Are X-ray Clusters Cooled by Heat Conduction to the Surrounding Intergalactic Medium?

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ABSTRACT

We show that X-ray clusters would have cooled substantially over a Hubble time by transport of heat from their hot interior to the their envelope, if the heat conductivity had not been heavily suppressed relative to the Spitzer value due to magnetic fields. The suppression is required in order for the observed abundance of hot X-ray clusters to be consistent with predictions from popular cosmological models. If a similar or stronger suppression factor applies to cluster cores, then thermal conduction can not be the mechanism that prevents cooling flows there.

Key Words: galaxies: clusters: general – cooling flows – conduction – hydrodynamics
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1. Introduction

Recently, the old idea that heat conduction may suppress cooling flows in X-ray clusters (Binney & Cowie 1981; Tucker & Rosner 1983; Bertschinger & Meiksin 1986; Bregman & David 1988; Gaetz 1989; Rosner & Tucker 1989; David et al. 1992; Pistinner & Shaviv 1996; Dos Santos 2001) has been revived due to the apparent lack of strong cooling flows in Chandra and XMM-Newton data (Fabian et al. 2001; Böhringer et al. 2001; Molendi & Pizolato 2001). It was argued that if the heat conductivity is not suppressed by more than a factor of a few relative to the Spitzer value, then the inward heat flow due to the positive temperature gradient in cluster cores would be sufficient to compensate for the energy loss caused by Bremsstrahlung cooling of the gas (Narayan & Medvedev 2001; Gruzinov 2002; Voigt et al. 2002).

The purpose of this paper is to caution that a large heat conduction coefficient would also lead to dramatic cooling of the entire cluster gas due to energy transport outwards into the cooler, surrounding intergalactic medium. By analyzing ASCA data for 30 X-ray clusters, Markevitch et al. (1998) have identified a composite temperature profile that declines by a
factor of $\sim 2$ from the core out to about half the virial radius (see also Finoguenov et al. 2001). This profile has been confirmed in a recent BeppoSAX data set of 21 clusters (De Grandi & Molendi 2002). Here we use this profile to calculate the resulting conductive heat transfer from the cluster interior to the surrounding envelope.

We note that the above ASCA results were challenged in several clusters by preliminary XMM-Newton data which showed a nearly isothermal profile (Arnaud et al. 2001a,b; Pratt et al. 2001). However, since clusters represent the hottest structures in the universe there is no doubt that they are surrounded by cooler gas at a sufficiently large radius. In fact, if the temperature profile is nearly flat all the way out to the radius where the surface brightness of the cluster is too faint to be detectable, then the temperature gradient around the (more distant) virial radius of the cluster must be even steeper than assumed here (since the temperature must eventually approach the ambient value over a shorter range of radii). Hence, the heat flux that we calculate based on the Markevitch et al. (1998) temperature profile provides a conservative lower limit for the conductive energy loss of cluster interiors.

Infall of gas onto the cluster could in principle suppress conduction of heat outwards. However, numerical simulation show that much of this infall is confined within filaments that cover only a small fraction of the surface area of the accreting object, and the gas flow is often clumpy and episodic (e.g., Yoshida et al. 2002, and references therein). Hence, conduction is unlikely to be suppressed by infall in all directions at all times. In this paper we focus our attention on the virialized region of the cluster, where the gas is stationary and in hydrostatic equilibrium. Since most of the mass is located in the outer envelope of the cluster, a considerable transport of heat out of the cluster core would only have a minor effect on the cluster envelope. For example, a reduction by $\sim 50\%$ in the X-ray temperature of the cluster – which is dictated by the core at $\sim 300$ kpc – would typically only lead to a $\sim 5$–$10\%$ increase in the outer envelope temperature at a radius of $\sim 3$ Mpc. In the following we examine the question of whether the cores of clusters, which dominate their X-ray emission, would cool through thermal conduction by more than they are allowed to cool over a Hubble time, given the observed temperature profiles of Markevitch et al. (1998). Throughout the discussion we assume a fully-ionized, hydrogen-helium plasma with a helium mass fraction of 24\%, for which the mean particle mass (including the electrons) is $\mu = 0.59$ in units of the proton mass $m_p$.

2. Cooling of X-ray Clusters by Heat Conduction

The time over which thermal energy is drained out of an X-ray cluster by conduction can be found by dividing the total thermal energy of the cluster, $(M_g/\mu m_p)(3/2k_BT)$, by the
rate of conductive heat loss across its boundary radius $r_b$, 

$$t_{\text{cond}} = \frac{3}{8\pi G \mu m_p} \frac{(M_g/M_{\text{tot}})k_B T}{\kappa |\partial T/\partial r|_{r_b}}, \quad (1)$$

where $\bar{T} = M_g^{-1} \int_0^{r_b} T(r) \rho_g(r) 4\pi r^2 dr$ is the (mass-weighted) mean temperature of the cluster, $\rho_g(r)$ is the mass density of the gas, $M_g = \int_0^{r_b} \rho_g(r) 4\pi r^2 dr$ is the total gas mass out to the radius $r_b$, $\kappa$ is the coefficient of heat conductivity, and $k_B$ is Boltzmann’s constant. The hydrostatic equilibrium equation, $(GM_{\text{tot}}\rho_g/r^2) = -\partial_r (\rho_g k_B T/\mu m_p)$, yields

$$\frac{M_g}{r_b} = -f_g \left[ \left( \frac{k_B T}{G \mu m_p} \right) \left( \frac{\partial \ln \rho_g}{\partial \ln r} + \frac{\partial \ln T}{\partial \ln r} \right) \right] \bigg|_{r_b}, \quad (2)$$

where $f_g = (M_g/M_{\text{tot}})$ is the gas mass fraction at $r_b$, $G$ is Newton’s constant, and $\partial_r \equiv \partial/\partial r$. By substituting equation (2) into equation (1) we get

$$t_{\text{cond}} = \frac{3}{8\pi G \mu m_p} f_g k_B T \left[ \kappa^{-1} \left( 1 + \frac{\partial_r \ln \rho_g}{\partial_r \ln T} \right) \right] \bigg|_{r_b}. \quad (3)$$

Thus, the characteristic cooling time for the entire cluster depends on the boundary values of the conductivity coefficient, $\kappa(r_b)$, and the effective “adiabatic index” of the gas, $\gamma_{\text{eff}} \equiv [1 + (\partial_r \ln T/\partial_r \ln \rho_g)]_{r_b}$.

As customary in the literature, we identify the boundary of the hot interior of the cluster as the radius, $r_{180}$, where the average interior density of the gas is 180 times the mean cosmological density. The universal temperature profile derived by Markevitch et al. (1998) from ASCA data implies $[\partial \ln T/\partial \ln r]_{r_b} \approx -0.4$, $\beta_b \equiv [T(r_b)/\bar{T}] \approx 0.6$, and $\gamma_{\text{eff}} \approx 1.24$. In order to get a numerical value for the cooling time $t_{\text{cond}}$, we normalize the conductivity coefficient by the Spitzer (1962) value, $\kappa_{\text{Sp}}(r_b) = 5 \times 10^{29} k_B (\beta_b \bar{T}_{10})^{5/2} \text{cm}^{-1} \text{s}^{-1}$ where $\bar{T}_{10} = (k_B T/10 \text{ keV})$, and define the suppression factor $\eta \equiv \kappa/\kappa_{\text{Sp}}$. By substituting the above parameter values into equation (3) we get$^1$,

$$t_{\text{cond}} = 5 \eta^{-1} \left( \frac{f_g}{0.15} \right) \left( \frac{k_B \bar{T}}{10 \text{ keV}} \right)^{-3/2} \text{Gyr}. \quad (4)$$

Over a cluster lifetime, $\tau_{\text{cl}}$, the cluster temperature is expected to decline by a fraction

$$\frac{\Delta \bar{T}}{\bar{T}} \approx \frac{\tau_{\text{cl}}}{t_{\text{cond}}} = 0.2 \left( \frac{\eta}{0.1} \right) \left( \frac{\tau_{\text{cl}}}{10 \text{ Gyr}} \right) \left( \frac{f_g}{0.15} \right)^{-1} \left( \frac{k_B \bar{T}}{10 \text{ keV}} \right)^{3/2}, \quad (5)$$

$^1$Note that the heat flux saturates when the Coulomb mean-free-path $\lambda_{\text{Coul}}$ becomes longer than the characteristic scale of the temperature variation $(\partial \ln T/\partial r)^{-1}$ (Sarazin 1988). For a conductivity coefficient which is lower than the Spitzer value by a factor of $\eta$, the effective mean-free-path (at the same thermal speed) is $\lambda_{\text{eff}} \sim \eta \lambda_{\text{Coul}}$. From the $T$-vs-$r_{180}$ relation of Evrard et al. (1996) we get $(\lambda_{\text{eff}}/r_{180}) \sim 0.1(\eta/0.1)T_{10}^{3/2}$. 


where we have assumed that $\tau_{cl} \ll t_{\text{cond}}$. Note that the cluster lifetime cannot be shorter than the sound crossing time across its diameter, $\sim 6(\tau_{180}/5 \text{ Mpc})\bar{T}^{-1/2} \text{ Gyr}$. Cooling is inevitable (and cannot be eliminated by adiabatic heating of the gas as it settles towards the center) since the gravitational potential that confines the gas is dominated by the dark matter.

Equation (5) implies that hot X-ray clusters in the local universe must have been even hotter when they formed. The abundance of X-ray clusters is exponentially suppressed at high temperatures (Henry & Arnaud 1991; Eke et al. 1996; Viana & Liddle 1996; Pierpaoli et al. 2001; Ikebe et al. 2002) and even more so at earlier cosmic times (Fan, Bahcall, & Cen 1997; Bahcall & Fan 1998; Evrard et al. 2002). It therefore becomes exponentially more difficult to account for the abundance of hot clusters in the present-day universe if those same clusters had to be even hotter $\sim$ 5 billion years ago. The agreement between the measured abundances of hot ($k_B\bar{T} > 6 \text{ keV}$) clusters and those predicted by popular cosmological models (see Figures 9 and 12 in Evrard et al. 2002) would be significantly spoiled unless we require $(\Delta \bar{T}/\bar{T}) \lesssim 0.3$. From equation (5) we then find $\eta \lesssim 0.15(\tau_{cl}/10 \text{ Gyr})^{-1}\bar{T}^{-3/2}$. Note that this constraint is strongest for the hottest clusters where the total thermal energy is $\sim 10^{64}$ ergs, and in which plausible astrophysical heating sources (such as supernovae or active galactic nuclei) are unable to compensate for the energy loss due to thermal conduction. Of particular interest is the cluster 1E 0657-56 at $z = 0.296$ for which the inferred emissivity-weighted temperature is $14.8^{+1.7}_{-1.2} \text{ keV}$, although it may be a relatively young merger (Tucker et al. 1998; Markevitch et al. 2002). Since heat conduction is temperature dependent, it distorts the shape of the abundance distribution of cluster temperatures in a generic way that is not degenerate with variations in cosmological parameters such as the normalization of the power-spectrum of density fluctuations. Inclusion of thermal conduction in future high-resolution hydrodynamic simulations can be used to refine the above upper limit on $\eta$. In these simulations, it would be important to treat the electron and ion temperatures separately since the thermal equilibration timescale is long near the virialization shock of clusters (Fox & Loeb 1997).

We reiterate that the emission-weighted temperature of an X-ray cluster is dominated by its core which amounts to only a small fraction of the total cluster mass. A substantial reduction in the core temperature would merely result from the transfer of heat out of the hot core to the cooler, stationary cluster envelope without requiring that this heat be transferred further to accreting material in the surrounding large-scale structure. Nevertheless, heat conduction is inevitably expected to preheat the surrounding gas and suppress smooth accretion of gas onto the gravitational potential well of the hottest clusters. If substantial, such a suppression would have implied that the baryon mass fraction in the hottest clusters is lower than its cosmic average, a result that would have been at odds with the concordance
model of Big Bang Nucleosynthesis and structure formation (Burles et al. 2001; Tegmark, Zaldarriaga, & Hamilton 2002).

3. Conclusion

We find that heat conduction must be suppressed by a factor \( \eta \lesssim 0.15(\tau_{cl}/10 \text{ Gyr})^{-1}T^{-3/2}_{10} \)
relative to the Spitzer value, or else the cores of X-ray clusters would have cooled significantly over their lifetime. This suppression can be naturally produced (see Malyshkin & Kulsrud 2000 and §5 in Malyshkin 2001) by the magnetic fields that are inferred to exist in the halos of X-ray clusters (Carilli & Taylor 2002). The recent Chandra detections of sharp temperature jumps (cold fronts) in several clusters (Markevitch et al. 2000; Vikhlinin et al. 2001a) indicate an even stronger suppression of heat conduction across these jumps (Markevitch et al. 2000; Ettori & Fabian 2000). Similarly, a suppression factor of \( \eta \sim 1\text{–}3\% \)

is required to account for the conditions in the interstellar gas of cluster galaxies (Vikhlinin et al. 2001b). If this suppression applies also to the diffuse gas in cluster cores, then thermal conduction could not account for the apparent lack of cooling flows in them. Mixing of gas due to mergers or central heating sources, such as active galactic nuclei, could in principle compensate for the radiative losses in these environments (Böhringer et al. 2002; Churazov et al. 2002). In this paper we have shown that if the thermal conductivity had been comparable to the Spitzer value as recently suggested (Voigt et al. 2002), then cooling flows would have not been suppressed but rather induced in hot X-ray clusters.

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