SUZAKU OBSERVATIONS OF THE OUTSKIRTS OF A1835: DEVIATION FROM HYDROSTATIC EQUILIBRIUM

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ABSTRACT

We present results of four-pointing Suzaku X-ray observations (total ∼200 ks) of the intracluster medium (ICM) in the A1835 galaxy cluster (kT ∼ 8 keV, z = 0.253) out to the virial radius (r_vir ∼ 2.9 Mpc) and beyond. Faint X-ray emission from the ICM out to r_vir is detected. The temperature gradually decreases with radius from ∼8 keV in the inner region to ∼2 keV at r_vir. The entropy profile is shown to flatten beyond r_500, in disagreement with the r_1.1 dependence predicted from the accretion shock heating model. The thermal pressure profile in the range 0.3r_500 < r < r_vir agrees well with that obtained from the stacked Sunyaev–Zel’dovich effect observations with the Planck satellite. The hydrostatic mass profile in the cluster outskirts (r_500 < r < r_vir) falls well short of the weak-lensing one derived from Subaru/Suprime-Cam observations, showing an unphysical decrease with radius. The gas mass fraction at r_vir defined with the lensing total mass agrees with the cosmic baryon fraction from the Wilkinson Microwave Anisotropy Probe seven-year data. All these results indicate, rather than the gas-clumping effect, that the bulk of the ICM in the cluster outskirts is far from hydrostatic equilibrium and infalling matter retained some of its kinetic energy. Finally, combining with our recent Suzaku and lensing analysis of A1689, a cluster of similar mass, temperature, and redshift, we show that the cluster temperature distribution in the outskirts is significantly correlated with the galaxy density field in the surrounding large-scale environment at (1−2)r_vir.

Key words: galaxies: clusters: individual (A1835) – gravitational lensing: weak – intergalactic medium – X-rays: galaxies: clusters

Online-only material: color figures

1. INTRODUCTION

Clusters of galaxies are the largest self-gravitating systems in the universe, where thousands of galaxies and hot thin plasma (intracluster medium, ICM) are bound to the potential of the dark matter halo. Gravity of dark matter, which is the dominant mass component of clusters of galaxies, plays an important role in structure formation and cluster evolution. According to the hierarchical structure formation scenario based on the cold dark matter (CDM) paradigm, less massive systems collapse first and then massive ones later. X-ray observables of the ICM properties keep original records of cluster evolution. During the hierarchical formation, gas and galaxies in the large-scale structure are falling on the clusters. Since the cluster outskirts is located around the boundary of the cosmological environment, the gas in the outskirts would be significantly affected by structure formation. The cluster outskirts is, therefore, a good spot to refine the details of how the gas physics is involved in hierarchical clustering. It is, however, difficult to efficiently observe faint X-ray emission from cluster outskirts with Chandra and XMM-Newton because of their relatively high levels of instrumental background.

Thanks to the low and stable particle background of the X-ray Imaging Spectrometer (XIS; Koyama et al. 2007), Suzaku (Mitsuda et al. 2007) was able to unveil for the first time the ICM beyond r_500, within which the mean cluster-mass density is 500 times the cosmic critical density. Indeed, Suzaku’s ability to probe the ICM out to the virial radius has been shown for a number of relaxed clusters (e.g., Fujita et al. 2008; George et al. 2009; Reiprich et al. 2009; Bautz et al. 2009; Kawaharada et al. 2010; Hoshino et al. 2010; Simionescu et al. 2011; Akamatsu et al. 2011; Walker et al. 2012a, 2012c; Sato et al. 2012). One common feature is a flattening of the entropy profile beyond r_500, contrary to the power-law prediction of the accretion shock heating model (Tozzi & Norman 2001; Ponman et al. 2003; Voit et al. 2005). The entropy profiles, scaled with the average ICM temperature, are universal irrespective of cluster mass (Sato et al. 2012). One possible explanation for the low entropy is deviations from hydrostatic equilibrium (H.E.) in the outskirts (e.g., Kawaharada et al. 2010; Sato et al. 2012). With simulations, Nagai & Lau (2011) showed that beyond r_200, gas clumping leads to an overestimation of the observed gas density. Simionescu et al. (2011) interpreted that, based on the results for Perseus cluster, entropy flattening is a consequence...
of the gas density in the outskirts being overestimated due to gas clumping.

A gravitational lensing study is complementary to X-ray measurements, because lensing observables do not require any assumptions on the cluster dynamical states. Weak gravitational lensing analysis is a powerful technique to measure the mass distribution from outside the core to the virial radius. The exquisite Subaru/Suprime-Cam lensing data allow us to study properties of cluster mass distribution, thanks to its high image quality and wide field of view (FoV; e.g., Broadhurst et al. 2005; Okabe & Umetsu 2008; Umetsu & Broadhurst 2008; Okabe et al. 2010a). Comparisons of X-ray observables with weak-lensing mass allow us to conduct a powerful diagnostic of the ICM states, including a stringent test for H.E. (Okabe & Umetsu 2010; Kawaharada et al. 2010; Zhang et al. 2010; Okabe et al. 2010b). Kawaharada et al. (2010), incorporating Suzuki X-ray and lensing data, found a large discrepancy between H.E. and lensing masses in A1689, and significantly discovered that H.E. mass significantly drops off in the outskirts ($r > r_{500}$).

A1835, with an ICM temperature of $\sim 8$ keV, is a luminous cool-core galaxy cluster. The X-ray properties of this cluster were measured within $r_{500}$ with XMM-Newton (Jia et al. 2004; Zhang et al. 2007) and with Chandra (Li et al. 2012). The temperature measurement in the outskirts were reported out to 9.0 by XMM-Newton (Snowden et al. 2008) and to 10.0 in the western direction by Chandra (Bonamente et al. 2013). Okabe et al. (2010a) have conducted weak-lensing analysis of Subaru/Suprime-Cam data to measure the mass profile using the tangential distortion profile outside the core. Pereira et al. (2010) presented a complex velocity distribution, suggesting ongoing mass accretion associated with smaller satellite systems and found that a third of Herschel sources are located in the southwest region. Morandi et al. (2012) presented a full three-dimensional structure reconstructed from X-ray, Sunyaev–Zel’dovich (SZ), and strong lensing data available for the core region and discuss the non-thermal pressure with an extrapolation to $r_{200}$.

This paper reports the results of four Suzuki observations of the A1835 cluster out to the virial radius ($r_{vir} \sim 2.9$ Mpc or 12.0) and beyond. The Suzuki observations and data reduction are described in Section 2. The spectral analysis to obtain radial profiles of temperature, electron density, and entropy is shown in Section 3. We discuss, in Section 4, a comparison of H.E. and lensing masses, and gas mass fraction. We also compare thermal properties with those of other clusters, including stacked SZ pressure profile with Planck. A statistical approach to investigate the correlation between temperature distribution in the outskirts and the large-scale structure derived from the Sloan Digital Sky Survey (SDSS) photometric data is conducted for a sample of two lensing clusters, A1835 and A1689, for which Suzuki data fully cover the whole region out to the virial radius.

We use the Hubble constant $H_0 = 70$ km $s^{-1}$ Mpc$^{-1}$ ($h = H_0/100$ km $s^{-1}$ Mpc$^{-1} = 0.7$), assuming a flat universe with $\Omega_{m,0} = 0.27$ in this paper. The angular-size distance $D_A$ of A1835 is 819 Mpc $h^{-1}$. This gives the physical scale $1^\prime = 237.9$ kpc at the cluster redshift $z = 0.2532$. We adopt the virial radius $r_{vir} = 2.89$ Mpc $h^{-1}$, within which the mean cluster-mass density is 112 times the cosmic critical density, determined by weak-lensing analysis (Okabe et al. 2010a). The galactic hydrogen column density $n_H$ of A1835 is $2.04 \times 10^{15}$ cm$^{-2}$ (Kalberla et al. 2005). The definition of solar abundance is taken from Lodders (2003), in which the solar Fe abundance relative to H is $2.95 \times 10^{-5}$. Errors are given at the 90% confidence level (CL) except as otherwise noted.

### Table 1

| Observation (ID)     | Start* | End*  | Exposure (ks) |
|----------------------|--------|-------|---------------|
| east (805037010)     | 2010/07/05 16:26:02 | 2010/07/07 02:55:18 | 49.4 |
| south (805038010)    | 2010/07/02 05:26:23 | 2010/07/08 11:12:11 | 45.6 |
| west (805039010)     | 2010/07/08 11:13:00 | 2010/07/09 23:39:12 | 53.7 |
| north (805040010)    | 2010/07/13 23:47:30 | 2010/07/15 09:36:15 | 48.8 |

Note. * Time is shown in UT.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Observations

We performed four-pointing Suzuki observations of A1835, named east, south, west, and north, in 2010 July with exposure of $\sim 50$ ks for each pointing. The observation log is summarized in Table 1. Figure 1 shows the XIS image of A1835. The pointings were coordinated so that the X-ray emission centroid of A1835 was located at one corner of each pointing. The Suzuki mosaic covered the ICM emission out to the virial radius ($\sim 2.9$ Mpc or 12.0) and beyond.

2.2. XIS Data Reduction

We used only XIS data in this study. Three out of the four CCD chips were available in these observations: XIS0, XIS1, and XIS3. The XIS1 is a back-illuminated chip with high sensitivity for the soft X-ray energy range, while the XIS0 and XIS3 are front-illuminated. The instrument was operated in the normal clocking mode. We included the data formats of both $5 \times 5$ and $3 \times 3$ editing modes in our analysis using xselect (Ver.2.4b). We used version 2.5.16.28 of the processed data screened with the standard filtering criteria. In order not to reduce the exposure time, event screening with the cutoff rigidity was not performed in our data because we can estimate the non-X-ray background (NXB) reasonably using data outside $r_{\alpha \phi}$. The analysis was performed with HEAsoft ver 6.11 and CALDB 2011-09-06.

For each pointing (four azimuthal directions), we divided the FoV into six concentric annular regions centered on the X-ray emission centroid, $(\alpha, \delta) = (14^h01^m01.865, +02^\circ32^\prime35^\prime.48)$ in J2000 coordinates (Zhang et al. 2007), to obtain the temperature and electron density profiles. The inner and outer radii of the annular regions are $0.0–2.0$, $2.0–4.0$, $4.0–6.0$, $6.0–9.0$, $9.0–12.0$, and $12.0–20.0$ (Figure 1). The circular regions around 32 point sources were excluded from the analysis. Furthermore, we subtracted the contribution of luminous point sources outside the excluded regions. The details are described in Appendix A. In the $0.0–2.0$ region, all the spectra of the east, south, and north directions are unavailable because of calibration sources.

Redistribution matrix files of the XIS were produced by xisrmgen version 2009-02-28. We generated two ancillary response files (ARFs) using xissimarfgen version 2010-11-05 (Ishisaki et al. 2007), assuming uniform sky (circular region of 20$^\circ$ radius, hereafter UNI-ARF) and surface brightness profile of A1835, where we used a $\beta$-model image of $48.6 \times 48.6$ with $\beta = 0.55$ and $r_{\alpha \phi} = 0.192$ based on the ROSAT HRI result as

13 http://www.astro.isas.ac.jp/suzaku/process/v2changes/criteria_xis.html
the input X-ray image (Ota & Mitsuda 2004, hereafter and smoothed by a two-dimensional Gaussian with σ = 16 pixels ≈ 17′ (counts pixel$^{-1}$ Ms$^{-1}$). Here, the effect of vignetting was not corrected for and regions where $^{56}$Fe calibration sources are irradiated (Koyama et al. 2007) are excluded. Green circles indicate the regions used for spectrum analysis. Thick green circle shows the virial radius of A1835 ($r_{\text{vir}} \approx 2.9$ Mpc or 12′). Small white circles are the excluded regions around point sources. Yellow boxes show the field of views (FoVs) of Suzaku Observations named east, south, west, and north. Right: XMM-Newton MOS1 + MOS2 image of A1835 (0.5–2 keV). Background was not subtracted and vignetting was not corrected.

3. SPECTRAL ANALYSIS AND RESULTS

3.1. Spectral Fit

We used the XSPEC v12.7.0 package and ATOMDB v2.0.1 for all spectral fitting. The NXB components were subtracted before the fit. To avoid systematic uncertainties in the background, we used energy ranges of 0.6–7.0 keV for the XIS0, 0.5–5.0 keV for the XIS1, and 0.6–7.0 keV for the XIS3 in all the regions. In addition, we excluded energy band around the Si-K edge (1.82–1.84 keV), because its response was not modeled correctly. We simultaneously fitted all the spectra of the three detectors for the six annular regions toward four azimuthal directions by minimizing the total χ$^2$ value. In this fit, relative normalizations between the three sensors were left free to compensate for the cross-calibration errors. The model for the spectral fit was an absorbed thin-thermal emission model represented by phabs × apec for the ICM emission of the cluster, added to the X-ray background (XRB) model. We employed the β-ARF for the ICM component (see Section 2.2). The phabs component models the photoelectric absorption by the Milky Way, parameterized by the hydrogen column density that we fixed to the Galactic value of 2.04 × 10$^{20}$ cm$^{-2}$ (Kalberla et al. 2005). Even if we allowed the hydrogen column density for the phabs model to vary or employ the wabs model fixed at the Galactic column density in the direction of A1835 in the spectral analysis, the resultant temperatures and electron densities of the ICM component are almost the same within $\sim$3%. The apec is a thermal plasma model by Smith et al. (2001). For a given annulus, each parameter of the ICM component for four azimuthal directions was assumed to have the same value. In the central regions, metal abundance of the ICM component was allowed to vary, while at $r > 4′$, we fixed the metal abundance of the ICM at 0.2. The redshift of the ICM component was fixed to 0.2532.

In order to study the faint X-ray emission from the cluster outskirts, an accurate estimation of the XRB is vitally important. We fitted the spectra in the innermost annulus (12′–20′ region, which is outside $r_{\text{vir}}$) for the following three cases. Case-GAL: The XRB model includes three components of the cosmic X-ray background (CXB), unabsorbed 0.1 keV Galactic emission (LHB; representing the local hot bubble and the solar wind charge exchange), and absorbed 0.3 keV Galactic emission (MWH1; representing the Milky Way halo; Yoshino et al. 2009). The normalization for the ICM flux is fixed to zero. Case-GAL+ICM: The XRB model was the same as Case-GAL, but the temperature and normalization for the ICM component were left free. Case-GAL2: In addition to Case-GAL, we added an absorbed 0.6 keV Galactic emission (MWH2; representing the Milky Way halo; Yoshino et al. 2009). This is because several blank fields observed with Suzaku contain the emission with 0.6–0.8 keV (Yoshino et al. 2009). The normalization for the ICM flux was fixed to zero. In all cases, we assumed a power-law spectrum for the CXB with $\Gamma = 1.4$. In addition, we modeled the LHB, MWH1, and MWH2 with the apec model, where the redshift and abundance were fixed at 0 and unity, respectively. The temperatures of the LHB, MWH1, and MWH2 were fixed at 0.1 keV, 0.3 keV, and 0.6 keV, respectively. We used UNI-ARF for the XRB components, assuming that the XRB components have flat surface brightness (see Section 2.2). Normalizations of the XRB components were also left free.
For the XRB components, we adopted the model formula, \( \text{phabs} \times (\text{powerlaw} + \text{apec}_{\text{MWH1}}) + \text{apec}_{\text{LHB}} \) for Case-GAL and Case-GAL+ICM, and \( \text{phabs} \times (\text{powerlaw} + \text{apec}_{\text{MWH1}} + \text{apec}_{\text{MWH2}}) + \text{apec}_{\text{LHB}} \) for Case-GAL2. Results of the spectral fit are shown in Sections 3.2 and 3.4.

### 3.2. Result of the XRB Components

Figure 2 shows the results of the spectral fit for the outermost annulus of 12.0–20.0° toward the east and west (opposite azimuthal directions). The best-fit parameters for the XRB components and \( \chi^2 \) values are listed in Table 2. The \( \chi^2 \) values for Case-GAL and Case-GAL2 are worse than that for Case-GAL+ICM. We estimate F-test probabilities for Case-GAL and Case-GAL+ICM of \( \sim 1 \times 10^{-7} \) and for Case-GAL and Case-GAL2 of \( \sim 1 \times 10^{-4} \), respectively. Case-GAL is therefore not supported. The intensity of the Galactic emissions (LHB, MWH1) is somewhat higher than that of the typical Galactic emissions (Yoshino et al. 2009). The plausible cause of the higher intensity would be the fact that A1835 is located near the North Polar Spur. For Case-GAL2, we refitted spectra with the temperature for 0.6 keV Galactic emission (MWH2) allowed to be a free parameter. We found that the \( \chi^2 \) (2869) becomes slightly better and the resultant MWH2 temperature increases to 0.92\(^{+0.11}_{-0.07} \) keV. In the \( r < 12.0 \) region, the best-fit ICM parameters were almost the same as those from Case-GAL+ICM. For example, the ICM temperature and electron density in the 9.0–12.0° region increased by 8% and 10%, respectively, compared to those for Case-GAL+ICM.

We investigated the validity of the CXB intensity obtained from the spectral fit. To estimate the amplitude of the CXB fluctuations, we scaled the fluctuations measured from \( \text{Ginga} \) (Hayashida et al. 1989) to our flux limit and FoV area using the method of Hoshino et al. (2010). The fluctuation width is given by the following relation:

\[
\sigma_{\text{CXB}} \bigg/ \sigma_{\text{ICXB}} = \left( \Omega_{\text{ICXB}} / \Omega_{\text{Ginga}} \right)^{0.5} \left( S_{\text{CXB}} / S_{\text{Ginga}} \right)^{0.25},
\]

(1)

where \( \sigma_{\text{CXB}} / \sigma_{\text{ICXB}} \) means the fractional CXB fluctuation width due to the statistical fluctuation of the discrete source number in the FoV. Here, we adopt \( \sigma_{\text{Ginga}} / \sigma_{\text{ICXB}} = 50\% \), with \( S_{\text{CXB}} \) (\( \text{Ginga} \): 6 \( \times \) 10\(^{-12} \) erg cm\(^{-2} \) s\(^{-1} \)) representing the upper cutoff of the source flux, and \( \Omega_{\text{Ginga}} \) (\( \text{Ginga} \): 1.2 deg\(^2 \)) representing the effective solid angle of the detector. We show the result, \( \sigma / \sigma_{\text{ICXB}} \), for each annular region in Table 3, where \( \sigma \) is the standard deviation of the CXB intensity, \( \sigma_{\text{ICXB}} \).

Table 2: Best-fit Parameters of the X-Ray Background Components

| Case     | CXB \( \Omega_{\text{CXB}} \) | LHB (0.1 keV) \( \Omega_{\text{LHB}} \) | MWH1 (0.3 keV) \( \Omega_{\text{MWH1}} \) | MWH2 (0.6 keV) \( \Omega_{\text{MWH2}} \) | \( 12^h–20^h \) Region \( \chi^2/d.o.f. \) |
|----------|--------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| GAL      | \( 5.78^{+0.17}_{-0.17} \)   | \( 7.32^{+0.54}_{-0.63} \)    | \( 1.05^{+0.05}_{-0.05} \)    | \( \ldots \)                   | \( 694/420 \)                  |
| GAL+ICM  | \( 5.17^{+0.28}_{-0.23} \)   | \( 7.54^{+0.44}_{-0.43} \)    | \( 0.96^{+0.07}_{-0.07} \)    | \( \ldots \)                   | \( 655/420 \)                  |
| GAL2     | \( 5.66^{+0.18}_{-0.18} \)   | \( 8.13^{+0.72}_{-0.71} \)    | \( 0.77^{+0.12}_{-0.12} \)    | \( 0.16^{+0.16}_{-0.16} \)    | \( 667/420 \)                  |

Notes.
- \( a \) Estimated source efficiency of the CXB after the point-source exclusion in units of 10\(^{-8} \) erg cm\(^{-2} \) s\(^{-1} \) sr\(^{-1} \) (2.0–10.0 keV).
- \( b \) Normalization of the \( \text{apec} \) component scaled by a factor 1/4000 \( r \) assumed in the uniform-sky ARF calculation (circle radius \( r = 20^\circ \)).

Normal \( \Omega \) of the CXB is given in units of arcmin\(^2 \).

Table 3: Estimation of CXB Fluctuation for All Directions

| Region | \( \Omega_{\text{ICXB}} \) \( (\text{arcmin}^2) \) | Coverage \( (\% ) \) | SOURCE \( \text{RATIO REG} \) \( (\% ) \) | \( \sigma / \sigma_{\text{ICXB}} \) \( (\% ) \) |
|--------|-----------------|-----------------|-----------------|-----------------|
| 0°–2°  | \( \ldots \)     | 11.1            | 88.1            | 59.37           |
| 2°–4°  | 33.4            | 88.6            | 10.90           |
| 4°–6°  | 53.3            | 84.8            | 5.19            |
| 6°–9°  | 119.2           | 84.3            | 4.57            |
| 9°–12° | \ldots \ldots   | 84.6            | 2.94            |
| 12°–20°| 590.3           | 73.4            | 4.01            |

Notes.
- \( a \) The average value of the three detectors.
- \( b \) Solid angle of each observed region.
- \( c \) Fraction of each area to entire annulus.
- \( d \) Fraction of the simulated cluster photons which fall in the region compared with the total photons generated in the entire simulated cluster.

\( \text{SOURCE \_ RATIO REG} = \text{Coverage} \times \int_{\text{reg}} S(r) dr / \int_{\text{fov}} S(r) dr \), where \( S(r) \) represents the assumed radial profile of A1835. We confined \( S(r) \) to a 49°–49° region on the sky.

\( \sigma / \sigma_{\text{ICXB}} \) is assumed for all regions.

The best-fit parameter of the CXB surface brightness (after subtraction of point sources brighter than 2 \( \times \) 10\(^{-14} \) erg cm\(^{-2} \) s\(^{-1} \) keV band) is 5.17\(^{+0.26}_{-0.23} \) \( \times \) 10\(^{-8} \) erg cm\(^{-2} \) s\(^{-1} \) sr\(^{-1} \) for Case-GAL+ICM which agrees with that of Hoshino et al. (2010), 4.73\(^{+0.13}_{-0.12} \) \( \times \) 10\(^{-8} \) erg cm\(^{-2} \) s\(^{-1} \) sr\(^{-1} \), within statistical errors taking into account the CXB fluctuation. Using the same threshold, \( S_{\text{CXB}} \) derived from previous \( \text{Ginga} \) observations were 4–6 \( \times \) 10\(^{-8} \) erg cm\(^{-2} \) s\(^{-1} \) sr\(^{-1} \) (e.g., Moretti et al. 2009; Kawaharada et al. 2010; Hoshino et al. 2010; Sato et al. 2012). Case-GAL and Case-GAL2 gave higher CXB surface brightness by 10%. If point sources brighter than 1.0 \( \times \) 10\(^{-13} \) erg cm\(^{-2} \) s\(^{-1} \) are subtracted, \( S_{\text{CXB}} \) were measured to be 6–7 \( \times \) 10\(^{-8} \) erg cm\(^{-2} \) s\(^{-1} \) sr\(^{-1} \) (e.g., Bautz et al. 2009; Simionescu et al. 2011; Akamatsu et al. 2011; Walker et al. 2012a, 2012c). Using this threshold, the CXB surface brightness around A1835 for Case-GAL+ICM is 6.8 \( \times \) 10\(^{-8} \) erg cm\(^{-2} \) s\(^{-1} \) sr\(^{-1} \) which agrees well with the previous studies.
3.3. X-Ray Surface Brightness Profile

In order to see how far the ICM emission of A1835 is detected, we derived a surface brightness profile in the energy band of 1–2 keV from the XIS mosaic image (XIS0, XIS1, and XIS3 images) excluding the circular regions around 32 point sources (Figure 1). The left panel of Figure 3 shows the raw surface brightness profile in the 1–2 keV band (black crosses) where the background is included and the vignetting effect is not corrected. The 1–2 keV NXB profile, derived from an NXB mosaic image

Figure 2. NXB-subtracted spectra of XIS3 (black crosses) and XIS1 (red crosses) for the outermost annulus (12′–20′). Top, middle, and bottom panels correspond to Case–GAL, Case–GAL+ICM, and Case–GAL2, respectively. The ICM, CXB, LHB, MWH1, and MWH2 emissions for the XIS3 spectra are shown in magenta, blue, orange, green, and cyan lines, respectively. The sum of the CXB, LHB, and MWH1 emissions for the XIS3 spectra are indicated by the green-cyan line. The total model spectra of XIS3 and XIS1 are shown in black and red lines, respectively. Left and right panels correspond to east and west, respectively. The lower panels show the residuals in units of $\sigma$. 

In order to see how far the ICM emission of A1835 is detected, we derived a surface brightness profile in the energy band of 1–2 keV from the XIS mosaic image (XIS0, XIS1, and XIS3 images) excluding the circular regions around 32 point sources (Figure 1). The left panel of Figure 3 shows the raw surface brightness profile in the 1–2 keV band (black crosses) where the background is included and the vignetting effect is not corrected. The 1–2 keV NXB profile, derived from an NXB mosaic image
with \( \chi^{\text{nsrbgen}} \), is shown in red in the left panel of Figure 3. We then obtained an XRB mosaic image. Based on the CXB and Galactic (LHB+MWH1) models of A1835 obtained from fitting for the three background cases, we simulated CXB and Galactic images of the four offset observations using \( \chi^{\text{assim}} \) with exposures 10 times longer than those of actual observations. The 1–2 keV CXB and Galactic (LHB+MWH1) profiles for Case-GAL+ICM are shown in green and blue in the left panel of Figure 3, respectively. Since there is a contribution of luminous point sources outside the excluded regions, we simulated this residual-point-source signals. Details of the simulation are described in Appendix A. The 1–2 keV residual-point-source profile is shown in orange in the left panel of Figure 3. In the end, we obtained background (CXB+Galactic+NXB+residual-point-source) and background-subtracted (raw—background) profiles for Case-GAL+ICM, as shown in cyan and magenta in the left panel of Figure 3. Here, ±10% systematic error for the CXB intensity is included.

Since these images were not corrected for the vignetting, we calculated the ratio of the background-subtracted surface brightness to the CXB brightness in the right panel of Figure 3 for the three background cases. As a result, this ratio decreases with radius out to the virial radius \( r_{\text{vir}} \sim 12.0 \) and becomes flatter beyond. Beyond \( r_{\text{vir}} \), the background-subtracted signal in the brightness for Case-GAL+ICM accounts for 29% and 26% of the CXB and CXB+LHB+MWH1, respectively. It cannot be explained by the fluctuations of the CXB intensity (∼3.3% in the 12’0–20’0 region in Table 3). An additional emission component is required to explain the observed flux beyond \( r_{\text{vir}} \). However, it is uncertain whether this emission comes from the ICM (Case-GAL+ICM) or from the relatively hot (∼0.9 keV) Galactic emission. Since A1835 is located close to the North Polar Spur, it is clear that the background-subtracted signal suffers from Galactic emission uncertainties. The ratios of the remaining signal to the background for Case-GAL and Case-GAL2 are a factor of two smaller than those for Case-GAL+ICM. From \( \chi^{2} \), Case-GAL+ICM reproduces the spectra beyond \( r_{\text{vir}} \) better. We will quantify the systematic errors of the ICM temperature associated with the background subtraction in Section 3.6 and Table 8.

### 3.4. Result of the ICM Components in All the Directions

Figure 4 shows results of the spectral fit in the particularly important regions (4:0–6:0, 6:0–9:0, and 9:0–12:0) toward the east and west (opposite azimuthal directions) for Case-GAL+ICM. The best-fit parameters of the ICM components and \( \chi^{2} \) values in each region, when parameters are tied between the four offset pointings, are listed in Table 4.

#### 3.4.1. Temperature Profile

Figure 5 shows radial profiles of projected temperature in all directions, observed with XMM-Newton (Zhang et al. 2007; Snowden et al. 2008), Chandra (Bonamente et al. 2013), and Suzaku (this work). The temperature is ∼8 keV within 2’0 (∼480 kpc), and it gradually decreases toward the outskirts down to ∼2 keV around the virial radius \( r_{\text{vir}} \sim 12.0 \). At a given radius, the temperatures for the three background cases with Suzaku agree well with each other. For Case-GAL+ICM, the temperature in the 12’0–20’0 region joins smoothly with those of inner regions. We shall quantify the systematic error of the Suzaku ICM temperature in Section 3.6. The temperature profile derived from Suzaku agrees well with those from XMM-Newton within 4’0 (∼0.95 Mpc) and from Chandra (Bonamente et al. 2013) within 7.5 (∼1.8 Mpc). Bonamente et al. (2013) measured temperature profiles for A1835 out to 10’0 with Chandra. As their outermost temperature is in the 7.5–10.0 regions, we shall compare this with our result at the outskirts in the west in Section 3.5.

#### 3.4.2. Electron Density Profile

The electron number density profile was calculated from the normalization parameter of the apec model, defined as

\[
\text{Norm} = \frac{10^{-14}}{4\pi(D_{A}(1+z))^{2}} \int n_{e}n_{H}dV,
\]
Figure 4. NXB-subtracted spectra of XIS3 (black crosses) and XIS1 (red crosses) in Case-GAL+ICM. The ICM, CXB, LHB, and MWH1 emissions for the XIS3 spectra are shown in magenta, blue, orange, and green lines, respectively. The sum of the CXB, LHB, and MWH1 emissions for the XIS3 spectra are indicated by the green-cyan line. The total model spectra of XIS3 and XIS1 are shown in black and red lines, respectively. Left and right panels correspond to east and west, respectively. The lower panels show the residuals in units of $\sigma$.

where $D_A$ is the angular-size distance to the source in units of cm, $n_e$ is the electron density in units of cm$^{-3}$, and $n_H$ is the hydrogen density in units of cm$^{-3}$. We note that the resultant normalization using an ARF generated by xissimarfgen needs a correction by a factor of $\text{SOURCE} \times \frac{\text{RATIO}}{\Omega_e}$ (see details in Section 5.3 of Ishisaki et al. 2007). The left panel of Figure 6 shows the radial profiles of normalization of the apec model for the ICM component scaled with this factor.
Each annular region, projected in the sky, includes emission from different densities due to integration along the line of sight. Assuming spherical symmetry, we de-convolved the normalization and calculated $n_e$ for each annular region from the outermost region using the method described in Kriss et al. (1983). The resultant radial profiles of $n_e$ in all directions with XMM-Newton (Zhang et al. 2007) and Suzaku (this work) are shown in the right panel of Figure 6 and listed in Table 5. The deprojected electron density profile derived from Suzaku agrees well with that from XMM-Newton within 5′0 (∼1.2 Mpc).

The electron density profile of A1835 for Case-GAL+ICM from 6/0 (∼0.69 $r_{200}$) to 12/0 (∼1.3 $r_{200}$) is well represented by a power-law model with $\beta = 0.88$. This value agrees very well with the $\beta = 0.89$ derived for electron density profiles in 0.65–1.2 $r_{200}$ of 31 clusters observed with ROSAT (Eckert et al. 2012). For Case-GAL and Case-GAL2, the $\beta$ values derived in the same way are 0.38 and 0.51, respectively, which are significantly smaller than those derived by Eckert et al. (2012). Here, $r_{200}$ is calculated using the average ICM temperature, $(kT)$, $r_{200} = 2.47 h_{70}^{-1} \sqrt{(kT) / 10\text{keV} \text{Mpc}}$. This relation was expected from numerical simulations for our cosmology (Henry et al. 2009). The average temperature of A1835 integrated over the radial range of 70 kpc to $r_{500}$ (= 1.39 Mpc $h_{70}^{-1}$ or 5.85) with XMM-Newton is 7.67 ± 0.21 keV (Zhang et al. 2007), where $r_{500}$ is defined by weak-lensing analysis (Okabe et al. 2010a). Thus, from the average temperature, $T_{200} = 2.16 \text{Mpc} h_{70}^{-1}$ or 9.08, which is close to $9.29$ for $r_{200}$ defined by the weak-lensing analysis.

### 3.4.3. Entropy Profile

Figure 7 shows the entropy profiles with XMM-Newton and Suzaku calculated as

$$K = \frac{kT}{n_e^{3/2}},$$

(3)

where $T$ and $n_e$ are the temperature and deprojected electron density obtained above, respectively. At a given radius, the entropies for the three background cases are consistent within statistical errors with each other. Within $r_{500}$, the derived entropy profiles with XMM-Newton and Suzaku follow a power-law.
Figure 6. Left: the radial profiles of the normalization of the apec model obtained by spectral analyses scaled with a factor of $\text{SOURCE\_RATIO\_REG}/\Omega_\text{e}$, when all spectra of azimuthal regions at the same distance are summed (All). Dotted (black), solid (red), and dashed (green) diamonds show our Suzaku results for Case-GAL, Case-GAL+ICM, and Case-GAL2, respectively. The uncertainty range due to the $\pm 10\%$ variation of the CXB levels from the CXB nominal levels for Case-GAL+ICM is shown by two dashed (blue) lines. Vertical dotted lines show $r_{500}$ (5.85) and $r_{\text{vir}}$ (12.0). Right: same as the left panel, but for deprojected electron number density profiles. See the text for the detailed method of derivation (Section 3.4.2). XMM-Newton results by Zhang et al. (2007) are shown by the crosses (orange). The solid (orange) line extrapolates which has a fixed index of 1.1.

Figure 7. Radial profiles of entropy in all directions obtained by calculating $K = \frac{kT}{n_e^{2/3}}$ from profiles in Figure 5 and in the right panel of Figure 6. Dotted (black), solid (red), and dashed (green) diamonds show our Suzaku results for Case-GAL, Case-GAL+ICM, and Case-GAL2, respectively. The uncertainty range due to the $\pm 10\%$ variation of the CXB levels from the CXB nominal levels for Case-GAL+ICM is shown by two dashed (blue) lines. Vertical dotted lines show $r_{500}$ (5.85) and $r_{\text{vir}}$ (12.0). XMM-Newton results by Zhang et al. (2007) are shown by the crosses (orange). The solid (orange) line extrapolates the XMM-Newton data with a power-law formula fit for the data beyond 70 kpc, which has a fixed index of 1.1.

We investigated the effect of systematic errors on the derived spectral parameters. The level of the CXB fluctuation was scaled from the Ginga result (Hayashida et al. 1989) as shown in Table 3. The CXB fluctuation in the cluster outskirts ($r \lesssim 9\prime$) is not significant. Bonamente et al. (2013) reported with Chandra a temperature of $kT = 1.26 \pm 0.26$ keV in the $7.5-10.0$ region. We note that they observed the western region of A1835. Their temperature is marginally consistent with our results for $r_{500}$ ($\lesssim 0.09$ keV) and at $9\prime-12\prime$ ($kT = 1.51^{+0.49}_{-0.23}$ keV) in the west (Figure 8 and Table 6). The electron number density and entropy profiles in the south, west, and north are consistent with one another within the statistical errors in any annulus region. The electron number density and entropy in the outskirts ($r_{500} \lesssim r \lesssim r_{\text{vir}}$) in the east are lower and higher than those in other directions, respectively.

### 3.6. Systematic Errors

We investigated the effect of systematic errors on the derived spectral parameters. The level of the CXB fluctuation was scaled from the Ginga result (Hayashida et al. 1989) as shown in Table 3. The CXB fluctuation in the cluster outskirts ($6\prime \lesssim r$), where correct estimations of the CXB intensity are of utmost importance, is less than $10\%$ in all the directions from Table 3. In the $9\prime-12\prime$ region, for example, the CXB fluctuation as for Case-GAL+ICM (Section 3.1), but the temperatures and normalizations for the ICM component within $12\prime$ for the four directions were independently determined. The derived $\chi^2$, 2669 for 2119 degrees of freedom, is smaller than the 2884 for 2146 degrees of freedom of the previous fit for all directions. Table 6 shows the derived temperatures, normalizations, and $\chi^2$ values for each region. Assuming spherical symmetry we calculated the deprojected electron number density and entropy profiles. The resultant radial profiles of $n_e$ in each direction are listed in Table 7. Figure 8 shows the radial profiles of the ICM temperature, scaled normalization, electron density, and entropy in each direction.

There is an azimuthal variation of the projected temperatures in the outskirts of $r_{500} \lesssim r \lesssim r_{\text{vir}}$. The best-fit temperature in the eastern region is highest, about twice of those in the western and northern regions. The temperature in the southern region is intermediate between them. The differences between individual values are larger than measurement uncertainties, but is not significant. Bonamente et al. (2013) reported with Chandra a temperature of $kT = 1.26 \pm 0.26$ keV in the $7.5-10.0$ region. We note that they observed the western region of A1835. Their temperature is marginally consistent with our measurements at $6\prime-9\prime$ ($kT = 2.09^{+0.68}_{-0.45}$ keV) and at $9\prime-12\prime$ ($kT = 1.51^{+0.49}_{-0.23}$ keV) in the west (Figure 8 and Table 6). The electron number density and entropy profiles in the south, west, and north are consistent with one another within the statistical errors in any annulus region. The electron number density and entropy in the outskirts ($r_{500} \lesssim r \lesssim r_{\text{vir}}$) in the east are lower and higher than those in other directions, respectively.

### 3.5. Result of Case-GAL+ICM in Each Direction

We fitted all the spectra simultaneously in the same way model with a fixed index of 1.1, which was predicted from the accretion shock heating model (Tozzi & Norman 2001; Ponman et al. 2003; Voit et al. 2005). In contrast, beyond $r_{500}$ ($\sim 6\prime$), the entropy profiles for the three cases become flatter, in disagreement with the $r^{1.1}$ relationship. For Case-GAL+ICM, the entropy profile is flat out to $20\prime$ ($\sim 1.7r_{\text{vir}}$).
value in all directions is about 6.1%. Although in the cluster center \((r \lesssim 6/0)\) the CXB fluctuation is higher, the systematic uncertainties caused by the fluctuation became smaller due to much brighter ICM emission. Therefore, we assume that the upper and lower limits of the CXB systematic changes in all directions are \(\pm 10\%\), even when considering uncertainty other than the systematic error due to the spatial variation. For Case-GAL+ICM, we repeated the spectral fit for all directions in the same way but fixed the CXB intensity at the upper and lower 10\% from their nominal levels. Table 8 shows the changes of ICM properties in the 9\,0–12\,0 region and the reduced \(\chi^2\) in each variation. In the 9\,0–12\,0 region, the effects of \(\pm 10\%\) error for the CXB, intensity, on the temperature, electron number density, and entropy are 20\%–30\%, less than 5\%, and 20\%–30\%, respectively. In each direction, the CXB fluctuation for each annular region should be a factor of two higher than that of for all directions. In the 9\,0–12\,0 region, for example, the CXB fluctuation values in the east, south, west, and north are about 11.5\%, 12.6\%, 11.2\%, and 10.6\%, respectively. Therefore, we assume that the upper and lower limits of the CXB systematic changes in each direction are \(\pm 15\%\). In each direction, the change of entropy in the 9\,0–12\,0 region is 20\%–40\% by \(\pm 15\%\) error for the CXB intensity, except for the CXB +15\% in the west. This systematic error is comparable to the statistical error. For the CXB +15\% in the west, the temperature and entropy are lower by a factor of \(~2\) and \(~3\), respectively.

The changes of the intensities of the Galactic emissions (LHB, MWH1), by systematic changes in the CXB levels to \(\pm 10\%\) and \(\pm 15\%\) from their nominal levels, are less than 10\%. Then, we repeated the spectral fit by fixing the Galactic (LHB, MWH1) intensity at the upper and lower 10\% from their nominal levels, for Case-GAL+ICM, and by fixing the metal abundance of the ICM at 0.1 and 0.3, instead of 0.2. We also show these results in Table 8. The systematic errors due to these effects are less than that for the CXB in the 9\,0–12\,0 region.

Since the spectra with azimuthal variations in temperature are focused to fit with a single temperature model, we obtain a relatively large reduced \(\chi^2\), over 1.3 (see Table 2 and Table 8).
A part of the large $\chi^2$ is due to the azimuthal variation in the temperature and normalization at the 2.0–4.0 region: when we set these parameters in the four azimuthal directions free, the $\chi^2$ for this annular region improved to 495 (Table 6) from 680 (Table 4) for all directions. Furthermore, we estimate changes of $\chi^2$ by adding an 8% systematic error in the spectral data points for uncertainty analysis. The minimum reduced $\chi^2 (\chi^2 / \text{d.o.f.})$ improved to 1.081 (2321/2146) in all the directions for Case-GAL+ICM. There was no significant effect on the results of the 6.0–9.0 and 9.0–12.0 regions. In particular, the minimum $\chi^2$ for the 9.0–12.0 region significantly improved from 486 to 412 for 420 bins. Accordingly, the ICM temperature and normalization of this region slightly changed from 2.00$^{+0.54}_{-0.35}$ keV to 2.03$^{+0.66}_{-0.40}$ keV and from 2.23 $\pm$ 0.40 $\times$ 10$^{-20}$ cm$^{-2}$ arcmin$^{-2}$ to 2.19$^{+0.45}_{-0.23} \times$ 10$^{-20}$ cm$^{-2}$ arcmin$^{-2}$, respectively.

We next discuss the influence of Suzaku’s point spread function (PSF). We examined how many of the photons that accumulated in the six annular regions actually came from somewhere else on the sky because of the extended telescope PSF following a procedure described by Sato et al. (2007). Table 9 shows the contribution from each sky region for the 0.5–2 keV energy range. Here, we averaged the values of the three detectors. Although the effect of leakage from the center < 2.0 to the 2.0–4.0 and 4.0–6.0 regions is severe, the temperature and normalization derived in this region agree well with those derived from XMM-Newton (Zhang et al. 2007; Snowden et al. 2008) and Chandra (Bonamente et al. 2013). In the cluster outskirts, outside 6.0, the contributions of the leakage from the central 4.0 region are less than 20%. We fitted the spectra for the 9.0–12.0 region, including the stray light component from the bright central region. Then, we obtained an 8% lower ICM temperature and a 9% smaller normalization. Even if the actual effect of the stray light was twice the current...
calibrations, the changes would be $-14\%$ and $-16\%$ for the temperature and normalization, respectively. These differences are significantly smaller than the present statistical errors. Therefore, the temperature changes due to the PSF correction should be mostly small as in previous *Suzaku* observations of cluster outskirts (George et al. 2009; Reiprich et al. 2009).

Although the temperature profile is a projected one obtained by the two-dimensional spectral analysis, the results of the deprojection fitting do not show any significant difference from the non-deprojection fitting (Bautz et al. 2009; Akamatsu et al. 2011; Walker et al. 2012c).

4. DISCUSSION

*Suzaku* performed four-pointing deep observations of A1835 toward four azimuthal directions (Figure 1). Faint X-ray emission from the ICM out to the virial radius was detected, and enabled us to measure radial profiles of gas temperature, electron density, and entropy. The X-ray observables outside the virial radius, for Case-GAL+ICM, are in good agreement with those extrapolated from the inside, although we cannot distinguish whether the emission comes from the ICM or from relatively hot Galactic emission. We here discuss cluster thermal properties within the virial radius, incorporating weak-lensing mass (Okabe et al. 2010) and gas masses (Okabe et al. 2010a) using the three background cases (Case-GAL+ICM, Case-GAL2, and Case-GAL), and weak-lensing mass. The mass ($M_{\text{H.E.}}$ and $M_{\text{gas}}$) profiles out to 9.0 for the three cases are consistent within statistical errors with each other. $M_{\text{H.E.}}$ outside 8.0 unphysically decreases with increasing radius. This means that the H.E. we assumed is inadequate to describe the ICM in the outskirts. The $M_{\text{H.E.}}$ agrees with $M_{\text{ens}}$ within 1.0–5.0 from the cluster center, but there is a significant difference in the regions $r < 1.0$ and $r > r_{500}$ ≃ 5.85. The H.E. mass is lower than the weak-lensing one outside $r_{500}$ because of the breakdown of the H.E. assumption. The weak-lensing mass inside 1.0, extrapolated from the best-fit model obtained by fitting in the region 1.0 < $r$ < 18.0, is significantly lower than the H.E. mass. As the weak limit of lensing distortion breaks down in this region, the strong lensing method plays an important role in the reconstruction of the mass distribution. Further study of a strong- and weak-lensing joint analysis, as demonstrated by Broadhurst et al. (2005), would be powerful in obtaining the lensing mass distribution for the entire radial range.
Numerical simulations (Kravtsov et al. 2005; Nagai et al. 2007). It is also consistent with the solid line represents the weak-lensing mass, $M_{\text{gas}}$, and the H.E. total mass, $f_{\text{gas}}^{(\text{H.E.})}(< r) = M_{\text{gas}}/M_{\text{H.E.}}$, respectively. Black, red, and green solid lines represent the gas mass fraction, along with the low temperature and entropy in the cluster outskirts, supports the fact that the underestimate in H.E. mass is due to the breakdown of H.E. in the cluster outskirts, rather than due to the gas-clumpiness effect. To balance fully the gravity of the lensing mass, we need additional pressure supports such as turbulent and bulk motions caused by infalling matter at the cluster outskirts. The other possibility is deviations in the electron and bulk motions caused by infalling matter at the cluster center, conflicting with numerical simulations (Kravtsov et al. 2005; Nagai et al. 2007) and showing that the cooling process increases the stellar fraction and, correspondingly, decreases the gas mass fraction. It implies that the lensing mass is underestimated in the central region in which strong lensing data are essential to reconstruct mass distribution. Future study of joint strong- and weak-lensing analysis will allow a detailed examination of the cluster center.

The gas mass fraction derived from X-ray data, $f_{\text{gas}}^{(\text{H.E.})}(< r) = M_{\text{gas}}/M_{\text{H.E.}}$, increases monotonically with increasing radius.

4.1.2. Gas Mass Fraction

We derived the cumulative gas mass fraction within the three-dimensional radius $r$, defined as

$$ f_{\text{gas}}(< r) = \frac{M_{\text{gas}}(< r)}{M_{\text{total}}(< r)}. \quad (5) $$

where $M_{\text{gas}}(< r)$ and $M_{\text{total}}(< r)$ are the gas mass and the gravitational mass (hydrostatic mass $M_{\text{H.E.}}$ or lensing mass $M_{\text{len}}$), respectively.

The gas mass fraction, $f_{\text{gas}}^{(\text{len})}(< r) = M_{\text{gas}}/M_{\text{len}}$, combined with complementary Suzaku X-ray and Subaru/Suprime-Cam weak-lensing data set, is shown in Figure 11. As lensing mass does not require an assumption of H.E., a comparison of results derived solely by joint analysis of X-ray data allows us to understand the ICM states and the systematic measurement bias. We found no significant difference between the three background cases. The gas mass fraction in the range $r_{500} < r < r_{\text{vir}}$ is approximately constant, accounting for ~90% of the cosmic mean baryon fraction, $\Omega_b/\Omega_m$, derived from seven-year data of the Wilkinson Microwave Anisotropy Probe (WMAP 7; Komatsu et al. 2011). It is in good agreement with recent numerical simulations (Kravtsov et al. 2005; Nagai et al. 2007). It is also consistent with $\Omega_b/\Omega_m$ in $r_{\text{vir}}$ within a large error. There is no significant radial dependence of gas mass fraction, contrary to recent statistical studies using lensing and X-ray data set (Mahdavi et al. 2008; Zhang et al. 2010). The best-fit value reaches $\Omega_b/\Omega_m$ at $r \sim 1.1r_{\text{vir}}$ ($r = 130'$). The gas mass fraction in the central region ($r < 1.0$) increases toward the cluster center, conflicting with numerical simulations (Kravtsov et al. 2005; Nagai et al. 2007) and showing that the cooling process increases the stellar fraction and, correspondingly, decreases the gas mass fraction. It implies that the lensing mass is underestimated in the central region in which strong lensing data are essential to reconstruct mass distribution. Future study of joint strong- and weak-lensing analysis will allow a detailed examination of the cluster center.

The gas mass fraction derived from X-ray data, $f_{\text{gas}}^{(\text{H.E.})}(< r) = M_{\text{gas}}/M_{\text{H.E.}}$, increases monotonically with increasing radius.

4.2. Comparison of Temperature Profile with Other Systems

The temperature was measured out to the virial radius $r_{\text{vir}} \sim 2.9$ Mpc, which shows that it decreases from about 8 keV around the center to about 2 keV at $r_{\text{vir}}$. Figure 12 compares azimuthally averaged temperature for Case-GAL+ICM with the fitting function for the outskirts temperature profile derived from numerical simulations (Burns et al. 2010). The fitting function,

$$ \frac{T}{T_{\text{avg}}} = A \left[ 1 + B \left( \frac{r}{r_{200}} \right)^{\beta} \right], \quad (6) $$

is scaled with average temperature and $r_{200}$, and the best-fit values of $A = 1.74 \pm 0.03$, $B = 0.64 \pm 0.10$, and $\beta = 0.25 \pm 0.03$.
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Figure 12. Comparison of the temperature profiles for Case-GAL+ICM and the function by Burns et al. (2010). The profiles are scaled with the average ICM temperature, $\langle kT \rangle$, and $r_{200}$ value derived from Henry et al. (2009) for fair comparison with previous studies. Circles (magenta) and boxes (orange) show our Suzaku result and XMM-Newton result (Zhang et al. 2007), respectively. Errors are the 68% CL uncertainty. The dotted line shows the simulation result of Burns et al. (2010). Two dashed lines show the standard deviation. (A color version of this figure is available in the online journal.)

$\beta = -3.2 \pm 0.4$ are obtained. The temperatures outside 0.3$r_{200}$ agree with those of Burns et al. (2010) within a 1σ error range (dashed lines) and with those of other clusters observed by Suzaku (Burns et al. 2010; Akamatsu et al. 2011). It implies that low temperature ($\sim 0.2\langle kT \rangle$) in cluster outskirts is a common feature. Burns et al. (2010) have shown that the kinetic energy of bulk and turbulent motions is as high as 1.5 times the thermal energy at the virial radius. As reported by recent numerical simulations (e.g., Nagai et al. 2007; Piffaretti & Valdarnini 2008; Jeltema et al. 2008; Lau et al. 2009; Fang et al. 2009; Vazza et al. 2009; Burns et al. 2010), the kinetic pressure in the ICM would contribute to balance the total mass.

4.3. Comparison of Entropy Profile with Other Systems

Sato et al. (2012) compared the entropy profiles with several clusters of galaxies observed with Suzaku. When scaled with average ICM temperature, the entropy profiles for clusters with ICM temperatures above 3 keV are universal irrespective of the ICM temperature. Walker et al. (2012a) confirmed that the function well represents the ICM entropy profiles of several clusters of clusters, in agreement with the entropy profiles obtained by combining Planck, ROSAT, and XMM-Newton. The entropy profile of A1835 also becomes flat beyond 0.5$r_{200}$, contrary to the $r^{1.1}$ relationship expected from the accretion shock heating model (Tozzi & Norman 2001; Ponman et al. 2003; Voit et al. 2005). One possible explanation for the low entropy profiles at cluster outskirts is that kinetic energy accounts for some fraction of energy budget to balance the gravity fully (Bautz et al. 2009; George et al. 2009; Kawaharada et al. 2010; Sato et al. 2012). The flattening of the entropy profile supports the fact that the discrepancy between the $M_{HE}$ and $M_{gas}$ beyond 0.5$r_{vir}$ is caused by the deviation from the H.E.

4.4. Comparison with Planck Stacked SZ Pressure Profile

X-ray emission is proportional to the square of the gas density integrated along the line of sight, and thus it is powerful in a denser region of hot gas. The thermal SZE (Sunyaev & Zeldovich 1972) is proportional to the thermal gas pressure integrated along the line of sight. The SZ observation therefore makes a powerful diagnostic of the less dense gas, as in cluster outskirts. As the sensitivity of the SZE to gas clumping (Nagai & Lau 2011) is a function of the pressure differential of the clumps with the surroundings, X-ray and SZE observables are thus complementary and allow us to further constrain the physics of the ICM. Planck is the only SZ experiment with full sky coverage, able to map even nearby clusters to their outermost radii and offering the possibility of an in-depth statistical study through the combination of many observations (Planck Collaboration et al. 2013). We compare the pressure profile, $P = kTn_e$, using Suzaku observed projected temperature and deprojected electron density for Case-GAL+ICM with that derived from stacked SZ flux for 62 nearby massive clusters from the Planck survey (Planck Collaboration et al. 2013). The results are plotted in Figure 13. Following Planck Collaboration et al. (2013), we normalized the pressure at $r_{500} = 1.39$ Mpc $h^{-1}$, measured by weak-lensing analysis (Okabe et al. 2010a). The thermal pressure at the outskirts measured by Planck agrees with our Suzaku X-ray measurement from 2.0 ($\sim 0.3r_{500}$) to 12.0 ($\sim 2r_{500}$ $\sim r_{vir}$), albeit with different sensitivities of gas density, which indicates the reliability of Suzaku measurements. Walker et al. (2012a) have shown this agreement for other clusters observed by Suzaku. The consistency between independent observables implies that there is no strong need to invoke the gas-clumping effect discussed by Simionescu et al. (2011).

4.5. Comparison of ICM Profiles with A1689

Gravitational lensing masses are available for two clusters, A1835 (Okabe et al. 2010a) and A1689 (Umetsu & Broadhurst 2008), which are among those clusters detected with Suzaku whose X-ray emissions are entirely within the virial radius. Gravitational lensing on background galaxies enables us to directly reconstruct the mass distribution without using any assumptions on the relation between dark matter and baryon
distributions. It is important to compare X-ray observables based on lensing properties in order to understand gas properties. Lensing distortion profiles for the two clusters are well expressed by the universal NFW model (Navarro et al. 1997) but not well expressed by a singular isothermal sphere (SIS) model. The virial masses and halo concentrations for the NFW model are $M_{\text{vir}} = 1.37^{+0.37}_{-0.29} \times 10^{15} M_\odot h^{-1}$ and $c_{\text{vir}} = 3.35^{+0.99}_{-0.79}$ for A1835 (Okabe et al. 2010a) and $M_{\text{vir}} = 1.47^{+0.59}_{-0.33} \times 10^{15} M_\odot h^{-1}$ and $c_{\text{vir}} = 12.7^{+2.9}_{-0.9}$ for A1689 (Umetsu & Broadhurst 2008; Kawaharada et al. 2010), respectively. The virial masses for two clusters are similar, whereas the concentration parameter for A1835 is lower than A1689. Indeed, the Einstein radius determined by strong-lensing analysis (Richard et al. 2010) for A1835 (30''5) is smaller than that for A1689 (47''1) in the case when the source redshift is at $z_s = 2$. It is well established from CDM numerical simulations that the halo concentration is correlated with the halo formation epoch (e.g., Bullock et al. 2001). This is because the central mass density for clusters, corresponding to the concentration, is correlated with those for their progenitors. Therefore, among clusters with similar mass, the age of clusters with higher concentration is likely to be longer (Fujita & Takahara 1999).

If the low thermal pressure and entropy in cluster outskirts discovered by Suzaku (e.g., Kawaharada et al. 2010; Sato et al. 2012; Walker et al. 2012b) are explained by a difference between electron and ion temperatures (e.g., Takizawa 1999), it is statistically expected that the thermalization between electrons and ions through the Coulomb interaction goes on for clusters with high concentration. This is because the thermal equilibration time ($< 1$ Gyr) in cluster outskirts is shorter than their ages, although Wong & Sarazin (2009) have shown that electron and ion temperatures differ by less than a percent within the $r_{\text{vir}}$. As both the virial mass and redshift for the two clusters are similar, they are a good sample for comparing the ICM properties and investigating a dependence of halo concentration.

Figure 14 shows a comparison of temperature, electron number density, and entropy profiles in all directions for A1835 and A1689, where the temperature and entropy are scaled with the average ICM temperature and $(kT)$, and are azimuthally averaged. The scaling radius $r_{\text{vir}}$ is determined by lensing analysis. Dashed (black) and solid (red) diamonds show the profiles of A1689 and A1835, respectively. XMM-Newton results of A1835 by Zhang et al. (2007) are the crosses (orange).

(A color version of this figure is available in the online journal.)

where $p_i(z, \theta')$ is a photometric redshift probability distribution for the $i$th galaxy and $W(\theta)$ is a weight function. The probability function is computed from the best-fit $z_{\text{pho}}$ and error $\sigma_e$, $p(z, \theta') = A \exp[-(\chi - z_{\text{pho}})^2/2/\sigma_e^2]$, ignoring a secondary solution of photometric redshift, where $A$ is the normalization by making the integration from $z = 0$ to $z = \infty$ equal to unity. We apply the Gaussian smoothing function $W(\theta) = 1/(\pi \sigma^2) \exp(-\theta^2/\sigma^2)$ with angular smoothing scale $\theta_s$. We used half the virial radius $\theta_s = 10.0$ (FWHM = 16.7) to reconstruct the two-dimensional map of galaxies. We select bright galaxies with magnitude $r < 22$ in a photometric redshift slice of $|z - z_c| < \delta z = 1.25 (1 + z_c)/c \simeq 0.0125$, where $z_c$ is the cluster redshift, $z$ is a photometric redshift, $\sigma_{e,\max} = 3000$ km s$^{-1}$, and $c$ is the velocity of light. The resultant map is shown in Figure 15. The white circle and boxes represent the virial radius obtained by weak-lensing analysis and the FoVs of the XIS pointings, respectively. A filamentary overdensity region outside the virial radius is apparently found in the eastern and southern regions of the XIS pointings. The broad filamentary structure is elongated out to $\sim 4 r_{\text{vir}}$ in the direction of the southern region. The galaxy number around the virial radius in the eastern region is higher than that in the southern region. The best-fit temperatures in the outermost region for these two regions are higher than those for the other region in Table 6. The northern and western regions with low temperature are in contact with low-density void environments.

![Figure 14. Comparison of temperature (top), deprojected electron number density (middle), and entropy profiles (bottom) between A1689 (Kawaharada et al. 2010) and A1835 (this work, Case-GAL+ICM). The temperature and entropy profiles are scaled with the average ICM temperature and $(kT)$, and are azimuthally averaged. The scaling radius $r_{\text{vir}}$ is determined by lensing analysis. Dashed (black) and solid (red) diamonds show the profiles of A1689 and A1835, respectively. XMM-Newton results of A1835 by Zhang et al. (2007) are the crosses (orange).](image-url)
The correlation between the temperature in cluster outskirts and the large-scale structure outside A1385 is consistent with the result of A1689 (Kawaharada et al. 2010).

In order to investigate more precisely this correlation, we compare the outskirt temperatures for these two clusters with the number density contrast, $\delta = n/\langle n \rangle - 1$, of the large-scale structure, without any smoothing procedures applied in making the map. The number densities $n$ in the azimuthal angles of the FoVs of Suzaku are computed using Equation (7) with $W(\theta) = 1$ and the area normalization. Here, $\langle n \rangle$ is the azimuthally averaged number density. We measure the density contrast in the annulus regions $(1-2)r_{\text{vir}}$ and $(2-4)r_{\text{vir}}$ centered on the brightest cluster galaxy. The photometric redshift slices are calculated using $\sigma_c = 3000$ km s$^{-1}$. The standard errors are estimated using the bootstrap method. We measure the deviation of temperatures, $T/T_{\text{All}} - 1$, with $T_{\text{All}}$ the temperature in all directions. For consistency with the X-ray analysis of A1689 (Kawaharada et al. 2010), we use for A1385 the temperatures measured in $6.0 < r < 12.0$ which is close to $r_{500} \lesssim r \lesssim r_{\text{vir}}$. There is an apparent correlation between the two quantities (Figure 16). In order to quantify this, we computed Spearman’s rank correlation coefficient, $r_s$. The errors are estimated using $10^4$ Monte Carlo redistributions, taking into account the uncertainties. The full data set for two clusters gives $r_s = 0.762 \pm 0.133$ for $(1-2)r_{\text{vir}}$ (Table 10), and the probability of a null hypothesis, $P = 0.028^{+0.007}_{-0.025}$, that there is no relationship between the two data sets. It indicates that the correlation does not occur by chance with more than 90% confidence. The result does not change by choosing a luminosity-weighted center or number-weighted center within the virial radius. We also confirmed the same results using the temperature and entropy in the outermost regions (Table 6). Spearman’s coefficient using the regions of $(2-4)r_{\text{vir}}$ is smaller and the probability of a null hypothesis is more than the significance level of 10%. The correlation with galaxy distribution in the large-scale structure at a distance of 10 Mpc is not statistically strong. We also investigated Spearman’s coefficient for each cluster and could not rule out a null hypothesis, as expected from the low significance level of the temperature anisotropic distribution.

Combining the results of the two clusters, we found that the anisotropic temperature distribution in the cluster outskirts is significantly associated with contacting regions of large-scale structure environment. Further study with a larger sample is of vital importance to obtain more robust result.

5. SUMMARY

We observed A1385 (temperature $\sim 8$ keV) with Suzaku and detected the ICM emission out to the virial radius, $r_{\text{vir}}$ ($\sim 2.9$ Mpc or 120'). Surface brightness profiles and results of the spectral fit need an emission component in addition to those of the CXB and Galactic (LXB+MWH1) beyond $r_{\text{vir}}$. We also investigated Spearman’s rank correlation coefficient for each cluster and could not rule out a null hypothesis, as expected from the low significance level of the temperature anisotropic distribution. Combining the results of the two clusters, we found that the anisotropic temperature distribution in the cluster outskirts is significantly associated with contacting regions of large-scale structure environment. Further study with a larger sample is of vital importance to obtain more robust result.

Notes.

* Spearman’s rank correlation coefficient.
* The probability of a null hypothesis.

| Name          | $(1-2)r_{\text{vir}}$ | $(2-4)r_{\text{vir}}$ |
|---------------|----------------------|----------------------|
|               | $r_s$ | $P$    | $r_s$ | $P$    |
| A1385         | 0.800 ± 0.122 | 0.200 ± 0.122 | 0.600 ± 0.171 | 0.400 ± 0.171 |
| A1689         | 0.800 ± 0.200 | 0.200 ± 0.123 | 0.800 ± 0.200 | 0.200 ± 0.247 |
| Two clusters  | 0.762 ± 0.133 | 0.028$^{+0.007}_{-0.025}$ | 0.571 ± 0.177 | 0.139$^{+0.105}_{-0.106}$ |
agrees well with those of clusters observed with ROSAT (Eckert et al. 2012) at the outskirts (0.65–1.2r200).

3. Within r500, the entropy radial profiles from the XMM-Newton and Suzaku observations follow a power-law form with a fixed index of 1.1 (K \( \propto r^{1.1} \)), as predicted by models of accretion shock heating. In contrast, beyond r500, the entropy profiles become flatter, in disagreement with the r^{1.1} relationship.

4. The H.E. and lensing mass estimates within r500, except within 1/0 from the center, are consistent within errors (Figure 10). The H.E. mass profile unphysically decreases with radius at r \( \gtrsim r_{500} \). Accordingly, the lensing masses are systematically higher than the H.E. masses in the cluster outskirts (\( \gtrsim r_{500} \)). This means that most of the ICM in the cluster outskirts is out of H.E., indicating additional pressure supports such as turbulence, bulk velocity, and/or high ion temperature.

5. The gas mass fraction profile, combined with lensing and gas masses, agrees with \( \sim 90\% \) of the cosmic mean baryon fraction from the WMAP seven-year results (Komatsu et al. 2011), in the range of r_{500} \( \lesssim r \lesssim r_{200} \). In contrast, the H.E.-based gas mass fraction profile, \( f_{\text{gas}}(r) = M_{\text{gas}}/M_{\text{H.E.}} \), continuously increases with radius beyond r_{500}, exceeding the cosmic mean value, as reported in the Perseus cluster (Simionescu et al. 2011). These results indicate that the breakdown of the strict H.E., rather than the gas-clumping effect, is significant in the cluster outskirts.

6. The pressure profile inside the cluster agrees with that derived from stacked SZ flux for 62 nearby massive clusters from the Planck survey and supports the reliability of Suzaku measurements of thermal pressure.

7. We compared our results for A1835 and A1689. These two clusters have different halo concentrations for the NFW mass profiles and the lensing mass profiles, and are thought

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to have different halo formation epochs. The radial profiles of scaled temperature, electron density, and scaled entropy of the two clusters agree well with each other. It implies that the thermalization timescale is much shorter than the difference of ages. Further statistical study with a larger sample would be important to obtain more robust result.

8. The temperatures in the outskirts have azimuthal variation greater than measurement uncertainties, though the significance level is low. The electron density and entropy profile in the south, west, and north are consistent within errors with one another. The temperature and entropy in the east is higher than those in other regions, while the electron density is lower. We investigate the correlation between the temperature in the outskirts ($r_{500} \lesssim r \lesssim r_{vir}$) and the large-scale structure, using Suzaku X-ray and SDSS photometric data for A1835 and A1689. We found using Spearman's rank correlation coefficient a significant correlation with the large-scale structure in $(1-2)r_{vir}$. The hot and cold temperature regions are in contact with filamentary structure and low-density void regions outside the clusters, respectively. The correlation does not occur by chance with more than 90% confidence.

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**APPENDIX A**

**POINT-SOURCE ANALYSIS**

We would like to excise point sources because we are only interested in the ICM. As for the point-source subtraction, we first analyzed the XMM-Newton data (Observation ID=0147330201) in which faint sources were resolved better than the Suzaku data. We detected 12 point sources using the wavelook task of SAS software version 8.0.0 with a detection threshold set to $3r$ and using the surrounding annular region for background subtraction. The source extraction radius is 30 arcmin, and the surrounding background ring in estimating the flux is defined by 30”–60”.

For the individual sources, we carried out spectral fits for the MOS1 and MOS2 spectra simultaneously using the same spectral model pegpowerlaw which gave the photon index and flux in the selected energy band. We fitted spectra in the energy range 2.0–5.0 keV. We show the best-fit parameters for the individual point sources in Table 11. Those fluxes were higher than $2 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in the energy range 2–10 keV.

We also searched for point sources with Suzaku, finding an additional 20 sources outside the XMM-Newton FoV using the CIAO tool wavdetect. We performed spectral fits to all point sources with Suzaku according to the following procedure. As in the case of XMM-Newton, we jointly fitted the XIS0, XIS1, and XIS3 spectra using pegpowerlaw. The source extraction radius is 1.0, and the NXB was subtracted before the fit. We fitted spectra in the energy range 2.0–7.0 keV and excluded the point sources. The fluxes of these sources were higher than $2 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in the energy range 2–10 keV.

**Table 12**

Best-fit Values of the 6’0–9’0 and 9’0–12’0 Regions Fitting in the East

| Case      | $kT$ (keV) | Norm$^a$ | Reduced $\chi^2$ b |
|-----------|------------|----------|---------------------|
| GAL       | 3.27±0.13  | 1.75±0.54 | 1.26 (258/204)      |
| GAL+ICM   | 3.43±0.34  | 2.16±0.52 | 1.24 (253/204)      |
| GAL2      | 4.76±0.04  | 1.74±0.49 | 1.30 (266/204)      |

Notes.

$^a$ Normalization of the apec component scaled with a factor of $\text{SOURCE\_RATIO\_REG}/\Omega_\text{a}$

$\text{Norm} = \frac{\text{SOURCE\_RATIO\_REG}/\Omega_\text{a}}{\int n_e n_\text{H} dV / [\text{d}^2 \text{d} \Omega_\text{a}]} \times 10^{-22}$ cm$^{-2}$, where $D_\text{a}$ is the angular distance to the source.

$^b$ $\chi^2$ of the fit when parameters are tied between the 6’0–9’0 and 9’0–12’0 regions in the east.

In the observation area of A1835 with Suzaku ($\sim$1000 arcmin$^2$), the number of point sources brighter than $2 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ and $1.0 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ expected from deep field observations of XMM-Newton, Chandra, and ASCA (Kushino et al. 2002) are $\sim$30 and $\sim$3, respectively, with $\Gamma = 1.4$. The actual numbers of point sources detected in this study above the two thresholds are 32 and 6 with $\Gamma = 1.4$, respectively, and are consistent with the above expectations when considering the Poisson error.

We excised all point sources detected in either the Suzaku or XMM-Newton observations. Normally, we excluded a region of 1’0 radius but used 2’0 radius for one source (No. 1 in Table 11). Although we excluded circular regions around the point sources, the signals from the brightest point sources are expected to escape from the excluded circular regions of 1’0 radius, since the PSF of Suzaku is $\sim$2’0 in half-power diameter (HPD; Serlemitsos et al. 2007). Therefore, we simulated this residual signal from the brightest point sources (Nos. 1, 2, and 5 in Table 11). Using the derived crude spectra of the four point sources, we simulated the XIS0, XIS1, and XIS3 images using xissim for the observation where each point source is present. We then subtracted the residual signals for all annular spectra before spectral fitting. In order to prevent the deterioration of the statistics, we only considered the residual signals from the four brightest point sources. The A1835 FoV contains two low-mass groups (see, e.g., Bonamente et al. 2013). One was excised in our analysis (No. 21 in Table 11). Another was not because its flux was less than 5% of the ICM flux in the corresponding annulus (6’0–9’0). Consequently, the spectral analysis did not suffer from the emission from these two groups.

**APPENDIX B**

**6’–9’ AND 9’–12’ REGIONS IN THE EAST**

It was difficult to constrain the model parameters in the 9’0–12’0 region in the east because of the influence of bright point sources (see Figure 1). We could neither constrain the 90\% CL upper limit of the temperature nor calculate deprojected electron density for the 9’0–12’0 region in the east (see Tables 6 and 7). Therefore, we fitted the spectra for the 6’0–9’0 and 9’0–12’0 regions in the east and linked the ICM temperature and normalization in these regions. Figure 17 show the results of the spectral fit in the 9’0–12’0 region for the three background cases. The best-fit parameters of the ICM components and $\chi^2$ values in this region are listed in Table 12. The best-fit parameters were consistent within the systematic errors for the two regions.
Figure 17. NXB-subtracted spectra of XIS3 (black crosses) and XIS1 (red crosses) for the 9′9–12′0 region in the east fitted with the ICM model plus the X-ray background model described in Section 3.1. Left, center, and right panels correspond to Case-GAL, Case-GAL+ICM, and Case-GAL2, respectively. The ICM, CXB, LHB, MWH1, and MWH2 emissions for the XIS3 spectra are shown in magenta, blue, orange, green, and cyan lines, respectively. Sum of the CXB, LHB, and MWH1 emissions for the XIS3 spectra are indicated by the green-cyan line. The total model spectra of XIS3 and XIS1 are shown in black and red lines, respectively. The lower panels show the residuals in units of $\sigma$.

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