THE HEATED CORE OF THE RADIO-QUIET GALAXY CLUSTER A644

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ABSTRACT

We present an analysis of a Chandra ACIS-I observation of the massive galaxy cluster A644. This cluster was previously classified as a cooling flow, but no radio emission has been detected from its cD galaxy. Outside the core ($R \sim 75$ kpc $\sim 0.03r_{\text{vir}}$) the hot ICM has properties consistent with a (relaxed) cool-core cluster out to the largest radii investigated ($R \sim 415$ kpc $\sim 0.14r_{\text{vir}}$). Over this region the gravitating mass profile is described well by a Navarro-Frenk-White profile with concentration parameter, $c = 6.1 \pm 1.2$, and virial radius, $r_{\text{vir}} = 2.9 \pm 0.4$ Mpc. However, inside the core the temperature and entropy profiles reverse their inward radial decline and rise at the center; the inner temperature profile is inconsistent with a constant at the 2.3$\sigma$ level. Although the core region does not display X-ray cavities or filamentary structures characteristic of radio-loud, cool-core clusters, the peak of the X-ray emission is offset from that of the centroid of the global X-ray halo by $\approx 60$ kpc. The position of the cD galaxy lies approximately between the X-ray peak and centroid, further testifying to a merger origin for the properties of the X-ray emission in the core. We discuss the implications of A644 and the small number of radio-quiet, cool-core clusters for the AGN feedback paradigm to suppress cooling flows in clusters.

Subject headings: X-rays: galaxies: clusters – galaxies: halos – galaxies: formation – cooling flows – galaxies: clusters: individual: A644

1. INTRODUCTION

XMM and Chandra grating and CCD observations of the cores of clusters previously believed to be harboring cooling flows find very little gas cooling below $T \sim 1$ keV (e.g., Peterson et al. 2001, 2003; Tamura et al. 2001; David et al. 2001; Molendi & Pizzolato 2001; Xu et al. 2002; Ettori et al. 2002; Buote et al. 2003a). This major discovery has led to the widely discussed picture where feedback on the hot intracluster medium (ICM) from an AGN in the central cluster galaxy is responsible for stifling the cooling flow, though the details of the heating process remain elusive (e.g., for reviews see Mathews & Brinkmann 2002; Fabian 2004). About 70% of clusters previously classified as cooling flows possess no radio emission from the central galaxy (e.g., Burns 1994). Chandra observations indicate that such clusters also have X-ray cavities and filamentary structures in the X-ray images that are related to the radio emission (e.g., Fabian et al. 2004; McNamara et al. 2004; Blanton et al. 2001; Mazzotta et al. 2003; Birzan et al. 2004).

What about clusters indicated to be cooling flows from previous low-resolution X-ray observations that do not display radio properties typical of cooling flows? We have previously analyzed Chandra observations of two such systems: A2029 (Lewis et al. 2002, 2003; and A2589 (Buote & Lewis 2004). A2589 has no observed radio emission associated with its cD galaxy; and, although the cD in A2029 does possess a Wide-Angle-Tail (WAT) radio source, such sources are generally not found in cooling flows (Owen et al. 1984; Burns 1994), though their morphology provides evidence for relative motions between the radio source and ICM (Eilek et al. 1984; Burns et al. 2002). Both of these clusters have high density cores with temperatures significantly lower than at larger radii. (Although the relatively low-quality Chandra data of A2589 are consistent with an isothermal gas, a new XMM observation clearly indicates that the temperature profile increases with radius – Zappacosta et al. 2005, in preparation.) These clusters also display no spectroscopic evidence for cooling flows and have unusually symmetric X-ray images without the pronounced surface brightness irregularities observed in the cores of “radio loud” cool-core clusters (e.g., Birzan et al. 2004). Finally, cool-core clusters also appear to preferentially display central metallicity enhancements, while flat metallicity profiles are characteristic of non-cooling flow, generally disturbed, systems (e.g., De Grandi et al. 2004; Böhringer et al. 2004). A2589 and A2029 both have pronounced central metallicity enhancements further attesting to their comparatively relaxed states.

Observations suggest that cooling flows are destroyed by large turbulent motions in the ICM since major merging activity in clusters anti-correlates with cooling mass-flow rate (Buote & Tson 1996), a conclusion supported by theoretical studies (e.g., Roettiger et al. 1996; Norman & Bryan 1999; Fujita et al. 2004). Likewise, theoretical studies (e.g., Loken et al. 1993; Roettiger et al. 1996) suggest that WAT radio morphology may also be a signature of hot shocks in on-going cluster mergers. Since the X-ray images of A2029 and A2589 are very regular all the way into their cores (though see Buote et al. 2003; and yet there is no evidence for ICM cooling or radio emission typical of cool-core clusters, in the context of the AGN feedback paradigm we are viewing these clusters at a special time after they have settled down from past mergers but very soon before the onset of AGN heating.

Here we examine a Chandra observation of A644, an-
other “radio quiet” cluster that was previously classified as a cooling flow based on analysis of both X-ray imaging and spectral data [Ed ee et al. 1992, Peres et al. 1993]. A644 is the only cooling flow cluster with large inferred $\dot{M}$ (> $100 \, M_\odot \, yr^{-1}$), which was not detected in the radio study of Burns et al. 1990. We wish to examine how its X-ray properties compare to the other cooling flow clusters with atypical radio properties and, in particular, whether it demonstrates a clearer connection between past merger activity and the suppression of a cooling flow. The redshift of A644 ($z = 0.0704$) corresponds to an angular diameter distance of 277 Mpc and $1'' = 1.34$ kpc assuming $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

The paper is organized as follows. In §2 we present the observation and discuss the data reduction. The analysis of the image and spectral data of the ACIS-I are presented in §3 and §4 respectively. We calculate the gravitating matter distribution in §6. Finally, in §8 we present our conclusions.

2. OBSERVATIONS AND DATA ANALYSIS

A644 was observed with the ACIS-I CCD array for approximately 30 ks during AO-2 as part of the Chandra Guest Observer program. We reduced the data using the CIAO v3.1 (with CALDB v2.28) and HEASOFT v5.3.1 software packages. We followed the standard CIAO threads$^3$ and reprocessed the level-1 events data to make use of the latest calibration information, including correcting for charge-transfer inefficiency and a time-dependent gain shift. From regions of least source contamination of the CCDs we extracted a light-curve (5.0-10.0 keV) to identify periods of high background. The observation was remarkably quiescent, and after removing a small period of modestly increased background rate, the total exposure used for subsequent analysis was 28.9 ks.

Because the cluster emission fills the entire ACIS-I field, we adopted for our default analysis the standard background events files provided in the CALDB collected from suitable blank fields. For comparison to results obtained using these standard background templates, we also modeled the background directly. Using regions as far away from the cluster center as possible, we extracted a spectrum (with point sources masked out) and fitted it with a combined source and background model (e.g., Buote et al. 2001). For the source, we adopted a thin thermal plasma component (apec) with $T = 6$ keV and half-solar metallicity. The background was modeled with components for the Cosmic X-ray Background (CXB) and instrumental background: two soft apec thermal plasmas and a hard power law for the CXB; a broken power law and two gaussians for the instrumental background. Comparison of results using the alternative background is presented in §4.

3. IMAGING ANALYSIS

In Figure 1 we display the ACIS-I image of A644 in the 0.3-7.0 keV band. The image was corrected for exposure variations using an exposure map created for a monochromatic energy 1 keV, approximately the counts-weighted average energy of the spectrum. For presentation purposes only, the image was also adaptively smoothed using the CIAO task csmooth with default parameter settings. The diffuse emission is seen to fill the entire ACIS-I field. The morphology of most of the cluster is quite regular and approximately elliptical in shape.

Visual inspection of the central $R \sim 30''$ region of the (smoothed) X-ray surface brightness reveals some irregular, non-azimuthally symmetric features (Figure 1). These deviations from a symmetric configuration, though statistically significant, do not represent large fluctuations (< 10%) in the mean surface brightness level. In particular, the data do not provide clear evidence for distinct subclumps in the core region.

We also searched for azimuthal fluctuations in the core by constructing a hardness ratio map (and also through spectral fitting in sectors, see §4). We did not find any corresponding azimuthal fluctuations either in the core or on larger scales. Instead, we found the spectrally softer core gives way at larger radius to a spectrally harder surrounding medium. This radial variation is consistent with the radially increasing temperature profile (see §4).

We measure the centroid and the ellipticity of the X-ray surface brightness using the moment method described by Carter & Metcalfe (1980) and implemented in our previous X-ray studies of galaxies and clusters (e.g., Buote & Canizares 1994). This iterative method is equivalent to computing the (two-dimensional) principal moments of inertia within an elliptical region. The ellipticity is defined by the square root of the ratio of the principal moments, and the position angle is defined by the orientation of the larger principal moment. Following our previous study of the ellipticity of the Chandra data of NGC 720 (Buote et al. 2002), we removed point sources and replaced them with smoothly distributed diffuse emission using the CIAO task dmfilth.

The centroid of the X-ray surface brightness shifts significantly (e.g., $\Delta R = 56 \pm 6$ kpc between 15-500 kpc), mostly directed toward the South. At the smallest radii the centroid is located within the region of image irregularities in the core mentioned above. Outside of the core region the X-ray isophotes are very regular and moderately elliptical. The ellipticity gently falls from 0.30$\pm$0.02 at $a = 100$ kpc to 0.24$\pm$0.004 at $a = 500$ kpc, where $a$ is the semi-major axis of the elliptical aperture within which the moments are calculated. Over this radius range the position angle (measured N through E) of the elliptical apertures is quite steady, varying between a maximum of 11$ \pm$ 2 degrees (at $a = 100$ kpc) and a minimum of 6$ \pm$ 0.5 degrees (at $a = 300$ kpc). Overall, the image properties suggest a relaxed cluster outside about $R \approx 100$ kpc but a disturbed cluster within $R \approx 50$ kpc.

We examined the radial surface brightness profile (with point sources masked out) located about the X-ray peak and also about the centroid computed within $a = 500$ kpc. In both cases the surface brightness profile is fitted fairly well out to $R = 600$ kpc by a $\beta$ model: $r_c = 79 \pm 2$ kpc, $\beta = 0.50 \pm 0.01$, $\chi^2 = 200.4$, 129 dof (peak) and $r_c = 118 \pm 3$ kpc, $\beta = 0.59 \pm 0.01$, $\chi^2 = 198.6$, 128 dof (centroid). The largest fit residuals ($\sim 20\%$) lie within the innermost region ($r \lesssim 10''$) and are modest ($< 5\%$) elsewhere. We note that the parameters $r_c$ and $\beta$ increase systematically when we include data from increasingly larger radii or exclude data from the

http://asc.harvard.edu/ciao/threads
very central region. Both of these issues likely account for the different values obtained from previous ROSAT studies which included data at larger radii; e.g., using the PSPC Ettori & Fabian (1999) obtain

\[ r_c = 157 \text{ kpc} \] and \[ \beta = 0.69. \]

4. SPECTRAL ANALYSIS

We focus our attention on the spectral properties of the hot gas obtained within a series of concentric circular annuli centered either on the X-ray centroid or peak. Below we also briefly discuss attempts to constrain azimuthal variations in the spectral properties. The widths of the circular annuli were chosen so that the temperatures were determined to similar precision in each radial bin. For the centroid case we list the annuli in Table 1. Annuli 1-4 contain \( 10^4 \) background-subtracted counts while bins 5-9 contain twice that amount in the 1.5-7 keV band. We restrict our analysis to energies above 1.5 keV because of uncertainties arising from excess absorption above the Galactic value discussed below, and because the gas temperature lies well above 1.5 keV within all annuli. For each annulus counts-weighted response matrices were generated using the CIAO tasks MKWRMF and MKARF.

We fitted the background-subtracted spectrum with an APEC thermal plasma modified by Galactic absorption \( (6.4 \times 10^{20} \text{ cm}^{-2}, \text{Dickey & Lockman 1990}) \) to each annulus. The free parameters are temperature, iron abundance, and normalization (emission measure). (The fitted abundance is technically a metallicity since we fit the iron abundance as a free parameter and the abundances of all the other elements tied to iron in their solar ratios. However, iron dominates the metallicity.) The spectral fitting was performed with XSPEC (11.3.1i, Arnaud 1996) using the \( \chi^2 \) minimization method. Hence, we rebinned all spectral channels to have a minimum of 20 counts per energy bin (necessary for the validity of the \( \chi^2 \) method) and a signal-to-noise ratio of at least 3. The solar abundances in XSPEC are taken to be those given by Grevesse & Sauval (1998) which use the correct “new” photospheric value for iron which agrees also with the value obtained from solar-system meteorites (e.g., McWilliam 1997). To estimate the statistical errors on the fitted parameters we simulated spectra for each annulus using the best-fitting models and fit the simulated spectra in exactly the same manner as done for the actual data. From 100 Monte Carlo simulations we compute the standard deviation for each free parameter which we quote as the “1σ” error. (We note that these 1σ error estimates generally agree very well with those obtained using the standard \( \Delta \chi^2 \) approach in XSPEC.) All quoted errors are 1σ unless stated otherwise.

The radial profiles of temperature and iron abundance are shown in Figure 2. Table 1 gives the parameters obtained from the spectral fits for the centroid case: Figure 3 shows the ACIS-I spectra of two representative annuli and the associated best-fitting one-temperature model. The simple one-temperature model provides a good description of the spectral data in all annuli. For \( R \gtrsim 75 \text{ kpc} \) the spectral fits for both the centroid and peak case agree very well. Over this region the temperature is consistent with a constant value \( \sim 8 \text{ keV} \) as found also by previous studies of A644 with ASCA (e.g., White 2000; Bauer & Sarazin 2000). In contrast to these previous ASCA studies, the Chandra data clearly reveal that the iron abundance declines with radius from a value of \( \sim 0.8Z_\odot \) at \( R \sim 75 \text{ kpc} \) to \( \sim 0.25Z_\odot \) at \( R \sim 400 \text{ kpc} \). Previous ASCA studies of A644 were consistent with a constant iron abundance profile (e.g., White 2000; Bauer & Sarazin 2000) within the large errors. We note also that the average iron abundance from ASCA (\( \sim 0.5Z_\odot \), scaled to our solar reference) obtained...
minimum value of $T = 6.5$ keV reached near $R = 50$ kpc. A power law fit to the temperature profile of the inner three radial bins is inconsistent with a constant value at the 2.3$\sigma$ level and is highly inconsistent with the declining temperature central profiles characteristic of cool core clusters.

Despite the good quality of the fits, we examined whether they could be improved further. Allowing abundances other than iron to vary separately did not yield noticeable improvement. Adding another temperature component also had no effect on the fits, even when energies down to 0.5 keV were included. Consequently, we found no need for an additional multiphase cooling flow component in the spectra. Previous ASCA studies were divided between indicating a massive cooling flow ($\gtrsim 60M_{\odot}$ yr$^{-1}$, Bauer & Sarazin 2000) and no cooling flow ($\lesssim 40M_{\odot}$ yr$^{-1}$, White 2000).

Using a standard model of a gas cooling at constant pressure as implemented in our previous studies (e.g., Buote et al. 2003a), our Chandra results indicate a best-fitting cooling rate of zero with 90% upper limits of...
The image contains a page from a document discussing the analysis of X-ray spectral data from clusters. The text is discussing the use of the "onion-peeling" method to deproject spectra, the importance of deprojecting to avoid systematic errors, and the use of APEC plasma models modified by Galactic absorption. The text also mentions the use of different energy bands and the analysis of column densities and temperature profiles.

For example, the text states:

"...and iron abundances obtained using our implementation of the "onion-peeling" method are very consistent with those obtained using the deprojection scheme provided in XSPEC using the PROJECT routine and require the same restrictions on the temperatures and iron abundances noted above."

The text also includes a figure showing ACIS-I spectra accumulated within specific annuli and the results of fitting these spectra with APEC plasma models.

The page includes mathematical equations and figures illustrating the spectral analysis techniques used in the study.
1.5 keV to avoid sensitivity to the precise value.

Background: As described in [2] for comparison to results obtained using the standard blank background fields we also constructed a model background by fitting the total (source plus background) spectrum of regions of the ACIS-I as far away from the center of A644 as possible. We found that results obtained using this modeled background agreed extremely well with those of the standard blank fields. As expected, by far the largest differences were observed in annulus 9; e.g., $T = 8.6 \pm 0.6$ keV using the modeled background compared to $T = 8.1 \pm 0.5$ keV for the standard blank fields.

Plasma Code: We investigated the sensitivity of our results to the plasma code using the MEKAL model. The quality of the fits and the temperature values were found to be very consistent within the 1σ errors. The iron abundance values also were consistent with those obtained using the APEC code, though the values obtained with the MEKAL code were generally smaller by 10%-20%. These results are consistent with previous studies ([3],[4]; [Humphrey et al. 2004]).

Calibration: We explored the sensitivity of our results to the version of the Chandra calibration using previous versions of CIAO (v3.0.2) and the CALDB (v2.26). We found the results on the fitted spectral parameters to be consistent with those quoted above within the estimated $\approx 1\sigma$ statistical errors.

5. GRAVITATING MASS AND GAS FRACTION

To determine the gravitating mass distribution from X-ray observations requires the hot gas to be in hydrostatic equilibrium. Both N-Body simulations and gravitational lensing studies confirm the reliability of X-ray mass measurements, particularly for clusters with regular X-ray image morphologies (e.g., for a review see [3]). The assumption of hydrostatic equilibrium should be valid outside the central $\sim 75$ kpc region of A644. Outside the core region the derived radial variations in the density and temperature of the hot gas agree for both the cases where the cluster center is defined as the surface brightness peak or centroid. Consequently, we exclude the central three annuli (defined in Table 1) from our default analysis, though for comparison we summarize results obtained using all annuli.

The approach we use to calculate the gravitating mass distribution follows closely our previous studies ([3],[5]; [Buote & Lewis 2003]). As is standard we assume spherical symmetry to provide a spherically averaged mass profile appropriate for comparison to other observations and to the spherically averaged mass profiles obtained from cosmological simulations. In the equation of hydrostatic equilibrium we evaluate the derivatives of the three-dimensional gas density ($\rho_g$) and temperature ($T$) using simple parameterized models as discussed below.

For our default analysis we projected parameterized models of the three-dimensional quantities, $\rho_g$ and $T$, and fitted these projected models to the results obtained from our analysis of the data projected on the sky (Table 1). In this manner we obtained good constraints on the three-dimensional radial profiles of $\rho_g$ and $T$. Although our analysis closely follows our previous studies, we note two minor improvements. First, when fitting models to the radial profiles of the gas density and temperature to the data binned in annuli on the sky (as given in Table 1) we integrated the models over each radial bin (rather than only evaluating at a single point within the bin) to provide a consistent comparison. Second, when projecting models of the gas density and temperature along the line of sight we also included the radial variation in the plasma emissivity ($\lambda(T, Z_{Fe})$).

In Figure 3 we show the radial profile of the emission-weighted projection of $\rho_g^2$; i.e., the “norm” parameter (see caption to Table 1) of the APEC model divided by the area of the annulus. A single $\beta$ model provides a good description of the data with fit residuals $\leq 5\%$ (Table 2). Because the inner three annuli were excluded, a marginally larger value of $\beta$ was obtained compared to the surface brightness fits ([3]). Adding a second $\beta$-model component provides small improvement in the fits with smaller residuals ($\leq 3\%$) than the $1\beta$ model (Table 2); the $2\beta$ model is displayed in Figure 4. Although the parameters for the $2\beta$ model are not as well constrained as those for the $1\beta$ model we adopt the $2\beta$ model for our analysis of the mass distribution because it describes the data a little better. Note that if the inner three annuli are included then the parameters obtained are consistent with those in Table 2 but are somewhat better constrained. For the case where the annuli are oriented about the emission peak the second component of a $2\beta$ model (fitted to all annuli) matches very well the $1\beta$-model results obtained for the centroided case listed in Table 2 demonstrating the similarity of the gas density profiles obtained outside the core region for the peak and centroid case.

The radial profile of the emission-weighted projection of $T$ is shown in Figure 4 (middle panel) along with the best-fitting power-law fit. The simple power law is an excellent fit (Table 2) and demonstrates that the temperature profile is consistent with isothermal within the estimated 1σ errors. Notice that despite the inner three annuli being excluded from the fits the model describes those data points well.

We constructed the mass profile using the models just described for the gas density and temperature. Following previous studies (e.g., [4]), for each annulus listed in Table 2 we assign a single (three-dimensional) radius value, $r \equiv [(R_{in}^3 + R_{out}^3)/2]^{1/3}$, where $R_{in}$ and $R_{out}$ are respectively the inner and outer radii of the (two-dimensional) annulus. The radial mass profile is plotted in Figure 4 using the $2\beta$-model for $\rho_g$ and the power law model for $T$. (We emphasize that although the mass values for the inner three data points are shown, being derived from the gas density and temperature models, they are not included in the fits.)

The NFW model is a good smooth fit when excluding the inner three radial bins (Figure 3). We obtain $\chi^2 = 6.9$ for 4 dof with fit residuals $\leq 15\%$. Because the mass data points are correlated it is necessary to recalculate the $\chi^2$ statistic to examine goodness of fit using our Monte Carlo simulations ([3]); i.e., for each set of parameters for the gas density and temperature profiles obtained from each simulation, a mass profile is constructed and then fitted with an NFW model. These simulations indicate the the $\chi^2$ value quoted above is within one standard deviation of the expected value.

In Table 3 we give the parameters of the NFW fit and
Fig. 4.— Models fitted to radial profiles (centroid case) as discussed in §5. In each case the inner three data points are excluded from the fits. (Left) Chandra radial profile of the projected gas density squared ($\int \rho g^2 \Lambda(T, Z_{Fe}) dl / \Lambda_{ann}$) obtained by dividing the norm parameter of the apec model (Table 1) by the area of the annulus; $\Lambda_{ann}$ is the plasma emissivity evaluated using $T$ and $Z_{Fe}$ of the annulus. The diamonds represent the binned data and the solid line the best-fitting double-beta model. The fit residuals are plotted in the lower panel. (Center) Temperature profile of the binned data (diamonds) and best-fitting power-law model. (Right) Mass profile (circles and error bars) and best-fitting NFW model.

**TABLE 2**

DEPROJECTED RADIAL PROFILES OF GAS DENSITY AND TEMPERATURE

| Model  | $(\chi^2$/dof) | $r_c$ (kpc) | $\beta$ | $\rho_0$ (10^{-26} g cm^{-3})$ | $r_{c,2}$ (kpc) | $\beta_2$ | $\rho_{2,0}$ (10^{-26} g cm^{-3}) |
|--------|----------------|-------------|---------|-----------------|---------------|---------|-----------------|
| $1\beta$ | 12.1/3        | 120 ± 8    | 0.64 ± 0.02 | 2.27 ± 0.12  |               |         |                  |
| $2\beta$ | 4.3/0         | 213 ± 33   | 2.0 ± 0.3  | 2.19 ± 0.24  | 352 ± 115    | 1.1 ± 0.3 | 0.82 ± 0.17  |

**Temperature**

| Model  | $(\chi^2$/dof) | $T_{100}$ (keV) | $p$ |
|--------|----------------|-----------------|-----|
| power law | 2.7/4         | 7.9 ± 0.4     | 0.04 ± 0.05 |

**Note.** — These models were (emission-weighted) projected along the line of sight and fitted to the data about the centroid excluding the inner three annuli. $T_{100}$ is the temperature evaluated at $r = 100$ kpc and $p$ is the exponent. Note that the best-fitting value of $\beta$ for the $2\beta$ model was not well constrained and pegged at the upper limit we allowed in the fits.

the estimated statistical and systematic errors. The estimates for the systematic errors are mostly based on our discussion in §4 and we have also included the differences obtained when using a 1$\beta$ model to parameterize the $\rho_b$ profile. (Note we do not provide an estimated error arising from the deprojection method because the statistical errors are considerably larger when using the onion-peeling method.) The derived concentration parameter ($\approx 6$) and virial radius ($\approx 2.9$ Mpc) imply a virial mass of $\approx 1.5 \times 10^{15} M_{\odot}$ appropriate for a massive galaxy cluster. The value of $c$ is consistent with that expected from CDM (e.g., Thomas et al. 2001; Tasitsiomi et al. 2004).

We mention that within the central region (i.e., the central three annuli), where the assumption of hydrostatic equilibrium is suspect, the mass density profile is flatter than NFW; i.e., the cumulative mass profile at small radii lies below NFW as seen in Figure 4. However, for the case where the annuli are centered about the emission peak we find the mass profile within the central $\approx 70$ kpc is highly uncertain but consistent with NFW. (To obtain a reasonable smooth fit to the centrally peaked temperature profile in this case, we modeled the profile with two power laws with exponential cut-offs at both ends.) The smaller mass values in the core for the centroid case are attributed to the flatter density and temperature profiles obtained with respect to the peak case; i.e., when the annuli are not positioned about the emission peak radial differences in spectral quantities are smeared out.

6. CONCLUSIONS

Outside the core ($R \sim 75$ kpc $\sim 0.03 r_{vir}$) the hot ICM has properties consistent with a (relaxed) cool-core cluster out to the largest radii investigated ($R \sim 415$ kpc $\sim 0.14 r_{vir}$). The X-ray surface brightness is very regular, moderately elliptical in shape, with no evidence of sub-
structure; previous ROSAT studies generally indicated a relaxed cluster on such scales (e.g., Buote & Tsai 1996). The radial profile of the density of the ICM is fitted well with a single $\beta$ model, with a double $\beta$ model providing slight improvement. The temperature profile is consistent with isothermal or gently rising (e.g., Allen et al. 2001) in the background, plasma code, bandwidth, and calibration. For the bandwidth case the data are fitted down to 0.5 keV using a fixed foreground column density of $14 \pm 0.76 \times 10^{20}$ cm$^{-2}$. Both the iron abundances and entropy profiles mirror the temperature profile is inconsistent with a constant at the 2 $\sigma$ level. The inner three annuli are excluded from the fits. The “Best” column indicates the best-fitting values obtained for different choices (see end of 4). The final column refers to differences obtained when using a 1.3 model to parameterize the gas density.

Nevertheless, a search for a steep-spectrum radio source would be worthwhile. The absence of low-frequency radio emission (e.g., VLA Low-Frequency Sky Survey; Cohen et al. 2004) would be an even more powerful test against the AGN heating model in A644, because 100 MHz-emitting cosmic rays have three times longer lifetimes in comparable magnetic fields. Moreover, although the higher temperature in the “hot spot” appears to be accompanied by a sharp increase in iron abundance, supernovae are a most unlikely heating source for even this small portion of the core because the required number of supernovae would need to be accompanied by a sharp increase in iron abundance, supernovae are a most unlikely heating source for even this small portion of the core because the required number of supernovae would need to be accompanied by a recent, galaxy-sized ($\geq 10^{9} M_{\odot}$) starburst. Neither a blue galaxy nor a luminous emission-line nebula are visible in the cluster core of A644 (Hu et al. 1985).

However, the morphological irregularities in the core of the X-ray image are very likely the result of merging. The cD galaxy (2MASX J08172559 -0730455) is located $\approx 20$ kpc South of the X-ray emission peak nearly along the direction of the centroid shift noted in 4. It is also $\approx 40$ kpc displaced from the centroid of the X-ray emission computed from larger radii. Evidently the cD galaxy and core ICM are “sloshing” in the potential well of the main cluster, and this energy has prevented the establishment of a cooling flow. The metallicity peak measured within the innermost radial bin probably indicates that previous merging did not destroy the initial peak, created when it was spatially coincident with the cD galaxy. This is because, as argued above, the peak is unlikely the result of very recent supernova enrichment. Also, the visual appearance of the A644 galaxies is quite diffuse, stretching $\sim 2$ Mpc linearly across the sky, suggesting a system far from relaxation. This morphology strengthens the argument for an on-going merger.

The properties of A644 (this paper), A2029 (Lewis et al. 2002, 2003), and A2589 (Buote & Lewis 2004) have important similarities. Their X-ray images indicate a peak which is offset from the centroid of the global X-ray halo, with A644 displaying the most extreme shift ($\approx 60$ kpc offset) compared to the others (A2589: $\approx 10$ kpc, A2029: $\approx 4$ kpc). Other than these offsets, the X-ray emission is very regular in each case with no indications of cavities as are seen in cool-core clusters with AGN. 4 Two of these clusters

| $c$ (Mpc) | $r_{\text{vir}}$ (Mpc) | $\Delta$Statistical | $\Delta$Background | $\Delta$Plasma | $\Delta$Bandwidth | $\Delta$Calibration | $\Delta_{\phi_{0}}$ |
|----------|----------------------|------------------|------------------|----------------|------------------|------------------|----------------|
| $6.1 \pm 1.2$ | $2.9 \pm 0.4$ | $-0.4$ | $+1.2$ | $-0.4$ | $+0.1$ | $+0.4$ |

Note: — The virial radius ($r_{\text{vir}}$) is defined to be the radius where the enclosed average mass density equals $10^{3} \rho_{c}(z)$ appropriate for the $\Lambda$CDM concordance cosmology (e.g., Eke et al. 1998). The inner three annuli are excluded from the fits.
have no detected AGN radio emission, while A2029 has a WAT morphology AGN, very unusual (unique to our knowledge) for a cool-core cluster. Finally, the lack of nebular emission lines in the cD galaxies are characteristic of non-cool-core clusters (Cardiel et al. 1998).

Of these three clusters only A644 possesses a central temperature peak. Although A644 appears to be unique in that its temperature profile declines toward the center and then rises, there are a few reports of clusters in the literature with temperature profiles measured by either Chandra or XMM that peak at their centers. The clusters A2218 (Govoni et al. 2004; Pratt & et al. 2005) and A3921 (Belsole et al. 2004) are violent, advanced mergers with with pronounced asymmetrical surface brightness and temperature distributions uncharacteristic of A644, A2029, and A2589. Another cluster with a reported central temperature peak is A401 (Sakellion & Ponman 2004), which is in the early stages of a major merger (with A399). Nevertheless, Sakellion & Ponman (2004) argue that the properties of A401 are determined primarily from its own hierarchical formation before interaction with A399. In this context it is interesting that A401 has a weak radio halo since we have suggested that radio halos form only in massive clusters where a violent merger has proceeded fully into the cluster core (Buote 2001).

If the other clusters had a similar history, their lack of radio halos indicate they are presently at much more evolved states than A401.

anticorrelates with these small fluctuations. Using a more recent, deeper (80 ks) Chandra exposure we confirm ≈10% deviations in the surface brightness (Zappacosta et al. 2005, in prep), but we do not confirm a strong anticorrelation with the WAT morphology as seen in other cool-core clusters. Compared to other cool-core clusters with obvious central disturbances these ≈10% deviations in the surface brightness, which translate to even smaller (≈5%) deviations in the gas density, indicate that the core of A2029 is in a much more relaxed state. For comparison, we find that Perseus, a cool-core cluster with an obvious disturbance in the core, displays up to 50% fluctuations in the surface brightness. It should be added that, unlike A2029, Perseus also has strong azimuthal fluctuations in the temperature and metallicity which, however, apparently conspire to produce approximate azimuthal balance in the gas pressure and therefore approximate hydrostatic equilibrium (Sanders et al. 2004).

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