligible effect relative to radiative cooling (Bregman & David 1988; Brighenti & Mathews 2003; Soker 2003). Moreover, thermal conduction alone cannot sufficiently heat the central regions of some clusters (Voigt et al. 2002; Zakamska & Narayan 2003). Although a "double heating model" that incorporates the effects of simultaneous heating by both the central AGN and thermal conduction may alleviate the stability problem (Ruszkowski & Begelman 2002), Brighenti & Mathews (2003) indicate that the conductivity must still be about $0.35 \pm 0.10$ times the Spitzer value.

In this paper, we consider another natural heating source. In the ICM, fluid turbulence is generated by substructure motion or cluster mergers. From numerical simulations, Nagai, Kravtsov, & Kosowsky (2003) showed that the turbulent velocities in the ICM are about 20%–30% of the sound speed even when a cluster is relatively relaxed. Such turbulence generates acoustic waves in the ICM. Compressive characters of the acoustic waves with a relatively large amplitude inevitably lead to the steepening of the wave fronts to form shocks. As a result, the waves can heat the surrounding ICM through the shock dissipation. A similar heating mechanism has also been proposed in the solar corona; the waves are excited by granule motions of surface convection (Osterbrock 1961; Ulmschneider 1971; McWhirter, Thonemann, & Wilson 1975). The idea of wave heating in the ICM was proposed by Pringle (1989), but the study was limited to order-of-magnitude estimates. In this paper, we study the wave heating by an analytical model and numerical simulations. We use cosmological parameters of $\Omega_0 = 0.3$, $\lambda = 0.7$, and $H_0 = 70\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ unless otherwise mentioned.

## 2. **Analytical Approach**

### 2.1. *Models*

In the ICM the magnetic pressure is generally negligible against the gas pressure (Sarazin 1986). Therefore, acoustic waves (strictly speaking, fast mode waves in high-$\beta$ plasma) could carry a much larger amount of energy than other modes of magnetohydrodynamical waves. We expect that turbulence in the ICM excites acoustic waves that propagate in various directions. In this paper, we focus on the acoustic waves traveling inward, which play an important role in the heating of the cluster center. These waves, having a relatively large but finite amplitude, eventually form shocks to shape sawtooth waves (N-waves) and directly heat the surrounding ICM by dissipation of their wave energy. We adopt the heating model for the solar corona based on the weak shock theory (Suzuki 2002; Stein & Schwartz 1972). In this section, we assume that a cluster is spherically symmetric and stationary. The equation of continuity is

$$\dot{M} = -4\pi r^2 \rho v \,, \tag{1}$$

where $\dot{M}$ is the mass accretion rate, $r$ is the distance from the cluster center, $\rho$ is the gas density, and $v$ is the gas velocity. The equation of momentum conservation is

$$v\frac{dv}{dr} = -\frac{GM(r)}{r^2} - \frac{1}{\rho}\frac{dp}{dr} - \frac{1}{\rho c_s\{1+[(\gamma+1)/2]\alpha_w\}}\frac{1}{r^2}\frac{d}{dr}(r^2 F_w)\,, \tag{2}$$

where $G$ is the gravitational constant, $M(r)$ is the mass within radius $r$, $p$ is the gas pressure, $c_s$ is the sound velocity, $\gamma(=5/3)$ is the adiabatic constant, and $\alpha_w$ is the wave velocity amplitude normalized by the ambient sound velocity ($\alpha_w = \delta v_w/c_s$). For the actual calculations, we ignore the term $vdv/dr$ because the velocity is much smaller than the sound velocity except for the very central region of a cluster where the weak shock approximation is not valid ($\alpha_w \gtrsim 1$; see §2.2). The wave energy flux, $F_w$, is given by

$$F_w = -\frac{1}{3}\rho c_s^3 \alpha_w^2 \left(1 + \frac{\gamma+1}{2}\alpha_w\right)\,. \tag{3}$$

Note that the sign of equation (3) is the opposite of equation (7) of Suzuki (2002), because we consider waves propagating inwards contrary to those in Suzuki (2002). The energy equation is written as

$$\rho v \frac{d}{dr}\left(\frac{1}{2}v^2 + \frac{\gamma}{\gamma-1}\frac{k_B T}{\mu m_H}\right) + \rho v \frac{GM(r)}{r^2} + \frac{1}{r^2}\frac{d}{dr}[r^2(F_w + F_c)] + n_e^2 \Lambda(T,Z) = 0\,, \tag{4}$$

where $k_B$ is the Boltzmann constant, $T$ is the gas temperature, $\mu(=0.61)$ is the mean molecular weight, $m_H$ is the hydrogen mass, $n_e$ is the electron number density, and $\Lambda$ is the cooling function. The term $\nabla\cdot\boldsymbol{F}_w$ indicates the heating by the dissipation of the waves. We adopt the classical form of the conductive flux for ionized gas,

$$F_c = -f_c \kappa_0 T^{5/2}\frac{dT}{dr} \tag{5}$$

with $\kappa_0 = 5\times10^{-7}$ in cgs units. The factor $f_c$ is the ratio of actual thermal conductivity to the classical Spitzer conductivity. The cooling function is a function of temperature $T$ and metal abundance $Z$, and is given by

$$\Lambda(T,Z) = 2.1\times10^{-27}\left(1+0.1\frac{Z}{Z_\odot}\right)\left(\frac{T}{\mathrm{K}}\right)^{-0.5} \tag{6}$$

$$+ 8.0\times10^{-17}\left(0.04+\frac{Z}{Z_\odot}\right)\left(\frac{T}{\mathrm{K}}\right)^{-1.0} \tag{7}$$

in units of ergs cm$^3$ s$^{-1}$. This is an empirical formula derived by fitting to the cooling curves calculated by Böhringer & Hensler (1989). We assume that wave injection takes place at radii far distant from the cluster center, and thus there is no source term of waves in equation (4).

The equation for the evolution of shock wave amplitude is given by

$$\frac{d\alpha_w}{dr} = \frac{\alpha_w}{2}\left[-\frac{1}{p}\frac{dp}{dr} + \frac{2(\gamma+1)\alpha_w}{c_s\tau} - \frac{2}{r} - \frac{1}{c_s}\frac{dc_s}{dr}\right]\,, \tag{8}$$

where $\tau$ is the period of waves, which we assume to be constant (Suzuki 2002). We give the period by $\tau = \lambda_0/c_{s0}$, where $c_{s0}$ is the sound velocity at the average temperature of a cluster ($T_{\rm av}$), and $\lambda_0$ is the wave length given as a parameter. The second term of the right side of equation (8) denotes dissipation at each shock front of the N-waves. We note that the sign of the term is the opposite of equation (6) of Suzuki (2002), because we consider waves propagating inwards contrary to those in Suzuki (2002).

For the mass distribution of a cluster, we adopt the NFW profile (Navarro, Frenk, & White 1997). The mass profile is written as

$$M(r) \propto \left[\ln\left(1+\frac{r}{r_s}\right) - \frac{r}{r_s(1+r/r_s)}\right]\,, \tag{9}$$

where $r_s$ is the characteristic radius of the cluster. The normalization can be given by $M(r_{\rm vir}) = M_{\rm vir}$, where $r_{\rm vir}$ and $M_{\rm vir}$ are the virial radius and mass of a cluster, respectively. We ignore the self-gravity of the ICM.

### 2.2. *Results*

We show that our model can reproduce observed ICM density and temperature profiles of clusters. We choose A1795 and Ser 159–03 clusters to be compared with our model predictions. Zakamska & Narayan (2003) showed that thermal conduction alone can explain the density and temperature profiles for A1795; $f_c = 0.2$ is enough and other heat sources are not required. On the other hand, the profiles for Ser 159 − 03 cannot be reproduced by thermal conduction alone (Zakamska & Narayan 2003). The parameters of the mass profiles for the clusters are the same as those adopted by Zakamska & Narayan (2003) and are shown in Table 1. The concentration parameter of a cluster, $c = r_{\rm vir}/r_s$ is given by

$$c = \frac{1}{r_s}\left[\frac{3\,M_{\rm vir}}{4\pi\,200\,\rho_{\rm crit}}\right]^{1/3}\,, \tag{10}$$

where $\rho_{\rm crit}$ is the critical density of the universe. We fix the metal abundance profiles. For A1795, we assume $Z(r) = 0.8\exp(-r/170\,\mathrm{kpc})\,Z_\odot$ (Ettori et

TABLE 1. CLUSTER PARAMETERS

| Cluster | $M_{\rm vir}$ ($10^{14}\,M_\odot$) | $T_{\rm av}$ (keV) | $r_s$ (Mpc) | $c$ |
|---|---|---|---|---|
| A1795 | 12 | 7.5 | 0.46 | 4.2 |
| Ser 159–03 | 2.6 | 2.7 | 0.31 | 4.7 |

TABLE 2. MODEL PARAMETERS

| Cluster | $f_c$ | $\dot{M}$ ($M_\odot$ yr$^{-1}$) | $\lambda_0$ (kpc) | $n_e(r_i)$ (cm$^{-3}$) | $T(r_i)$ (keV) |
|---|---|---|---|---|---|
| A1795 | $2\times10^{-3}$ | 50 | 100 | 0.5 | 0.6213 |
| Ser 159–03 | 0.2 | 30 | 70 | 0.14 | 0.780 |

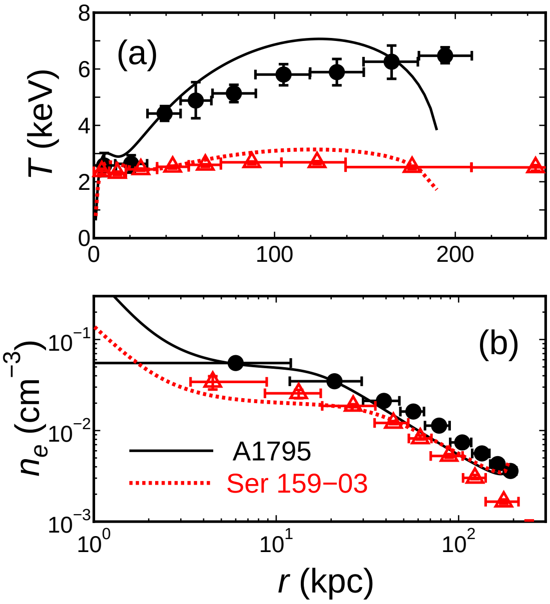


FIG. 1.— (a) Modeled temperature and (b) density profiles for A1795 (solid lines) and Ser 159–03 (dotted lines). Filled dots and empty triangles are the *Chandra* data for A1795 and Ser 159–03, respectively.

al. 2002), and for Ser 159–03, we assume $Z(r) = 0.51\exp(-r/171\,{\rm kpc})\,Z_\odot$ (Kaastra et al. 2001).

We carry out the modeling of ICM heating as follows. First, we select values of $f_c$, $\dot{M}$, and $\lambda_0$. Then, we set the boundary conditions of the equations (1), (2), (4), and (8) at $r_i = 1$ kpc, that is, well inside the central cD galaxy. From $r = r_i$, we integrate the equations outward and compare the model profiles of $n_e(r_i)$ and $T(r_i)$ with the data. While we fix the value of $\alpha_w(r_i)$, we adjust $n_e(r_i)$ and $T(r_i)$ to be consistent with the observed profiles. We restrict ourselves to a comparison by eye, since neither the data nor the models are reliable enough for a detailed $\chi^2$ fit. If we do not have satisfactory fits, we change the values of $f_c$, $\dot{M}$, and $\lambda_0$ and repeat the process. We show the values of $f_c$, $\dot{M}$, and $\lambda_0$ that we finally adopted in Table 2, and briefly summarize how the results depend on the choice of them as follows.

For A1795, we choose $f_c = 2\times10^{-3}$, because Zakamska & Narayan (2003) have already shown that ICM heating only by thermal conduction with $f_c \sim 0.2$ is consistent with the observations. In this study, we will show that even when $f_c$ is much smaller than 0.2, the observed profiles can be reproduced if wave heating is included. However, we found that if $f_c$ is too small, the obtained temperature profile is too steep to be consistent with the observation. For Ser 159–03, we adopt $f_c = 0.2$, which is suggested by Narayan & Medvedev (2001) in a turbulent MHD medium. If we take $f_c$ much smaller than this, the model cannot reproduce the relatively flat temperature distribution observed in this cluster.

For mass accretion rates $\dot{M}$, we take about 1/10 times the value claimed before the *Chandra* and *XMM-Newton* era. For A1795, $\dot{M} \sim 500 M_\odot {\rm yr}^{-1}$ ($h = 0.5$) was reported (Edge, Stewart, & Fabian 1992; Peres et al. 1998). Thus, we adopt $\dot{M} = 50\,M_\odot\,{\rm yr}^{-1}$, which is consistent with a recent *XMM-Newton* observation ($< 150\,M_\odot\,{\rm yr}^{-1}$; Tamura et al. 2001). For Ser 159–03, $\dot{M} \sim 300\,M_\odot\,{\rm yr}^{-1}$ ($h = 0.5$) was reported (White, Jones, & Forman 1997; Allen & Fabian 1997). Thus, we adopt $\dot{M} = 30 M_\odot {\rm yr}^{-1}$. We note that if we assume that wave heating is effective and that $\dot{M}$ is much smaller than the above values, we cannot reproduce both density and temperature profiles obtained by X-ray observations; we get too high temperature and too low density.

Typical wave length, $\lambda_0$, should be comparable to the typical eddy size of turbulence in ICM. From numerical simulations, Roettiger, Stone, & Burns (1999) showed that the typical eddy size is the core scale of a cluster. Thus, we take $\lambda_0 = 100$ kpc for A1795. For Ser 159–03, we use a smaller value of $\lambda_0 = 70$ kpc because of its small mass (Table 1). Smaller $\lambda_0$ means a smaller distance that waves propagate before dissipation.

Among three of the parameters for the boundary conditions at $r = r_i$ ($\alpha_w$, $n_e$, and $T$), we fix $\alpha_w = 3$ to reduce the number of fitting parameters. If we assume much smaller $\alpha_w$, wave heating becomes negligible. On the other hand, if we assume much larger $\alpha_w$, the region where the weak shock approximation is invalid ($\alpha_w \gtrsim 1$) extends.

Figure 1 shows the model fits for the two clusters. The boundary conditions are presented in Table 2. The temperature $T(r_i)$ is especially required to be fine-tuned for the fit. We use the *Chandra* data of A1795 obtained by Ettori et al. (2002) and the *XMM-Newton* data of Ser 159–03 obtained by Kaastra et al. (2001). The *XMM-Newton* data of A1795 are also obtained by Tamura et al. (2001) and they are similar to those obtained by Ettori et al. (2002), although the former is not deprojected contrary to the latter. The good agreement between the model and the data suggests that wave heating is a promising candidate of the mechanism that solves the cooling flow problem. In Figure 1, densities go to infinity and temperatures go down to zero at $r \sim 200$ kpc. This

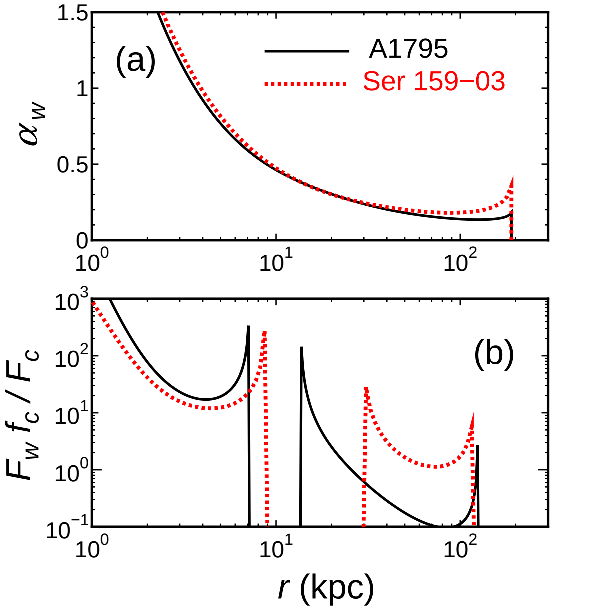


FIG. 2.— (a) Wave amplitudes and (b) the ratio of heat flux by waves to that by thermal conduction for A1795 (solid lines) and Ser 159–03 (dotted lines).

suggests that waves injected outside of this radius cannot reach the cluster center.

In Figure 2a, we present the wave velocity amplitude normalized by the sound velocity ($\alpha_w$). As the N-waves propagate into the central regions of the cluster, $\alpha_w$ increases rapidly. This is mainly because of the geometrical convergence to the cluster center, whereas the total wave luminosity (= energy flux times $r^2$) mostly dissipates through the inward propagation in itself. Since $\alpha_w > 1$ at $r \lesssim 4$ kpc for both A1795 and Ser 159–03, the results may not be quantitatively correct there. We note that the gas velocity for the region of $r \gtrsim 4$ kpc is very small compared with the sound velocity and thus our ignorance of $vdv/dr$ in equation (2) is justified.

In Figure 2b, the ratio $F_w f_c/F_c$ is presented. The gaps at $\sim 10$ kpc reflect $F_c < 0$. Assume that an observer made observations of the model clusters and the temperature distributions were exactly measured. If the observer *assumed* the classical conductivity, the heat flux measured by the observer should be $F_c/f_c$ ($f_c < 1$) because of the definition of $F_c$ (equation [5]). Figure 2b shows that the observer would measure an X-ray emission much larger than that predicted by the classical thermal conduction ($F_w f_c/F_c > 1$) if the energy swallowed by the black hole at the cluster center is small. Such large X-ray emissions have actually been estimated in some clusters (Voigt et al. 2002). The wave heating model can account for the observations without the help of heating by AGNs. The overall results shown here have been confirmed by one-dimensional numerical simulations (Fujita, Suzuki, & Wada 2003).

## 3. Discussion

Our analytical model shows that acoustic waves are amplified at the cluster center and can heat the cluster core. One should note that our assumption, that is, the spherical symmetry, could affect the amplification quantitatively. For more realistic modeling, we should consider that real clusters are not exactly spherically symmetric. However, Pringle (1989) indicated that even if a cluster is not spherically symmetric, the lower temperature and smaller sound velocity at the cluster center should have waves focus on the center. Since the focusing effect depends on the temperature gradient, it may solve the fine-tuning problem of the heating of cluster cores. If the cooling dominates heating, the temperature at the cluster center decreases and the temperature gradient in the core increases.

## 4. Conclusions

Through an analytical approach, we have shown that acoustic waves generated by turbulence in the ICM in the outer region of a cluster can effectively heat the central part of the cluster. The heat flux by the waves may exceed that by thermal conduction. In the analytical studies, we have obtained time-independent solutions and compared the predicted density and temperature profiles with the observed ones; they are consistent with each other. Since we assumed that a cluster is spherically symmetric and the assumption leads to artificial focusing of waves, one should take the quantitative results with care. However, it has been indicated that even if a cluster is not spherically symmetric, waves are focused by the temperature gradient at the cluster center. Thus, it is worthwhile to study the wave heating by multi-dimensional analyses.

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