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# Two Clusters of Galaxies with Radio-Quiet Cooling Cores

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## ABSTRACT

Radio lobes inflated by active galactic nuclei at the centers of clusters are a promising candidate for halting condensation in clusters with short central cooling times because they are common in such clusters. In order to test the AGN-heating hypothesis, we obtained *Chandra* observations of two clusters with short central cooling times yet no evidence for AGN activity: Abell 1650 and Abell 2244. The cores of these clusters indeed appear systematically different from cores with more prominent radio emission. They do not have significant central temperature gradients, and their central entropy levels are markedly higher than in clusters with stronger radio emission, corresponding to central cooling times  $\sim 1$  Gyr. Also, there is no evidence for fossil X-ray cavities produced by an earlier episode of AGN heating. We suggest that either (1) the central gas has not yet cooled to the point at which feedback is necessary to prevent it from condensing, possibly because it is conductively stabilized, or (2) the gas experienced a major heating event  $\gtrsim 1$  Gyr in the past and has not required feedback since then. The fact that these clusters with no evident feedback have higher central entropy and therefore longer central cooling times than clusters with obvious AGN feedback strongly suggests that AGNs supply the feedback necessary to suppress condensation in clusters with short central cooling times.

*Subject headings:* galaxies:clusters:general — galaxies:clusters:individual (A1650)  
— galaxies:clusters:individual (A2244) — cooling flows

## 1. Introduction

The cooling-flow problem in clusters of galaxies has been one of the most notorious issues in galaxy formation. The cooling time ( $t_c$ ) of gas within the central 100 – 200 kpc of many clusters is less than a Hubble time (e.g. Cowie & Binney 1977; Fabian & Nulsen 1977). If there is no compensating heat source distributing thermal energy over that same region, that gas ought to cool, condense, and relax toward the cluster’s center in a so-called “cooling flow,” but exhaustive searches in other wave bands have failed to locate the  $10^{12} - 10^{13} M_\odot$  of stars or cool gas that should have accumulated (e.g. O’Dea et al. 1994b; Antonucci & Barvainis 1994; McNamara & Jaffe 1994). Nevertheless, something unusual is happening in clusters with  $t_c \ll H_0^{-1}$ . Significantly smaller amounts of gas have been detected in the form of CO (Edge et al. 2002; Edge & Frayer 2003) or HI (O’Dea et al. 1994a), vibrationally excited  $H_2$  (Donahue et al. 2000; Falcke et al. 1998; Jaffe & Bremer 1997), and evidence for star formation (e.g. Cardiel et al. 1998; Crawford et al. 1999; Voit & Donahue 1997; O’Dea et al. 2004) are common in these systems, and *Chandra* observations have shown that radio lobes sometimes carve out huge cavities in the X-ray emitting gas at the centers of such clusters (e.g., McNamara et al. 2001; Fabian et al. 2000; Blanton et al. 2003).

This association of star formation, line emission, and relativistic plasma with cooling-flow clusters has fed speculation that feedback from active galactic nuclei modulates the condensation of hot gas, greatly reducing the mass-cooling rates naively inferred from X-ray imaging (e.g., Böhringer et al. 2002; Quilis et al. 2001). However, active feedback sources are not found in every cluster with  $t_c \ll H_0^{-1}$ . For example, the nearby cooling-flow sample of Peres et al. (1998) consists of twenty-three clusters with  $\dot{M} > 100 M_\odot \text{ yr}$  inferred from *ROSAT* imaging. Of these, thirteen have both an emission-line nebula and a strong radio source, two have no emission lines but a strong radio source (A2029, A3112), and three have emission lines but a weak radio source (A478, A496, A2142) leaving five with no emission lines and little or no radio activity (A1651, A2244, A1650, A1689, A644).

To test the idea that feedback from either an AGN, star formation, or some combination of the two suppresses cooling in the cores of clusters with  $t_c \ll H_0^{-1}$ , we observed two objects from this last set of five with *Chandra*: A1650 ( $z = 0.0845$ ) and A2244 ( $z = 0.0968$ ). These clusters are luminous X-ray sources, with bolometric  $L_x \sim 8 \times 10^{44} h_{70}^{-2} \text{ erg s}^{-1}$  and estimated gas  $T_x$  of 5.5–7.0 keV (David et al. 1993). Here we compare those clusters with an archival sample of clusters of similar X-ray luminosities ( $L_x = 0.4 - 30 \times 10^{44} \text{ erg s}^{-1} h_{70}^{-2}$ ) and

temperatures ( $T_x = 2.9 - 7.4$  keV), with  $t_c \ll H_0^{-1}$ , with evidence for active feedback in the form of central radio emission, and in most cases, with emission-line nebulae as well (Donahue et al. 2005). We will refer to these clusters as ”active clusters.” All of the clusters in the Donahue et al. (2005) sample and the two clusters discussed in this paper have single, optically luminous, brightest central galaxies residing at the centroid of their X-ray emission. § 2 describes the observations and calibration procedures. § 3 describes the data analysis and the extraction of entropy profiles, and § 4 discusses our results, which we summarize in § 5. For this paper we assume  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and a flat universe where  $\Omega_M = 0.3$ .

## 2. Observations and Calibration

The observation dates, flare-free exposure times, and count rates between 0.5-9.5 keV within a 4’ radius aperture are reported in Table 1. The back-illuminated CCD on the Chandra X-ray Observatory (Weisskopf et al. 2002), the ACIS-S3 detector, was used for its sensitivity to soft X-rays. Its field of view ( $8' \times 8'$ ) extends to about 10% of the virial radius of each cluster, limiting our analysis to the cluster cores.

We processed these datasets using the *Chandra* calibration software CALDB 2.29 and CIAO 3.1, released in July 2004<sup>1</sup>. Neither observation experienced flares. We used Chandra deep background observations for our background spectra.<sup>2</sup> Source and background spectra were extracted using identical concentric annuli containing a minimum of 20,000 counts per source spectrum. Bright point sources were excluded from the event files before spectral extraction. The spectra were binned to a minimum of 25 counts per energy bin.

Using XSPEC v11.3.1, we fit the projected and deprojected spectra from 0.7-7.0 keV

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<sup>1</sup>Chandra Interactive Analysis of Observations (CIAO), <http://cxc.harvard.edu/ciao/>

<sup>2</sup>M. Markevitch, author of [http://asc.harvard.edu/cal/Acis/Cal\\_prods/bkgrnd/acisbg/](http://asc.harvard.edu/cal/Acis/Cal_prods/bkgrnd/acisbg/) COOKBOOK

Table 1. Chandra Observations

Cluster	Observation Date	Exposure Time (s)	ACIS-S Count Rate (ct s <sup>-1</sup> )
Abell 1650	Aug 3-4, 2003	27,260	4.36
Abell 2244	Oct 10-11, 2003	56,965	4.35

to MekaL models (Mewe et al. 1995) with Galactic absorption attenuating the soft X-rays (Morrison & McCammon 1983). Since the best-fit absorption overlapped the Galactic values of  $N_{\text{H}} = 1.56$  and  $2.3 \times 10^{20}$  for A1650 and A2244 respectively (Dickey & Lockman 1990), we fixed  $N_{\text{H}}$  at those values for this analysis. The positions of the Fe-K lines were consistent with the cluster redshifts from galaxy velocities in Struble & Rood (1999). We computed 90% uncertainties ( $\Delta\chi^2 = 2.71$ ) for the temperature, normalization, and metallicity at each annulus. We constrained the metallicity to be constant across 2-3 annuli. The reduced  $\chi^2$  values for the fits were typically 1.10-1.15. More details about our data analysis strategy and further analyses are described in Donahue et al. (2005), where we also analyze Chandra archival observations of nine other cooling-flow clusters that have central radio sources and emission-line nebulae.

Neither cluster exhibits a strong temperature gradient across the core. Abell 2244 is nearly isothermal with  $kT = 5.5 \pm 0.5$  keV at every radius  $< 4'$ , and Abell 1650 varies from  $5.5 \pm 0.5$  keV in the core to  $7.0 \pm 1.0$  keV at  $4'$ , statistically consistent with but somewhat higher than the temperature profile over similar radii obtained with XMM measurements. (Takahashi & Yamashita (2004) adopted a lower redshift ( $z = 0.0801$ ) to fit the XMM data, which may indicate a calibration uncertainty.) These small inner temperature gradients contrast with those of most other cooling flow clusters, which tend to be more pronounced. Both cluster cores contain a significant metallicity gradient, ranging from 0.6-0.8 solar in the center to a more typical 0.2-0.3 solar outside the core, consistent with Takahashi & Yamashita (2004). This metallicity pattern is typical of the other cooling flow clusters we studied.

### 3. Data Analysis

The goal of our data analysis was to determine whether or not clusters without obvious signatures of feedback were systematically different from those with radio sources that do show signatures of feedback. Our primary results are that these two clusters do not show any evidence for ghost cavities and have higher central entropy levels than clusters showing evidence for feedback.

In order to search for cavities in the intracluster medium, we adaptively smoothed the X-ray data to a minimum significance of 5-sigma with both a Gaussian and a top-hat kernel. We found no “ghost bubbles.” On scales larger than about 50 kpc from the center, both clusters exhibited regular, nearly round intensity contours. We also did not see evidence for filaments, such as that found tracing the  $\text{H}\alpha$  emission in Abell 1795 (Fabian et al. 2001) or M 87 (Sparks et al. 2004).

We determined the entropy profiles of these clusters by computing the adiabatic constant  $K = kTn_e^{-2/3}$  at each radius to quantify the specific entropy. The temperature ( $kT$ ) profiles were measured as described in §2. The electron density profiles ( $n_e$ ) were derived by deprojecting the 0.5-2.0 keV surface brightness profiles within annuli having 5'' widths using the technique of Kriss et al. (1983). The uncertainties of the deprojected count rate profiles were estimated by bootstrapping 1000 monte-carlo simulations of the original surface brightness profiles. A spatially-dependent conversion of 0.5-2.0 KeV count rates to electron densities was obtained from the X-ray spectroscopy. For this paper, we assumed that the temperature and the count-rate conversion factor in the central bin were constants.

Figure 1 shows that the entropy profiles of Abell 1650 and Abell 2244 are systematically different from the nine cooling-flow clusters in the sample of active clusters from Donahue et al. (2005). The two radio-quiet clusters have flatter entropy profiles with larger values of central entropy. To quantify this difference, we fit both a simple power law of  $K = K_{100}(r/100 \text{ kpc})^\alpha$  and the same power law plus a central entropy  $K = K_0 + K_{100}(r/100 \text{ kpc})^\alpha$  to the entropy profiles, as was done for the active clusters in Donahue et al. (2005). Table 2 gives the best fits. We find that  $\alpha \approx 0.6 - 0.8$  and  $K_0 \approx 30 - 50 \text{ keV cm}^2$  in the radio-quiet clusters, in contrast to  $\alpha \sim 1$  and  $K_0 \approx 10 \text{ keV cm}^2$  for the active clusters. Figure 2 shows central entropy values plotted as a function of 20 cm radio power, from the NVSS (Condon et al. 1998). Abell 2244 has a weak, off-center radio source that may not be associated with the cluster, plotted as an upper limit.

#### 4. Discussion

The significance of elevated central entropy in Abell 1650 and Abell 2244 is that a larger central entropy implies a longer central cooling time compared to clusters in Donahue et al. (2005) of similar temperature. Assuming pure free-free cooling, the cooling time for gas of temperature  $T$  and entropy  $K$  is

$$t_c \approx 10^8 \text{ yr} \left( \frac{K}{10 \text{ keV cm}^2} \right)^{3/2} \left( \frac{kT}{5 \text{ keV}} \right)^{-1}. \quad (1)$$

Thus, these two clusters, which show no evidence for feedback, have a central cooling time  $\sim 1$  Gyr, while those that do show evidence for feedback have a central cooling time  $\sim 0.1$  Gyr. According to the definition of Peres et al. (1998), Abell 1650 and Abell 2244 were properly classified as cooling-flow clusters because  $t_c < 5$  Gyr. However, one does not expect to see significant cooling and condensation of gas in these clusters for at least another  $\sim 5 \times 10^8$  yr. In other words, evidence for feedback is seen in those clusters that can trigger it on a  $\sim 10^8$  yr

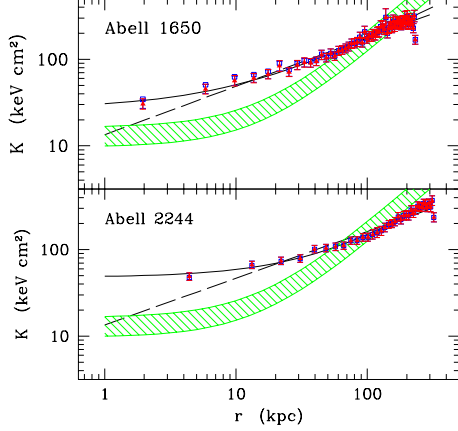


Fig. 1.— Entropy profiles for Abell 1650 and Abell 2244. All gas at  $\sim 5$  keV with entropy  $\lesssim 170$  keV cm<sup>2</sup> has  $t_c < H_0^{-1}$ . The hatched region shows the locus of entropy profiles for active clusters from the sample of Donahue et al. (2005).

Table 2. Entropy Profile Fit Results

Cluster	$K_0$ KeV cm <sup>2</sup>	$K_{100}$ KeV cm <sup>2</sup>	$\alpha$	Total $\chi^2$	N (d.o.f.)
Abell 1650	$27 \pm 5$	$150 \pm 7$	$0.80 \pm 0.07$	12	47
	$= 0.00$	177	$0.56 \pm 0.02$	28	48
Abell 2244	$48 \pm 5$	$102 \pm 8$	$0.97 \pm 0.08$	7	31
	$= 0.00$	$162 \pm 3$	$0.54 \pm 0.02$	42	32
Active Sample	$8 \pm 4$	$150 \pm 50$	$1.2 \pm 0.2$		
	$= 0.00^*$	$144 \pm 24$	$0.96 \pm 0.15$		

\*The fits set to 0.00 entropy in the cores for the sample in Donahue et al. (2005B) were quite poor, except for the case of Abell 2029.

timescale and not in clusters in which gas is not currently expected to be condensing. Here we discuss the implications of this finding.

The most straightforward interpretation of the cooling-time dichotomy between active and radio-quiet clusters is that radiative cooling in cluster cores triggers AGN feedback when the central gas begins to condense. Donahue et al. (2005) find that all nine of their active clusters have very similar core entropy profiles, suggesting that this set of clusters has settled into a quasi-steady configuration that is episodically heated by AGN outbursts on a  $\sim 10^8$  year timescale. Voit & Donahue (2005) show that outflows of  $\sim 10^{45} \text{ erg s}^{-1}$  naturally maintain the observed characteristics of the entropy profiles in these clusters.

If that is the correct interpretation, then it is possible that Abell 1650 and Abell 2244 have unusually long cooling times because they each experienced unusually strong AGN outbursts  $\gtrsim 1$  Gyr in the past. Raising the central entropy to the observed  $\sim 30 - 50 \text{ keV cm}^2$  levels would require an AGN outflow  $\sim 10^{46} \text{ erg s}^{-1}$  (Voit & Donahue 2005). Such outbursts are rare but not unprecedented. McNamara et al. (2005) have recently observed an outburst of this magnitude in MS0735+7421, which now has a central entropy  $\sim 30 \text{ keV cm}^2$ . The long cooling time following such an outburst would account for why we do not see any sign of X-ray cavities in these two clusters.

It is also possible that the central gas in Abell 1650 and Abell 2244 has never cooled to the point at which it can trigger a strong AGN outburst. That could happen, for example, if frequent merger shocks have been able to support the core entropy at the  $\sim 50 \text{ keV cm}^2$  level for several Gyr, or if electron thermal conduction can resupply the thermal energy radiated by the central gas. One can evaluate the efficacy of thermal conduction by comparing the size of a radiatively cooling system to the Field length

$$\lambda_F = \left( \frac{\kappa T}{n_e^2 \Lambda} \right)^{1/2} \approx 4 \text{ kpc} \left( \frac{K}{10 \text{ keV cm}^2} \right)^{3/2} f_c^{1/2}, \quad (2)$$

where  $\Lambda$  is the usual cooling function and  $\kappa = 6 \times 10^{-7} f_c T^{5/2} \text{ erg s}^{-1} \text{ cm}^{-1} \text{ K}^{-7/2}$  is the Spitzer conduction coefficient with suppression factor  $f_c$ . The approximation assumes free-free cooling ( $\Lambda \propto T^{1/2}$ ), which conveniently makes  $\lambda_F$  a function of entropy alone. At radii  $\sim 100 \text{ kpc}$ , we find that  $\lambda_F \sim r$  in all the cooling-flow systems we have studied, implying that conduction can plausibly balance cooling there, as long as  $f_c \sim 1$ . At radii  $\sim 10 \text{ kpc}$  in systems with signs of feedback, we find  $\lambda_F < r$  even for  $f_c = 1$ , implying that conduction cannot balance cooling at small radii, in agreement with the findings of Voigt & Fabian (2004). At those same small radii in the two systems without signs of feedback, we find  $\lambda_F \approx r$  for  $f_c \approx 1$ , suggesting that these systems are potentially stabilized by thermal conduction, which would account for their modest temperature gradients.



One speculation that emerges from this brief analysis of thermal conduction is that there is a critical entropy profile  $K(r) \approx 10 \text{ keV cm}^2 f_c^{-1/3} (r/4 \text{ kpc})^{2/3}$  dividing conductively stabilized systems from those that require feedback. Clusters with central entropy profiles below this line will continue to cool until some other heat source intervenes, while conduction stabilizes those clusters above the line. One would then expect the cluster population to bifurcate into systems with strong central temperature gradients and feedback and those without either. Furthermore, a very powerful AGN outburst could induce a transition from a feedback-stabilized state to a conductively-stabilized state by raising the central entropy level to  $\gtrsim 30 \text{ keV cm}^2$ .

Another potential heat source that has been suggested as a solution to the cooling-flow problem is annihilation of dark matter particles such as neutralinos (Qin & Wu 2001; Totani 2004). In the model of Totani (2004), the annihilation rate peaks in the center because of a spike in the density profile owing to the central black hole. The steady heating rate in this model is not linked as directly to baryon cooling as the AGN feedback model suggested here, but it is an interesting alternative mechanism that could be explored further.

## 5. Conclusions

In order to test whether AGN heating compensates for radiative cooling in the cores of clusters of galaxies, we have used *Chandra* to observe a small sample consisting of two clusters with central cooling times  $< H_0^{-1}$ , yet no evidence for prominent AGN activity: Abell 1650 and Abell 2244. The X-ray properties of the cores of these clusters indeed appear systematically different from cores with more prominent radio emission. While the central cooling times are shorter than a Hubble time and they have strong metallicity gradients, they do not have significant central temperature gradients, and their central entropy levels are markedly higher than in clusters with stronger radio emission, corresponding to central cooling times of a billion years. Also, there is no evidence in the X-ray surface brightness maps for fossil X-ray cavities produced by a relatively recent episode of AGN heating. In contrast to the central cores of the clusters with stronger radio emission, these cores may be stabilized by conduction if it is operating at close the Spitzer rate. We suggest that a tremendous AGN outburst, such as that shocking the ICM in MS0735+74 (McNamara et al. 2005) may have elevated the central entropy of these clusters some  $10^9$  years ago. Whether or not conduction is operative in stabilizing these clusters cannot be determined, but it is energetically feasible. Further theoretical development and a larger study is required to test whether the timescales are consistent with entropy profiles of a larger population. The fact that these clusters with no evident feedback have higher central entropy than clusters with

obvious feedback suggests that rare but influential AGN outbursts can dramatically change the original distribution of entropy in clusters of galaxies. Alternatively, the intracluster gas of these clusters may have started out with higher initial entropy than the ICM in the active clusters, and it has not cooled to the point of sparking strong AGN feedback.

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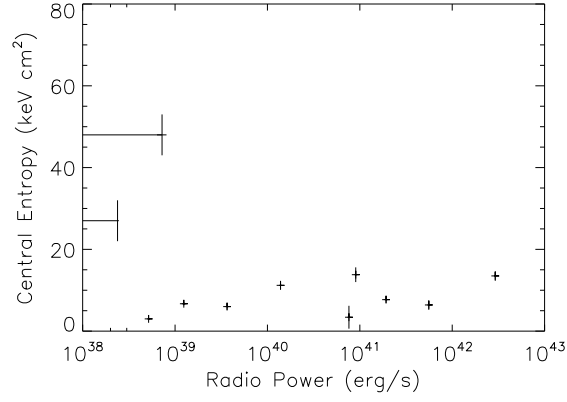


Fig. 2.— Radio power  $\nu L_\nu$  from 20 cm observations (Condon et al. 1998) (See also Ledlow & Owen (1995) and Sarazin et al. (1995), and 6 cm upper limits for A2244 and A1650 from Burns (1990).)