Suzaku observations of the low surface brightness cluster A76

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ABSTRACT

Aims. We present the results of Suzaku observations of a nearby galaxy cluster, A76 at $z = 0.0395$. This cluster is characterized by extremely low X-ray surface brightness and is hereafter referred to as the LSB cluster. We investigate the nature and thermodynamic evolution of the LSB cluster by studying the physical properties of the hot intracluster medium in A76.

Methods. We conducted two-pointed Suzaku observations of A76 and examined the global gas properties of the cluster by XIS spectral analysis. We also performed deprojection analysis of annular spectra and derived radial profiles of gas temperature, density, and entropy out to approximately 850 kpc ($-0.6r_{200}$) in A76 East and 560 kpc ($-0.4r_{200}$) in A76 West.

Results. The measured global temperature and metal abundance are approximately 3.3 keV and 0.24 solar, respectively. From the deprojection analysis, the entropy profile is found to be flat with respect to radius. The entropy within the central region ($r < 0.2r_{200}$) is exceptionally high ($\sim 400$ keV cm$^2$), a phenomenon that is not readily explained by either gravitational heating or preheating. The X-ray morphology is clumped and irregular, and the electron density is extremely low ($10^{-4} - 10^{-3}$ cm$^{-3}$) for the observed high temperature, suggesting that A76 is in the early phase of cluster formation and that the gas compression due to gravitational potential confinement is lagging behind the gas heating.

Key words. galaxies: clusters: individual: A76 – galaxies: clusters: intracluster medium – X-rays: galaxies: clusters – cosmology: observations

1. Introduction

With the exception of rare dramatic cluster mergers, galaxy clusters feature closely self-similar X-ray surface brightness profiles, with a steep decrease with radius (e.g., Ota & Mitsuda 2004; Croston et al. 2008). A small fraction of clusters (5–10%) exhibit very low surface brightness distribution and highly diffuse X-ray emission, as found, e.g., in cluster samples detected in the ROSAT All-Sky Survey (RASS; Böhringer et al. 2001).

Among representative subsamples of galaxy clusters from the RASS-based REFLEX survey of 33 objects (the REXCESS project; Böhringer et al. 2007), three such LSB clusters have been identified.

A possible interpretation of this characteristic is that the objects are dynamically very young. In most clusters, the core region presumably forms first, and subsequently, a large cluster mass accretes. In contrast, these objects may develop from rarer overdensities, which more closely resemble overdense homogeneous spheres. Such objects would show a nearly homogeneous collapse with a high degree of local clumping.

This scenario can be validated from the entropy distribution of the intracluster medium (ICM) in these cluster systems (e.g., Voit 2005). The three LSB clusters in the REXCESS sample are distinguished by high ($\geq 200$ keV cm$^2$) central entropy. This is puzzling, since the above scenario requires an intermediate stage with high central entropy that must be lowered again for normal cluster formation. Alternatively, we note that the temperature of the LSB clusters is higher than for normal clusters at any given gas density. When a cluster collapses, the deepening of its potential well is manifested by an increase in temperature (which approximately reflects the potential depth). The gas should be simultaneously compressed by potential confinement.

The very high entropy suggests that, by some unknown mechanism, the gas compression is lagging behind the heating of the gas. Alternatively, unexpected heating processes may have boosted the entropy and inflated the ICM in these systems.

To probe the nature of the LSB clusters and test the above scenarios further, we here focus on the extremely LSB galaxy cluster A76, which exhibits irregular morphology. Indeed, the surface brightness of A76 is the lowest among the ROSAT clusters studied in Neumann & Arnaud (1999). The main immediate objective of these studies is to assess the temperature and entropy structure of the clusters using Suzaku satellite data (Mitsuda et al. 2007). The aim is to better understand the formation process and history of these objects.

In this study, the cosmological model is adopted with the matter density $\Omega_M = 0.27$, the cosmological constant $\Omega_{\Lambda} = 0.73$, and the Hubble constant $H_0 = 70$/km/s/Mpc$^{-1}$. At the cluster redshift ($z = 0.0395$), 1 corresponds to 47 kpc. Unless otherwise noted, specified errors indicate the 90% confidence intervals.

2. Observation and data reduction

Two-pointed observations of A76 (in the western and eastern directions) were conducted between 2009 Dec. 18 and 2009 Dec. 19 in the Suzaku AO-4 period. The details of the observations are summarized in Table 1. The XIS instruments consist of four X-ray sensitive CCD cameras: three front-illuminated (XIS-0, −2, −3) and one back-illuminated (XIS-1; Koyama et al. 2007). The XIS-0, −1, and −3 CCD cameras were operated in normal mode with the space charge injection enabled (Uchiyama et al. 2009).

As shown in Fig. 1a, diffuse X-ray emission from the cluster is clearly detected by Suzaku/XIS. The X-ray peak position...
et al. (2011). In brief, the blank-sky data obtained from 93 ks determined by using the same method described in Sakuma local hot bubble (LHB) and the Milky Way halo (MWH) were background (CXB) and the Galactic emissions arising from the other background components, i.e., the cosmic X-ray while other background components, i.e., the cosmic X-ray

The spectral integration regions used in Sects. 3.1 and 3.2 lie within the green boxes and white circles, respectively.

3. Analysis and results

3.1. Global spectra

To measure the average temperature of A76 East and West, we first analyzed the XIS spectra extracted from two 18’ × 18’ square regions (solid boxes in Fig. 1). The observed 0.5–8 keV spectra of three sensors (XIS-0, XIS-1, and XIS-3) were simultaneously fitted to the APEC thermal plasma model (Smith et al. 2001). The redshift and Galactic hydrogen column density were fixed at $z = 0.0395$ and $N_H = 3.4 \times 10^{20}$ cm$^{-2}$ (LAB survey; Kalberla et al. 2005). For metal abundance, the tables in Anders & Grevesse (1989) were used. The $\chi^2$ fitting was performed using XSPEC version 12.7. The XIS spectra are given in Fig. 2 and model parameters in Table 3. In both regions, the temperature and metal abundance are $kT \sim 3$ keV and $Z \sim 0.24$ solar with fractional errors of 4–5% and 17–35%, respectively.

A simultaneous APEC-model fit to the A76 East and West spectra yields a global temperature $kT$ of $3.3 \pm 0.1$ keV ($\chi^2$/d.o.f. = 662/569). From the relationship given in Table 2

Table 1. Log of Suzaku observations of A76.

| Target   | Obs ID       | Date       | Coordinatesa | Exposureb |
|----------|--------------|------------|--------------|-----------|
| A76 East | 804087010    | 2009 Dec. 18 | 00:40:32.0 06:50:14.6 | 23 640    |
| A76 West | 804088010    | 2009 Dec. 18 | 00:39:36.7 06:50:16.8 | 15 130    |

Notes. (a) Pointing coordinates in J2000. (b) Net exposure time after data filtering.
To derive the radial temperature profile, we extracted spectra from 3′-wide concentric rings; 0′−3′, 3′−6′, 6′−9′, 9′−12′, 12′−15′, and 15′−18′, as shown in Fig. 1. Because the X-ray image is asymmetric, the data from A76 East and West were separately analyzed. Note that the 6th ring (15′−18′) is beyond the range of A76 West and is used only in A76 East. The XIS-0, 1, 3 spectra of each ring were then simultaneously fitted to the APEC model in the same manner as that mentioned in Sect. 3.1. The spectra of the innermost ring (0′−3′) were derived from the A76 West data alone, since the A76 East data cover only half of the area. In the spectra of the outer rings (15′−18′ in A76 East and 12′−15′ in A76 West), the metal abundance was fixed at its mean value (0.24 solar) because of large statistical uncertainty.

By summing the flux from all rings within r < 18′, the absorption-corrected flux and luminosity within r < 0.6r200 in the 0.5–8 keV are estimated to be 1.8 × 10^{-13} erg s^{-1} cm^{-2} and 6.7 × 10^{43} erg s^{-1}, respectively. The bolometric luminosity of the cluster is 8.2 × 10^{43} erg s^{-1} (r < 0.6r200), approximately 1/3 of the luminosity expected from the observed temperature and luminosity-temperature relationships of nearby clusters (e.g., Pratt et al. 2009).

3.3. Deprojection analysis

To further derive the three-dimensional structure of the gas density and entropy in the cluster, we performed a deprojection analysis by assuming spherical symmetry of the cluster gas distribution. Since the X-ray morphology of A76 is clearly irregular, this assumption introduces a systematic uncertainty into the analysis, which is examined below.

The APEC model corrected for the Galactic absorption was fitted to each radial bin, assuming that a metal abundance is related to the Galactic absorption. The results of spectral fitting for A76 East and West are shown in Fig. 3 and Table 5. The spectra of 12′ < r < 15′ were excluded from the analysis of A76 West because of poor statistics, which prevented convergence of model fit to the data. We confirmed that inclusion or exclusion of these outer spectra does not significantly affect the spectral parameters obtained for the remaining regions. In addition, since the uncertainty in the fitted temperature is large in the region 6′ < r < 9′, the temperature of that region is linked to that of the inner region (3′ < r < 6′).

The derived temperature profile is shown in Fig. 4a. The radius is normalized by r200, and the electron density is calculated from the APEC normalization factor \( \int n_e n_H dV/(4\pi(1+z)^2 D_L^2) \times 10^{-13} \text{cm}^{-5} \), where \( n_e = 1.2n_H \) (see Fig. 4b). The measured central electron density is approximately 10^{-3} cm^{-3}, the lowest among the known nearby clusters (Croston et al. 2008)
The gas entropy, defined as $S = k T n_{e}^{-2/3}$ (Voit 2005), is evaluated from the above quantities within $0.6 r_{200} - 0.4 r_{200}$ for A76 East/West (Fig. 4c). The entropy profile is found to be flat for $r < 0.2 r_{200}$ though large scatter occurs at larger radii. A very high entropy of $\sim 400$ keV cm$^2$ is revealed at the cluster center.

As discussed in Sect. 4, the entropy at the cluster center is of particular interest. Therefore, to check the robustness of the entropy measurement, we consider possible systematic errors due to the following three items: (i) the uniform X-ray surface brightness assumption; (ii) the background model; and (iii) the effect of the XRT’s point spread function (PSF). To assess the impact of (i), we repeated the spectral analysis using arf files created by assuming a uniform cluster surface brightness instead of the observed XMM-Newton image. Although the analysis increased the statistical uncertainty in the central entropy, the result agrees with the results listed in Table 6. For (ii), the impact of background uncertainty mentioned in Sect. 2 was examined by intentionally changing the background intensity by $\pm 10\%$. We find that this does not significantly influence the results. In assessing the effects of (iii), the width of the annular regions were made larger than the typical PSF of the Suzaku XRT ($\sim 2^\prime$) to avoid significant photon mixing between adjacent regions. The xissim raytracing simulations (conducted as described in Sato et al. 2007) confirmed that the PSF effect is as weak as $\sim 20\%$ (in terms of fraction of photons or spectral normalization factor). Accordingly, the systematic error in the central entropy is estimated to be approximately $10\%$, which is smaller than the statistical uncertainty.

### 4. Discussion

The temperature, gas density, and entropy profiles derived from Suzaku data were well constrained out to $0.6 r_{200}$ and $0.4 r_{200}$ in the A76 East and West directions, respectively. In this section, the entropy profile of A76 is compared with those of nearby clusters.

### Table 4. APEC model parameters for the annular regions in A76 East and West.

| Region | $kT$ [keV] | $Z$ [solar] | Norm | $\chi^2$/d.o.f. | $kT$ [keV] | $Z$ [solar] | Norm | $\chi^2$/d.o.f. |
|--------|------------|-------------|------|----------------|------------|-------------|------|----------------|
| $0' < r < 3'$ | $-$ | $-$ | $-$ | $-$ | $3.56 \pm 0.30$ | $0.28 \pm 0.15$ | $2.13 \pm 0.17$ | $71/78$ |
| $3' < r < 6'$ | $3.32 \pm 0.25$ | $0.21 \pm 0.10$ | $3.55 \pm 0.25 \times 10^{-3}$ | $96/120$ | $3.55 \pm 0.37$ | $0.28 \pm 0.15$ | $4.08 \pm 0.13 \times 10^{-3}$ | $80/70$ |
| $6' < r < 9'$ | $3.57 \pm 0.25$ | $0.18 \pm 0.09$ | $3.04 \pm 0.18 \times 10^{-3}$ | $15/155$ | $2.64 \pm 0.27$ | $0.26 \pm 0.19$ | $6.88 \pm 0.10 \times 10^{-3}$ | $60/64$ |
| $9' < r < 12'$ | $3.55 \pm 0.21$ | $0.19 \pm 0.11$ | $3.12 \pm 0.21 \times 10^{-3}$ | $140/127$ | $2.60 \pm 0.44$ | $0.33 \pm 0.22$ | $5.34 \pm 1.09 \times 10^{-3}$ | $31/36$ |
| $12' < r < 15'$ | $3.66 \pm 0.21$ | $0.31 \pm 0.22$ | $3.95 \pm 0.32 \times 10^{-3}$ | $90/82$ | $7.1 \pm 2.19$ | $0.24(\text{fix})$ | $1.87 \pm 0.42 \times 10^{-3}$ | $7/8$ |
| $15' < r < 18'$ | $2.79 \pm 0.35$ | $0.24(\text{fix})$ | $1.95 \pm 0.21 \times 10^{-3}$ | $53/45$ | $-$ | $-$ | $-$ | $-$ |

### Table 5. APEC model parameters obtained from the deprojection analysis of A76 East and West data.

| Region | $kT$ [keV] | $Z$ [solar] | Norm | $\chi^2$/d.o.f. | $kT$ [keV] | $Z$ [solar] | Norm | $\chi^2$/d.o.f. |
|--------|------------|-------------|------|----------------|------------|-------------|------|----------------|
| $0' < r < 3'$ | $4.04 \pm 1.14$ | $0.15 \pm 0.03$ | $8.99 \pm 0.08 \times 10^{-3}$ | $630/610$ | $3.99 \pm 1.28$ | $0.25 \pm 0.09$ | $7.05 \pm 0.90 \times 10^{-4}$ | $299/255$ |
| $3' < r < 6'$ | $3.00 \pm 0.40$ | $2.61 \pm 0.19$ | $2.22 \pm 0.17 \times 10^{-3}$ | $4.00 \pm 0.73$ | $0.59 \pm 0.99$ | $0.59 \pm 0.59$ | $5.70 \pm 6.05 \times 10^{-3}$ | $6/6$ |
| $6' < r < 9'$ | $4.37 \pm 0.65$ | $2.55 \pm 0.04 \times 10^{-3}$ | $2.30 \pm 0.34$ | $0.25 \pm 0.25$ | $1.12 \pm 0.15 \times 10^{-2}$ | $-$ | $-$ | $-$ |
| $9' < r < 12'$ | $1.67 \pm 0.35$ | $2.55 \pm 0.04 \times 10^{-3}$ | $4.66 \pm 0.04 \times 10^{-3}$ | $-$ | $-$ | $-$ | $-$ | $-$ |
| $12' < r < 15'$ | $6.76 \pm 1.36$ | $5.40 \pm 0.04 \times 10^{-3}$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ |
| $15' < r < 18'$ | $2.52 \pm 0.47$ | $5.40 \pm 0.04 \times 10^{-3}$ | $-$ | $-$ | $-$ | $-$ | $-$ | $-$ |

**Notes:**

- $0' < r < 3'$ spectra taken from the A76 West pointing were used in the deprojection analysis.
- Linked to the value for $3' < r < 6'$.
Fig. 4. a) Temperature; b) electron density; and c) entropy profiles derived from the deprojection analysis. The results for A76 East and West data are shown as red and blue crosses (the markers for A76 West are shifted horizontally by 5% for clarity). In panel c), the dashed line represents the baseline entropy profile, $S \propto r^{-1}$ (Voit et al. 2005).

4.1. Comparison of A76 entropy profile with those of other clusters

Pratt et al. (2010) derived the entropy profiles of the REXCESS sample from XMM-Newton data. Comparing our results with theirs (Fig. 5a), we find that A76 exhibits one of the highest entropies at $r \leq 100$ kpc. Comparison with other nearby clusters observed by Suzaku (for review, see Reiprich et al. 2013) yields similar results. On the other hand, the entropy increase at larger radii follows the overall trend of the REXCESS sample though the A76 data show significant scatter.

For a more quantitative analysis of the central entropy, Fig. 5b plots the mean gas temperature of the A76 East and West data (Table 3) and the entropy at $r < 3' \sim 0.1r_{200}$ on the $S - T$ plane. The mean $S - T$ relations at two different radii, $0.1r_{200}$ and $0.2r_{200}$, derived from ten morphologically relaxed clusters using XMM-Newton are also plotted (Pratt et al. 2006). This figure clearly shows that the central entropy in A76 is significantly higher than expected for the same temperature at $0.1r_{200}$.

4.2. Comparison with the baseline profile and possibility of preheating and AGN feedback

Voit et al. (2005) conducted simulations on gravitational heating and report that the radial gas entropy profile in clusters tends to follow a power law, $S(r) = 550$ keV cm$^2$/$(T_{200}/1$ keV)$^{1.1}$, which can be used as a baseline for assessing the impact of nongravitational processes in the ICM. Figure 4c compares the observed A76 profile with the baseline profile calculated for $K_{200} = 3.3$ keV. At $0.1r_{200}$, the observed entropy (~400 keV cm$^2$) is two times more than expected from gravitational heating alone (150 keV cm$^2$).

Nongravitational heating is a plausible mechanism, particularly in smaller systems such as groups of galaxies. According to Ponman et al. (2003), excess entropy is on the order of 140 keV cm$^2$. On the basis of Chandra analysis of 21 groups and 19 clusters, Wang et al. (2010) suggest that the entropy excess $\Delta K_0$ correlates with the K-band luminosity $L_K$ of the central dominating galaxies in the systems and is attributable to AGN feedback. Utilizing the K-band luminosity log($L_K$/L$\odot$) = 11.5 for IC 1568 and the relationship shown by Wang et al. (2010) $\Delta K_0 \propto L_1.6^0$, the entropy excess is estimated as $\Delta K_0 \sim 1$ keV cm$^2$. Therefore, the AGN feedback, as well as preheating, is an unlikely cause of the high-entropy generation in A76.

4.3. Implication for the origin of high entropy in A76

In Sect. 3, the gas properties were mainly derived from the radially averaged spectra. The X-ray image, however, reveals an inhomogeneous gas distribution. This suggests that the cluster is at an early stage in its formation. The lowest gas density at a relatively high temperature of 3–4 keV indicates that gas compression due to gravitational potential confinement is lagging behind the gas heating. Given the low electron density of $10^{-5}$–$10^{-3}$ cm$^{-3}$, the timescale of radiative cooling is significantly longer than the Hubble time across the cluster. At such a high central entropy level, the evolution of the gas in the deepening potential should be chiefly adiabatic. In this scenario, the entropy would remain unusually high even if the cluster existed in a relaxed state, a phenomenon not observed in other relaxed clusters. This discrepancy may be an artifact if the gas in the central region is heavily clumped. Low-entropy clumps in the high-entropy region could settle at the center as the cluster relaxes. As shown in the XMM-Newton image of Fig. 1, the ICM indeed appears clumpy, with small denser regions particularly common in the halos of several galaxies. This ICM could segregate to the center and form a lower entropy core during cluster relaxation.

A clumpy substructure is particularly apparent in the southeastern region of the cluster (hereafter, referred to as the SE blob). From the XIS spectra of the $r = 5/5$ circular region enclosing the SE blob (Fig. 1), $kT$ is obtained as 3.2 ± 0.2 keV. The density and entropy are estimated as $n_e = (7.1 \pm 0.3) \times 10^{-3}$ cm$^{-3}$ and $S = 397 \pm 32$ keV cm$^2$, assuming that the emission comes from a uniform sphere of radius $r = 5'.5$. Both temperature and density are significantly high within the same radial range (0.3–0.5)r$_{200}$ in A76 East (Fig. 4), resulting in entropy
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Table 6. Gas density and entropy in A76 East and West.

| Region         | A76 East       | A76 West       |
|----------------|----------------|----------------|
|                | \( n_{\text{H}_0} \) [cm\(^{-3}\)] | \( S \) [keV cm\(^2\)] | \( n_{\text{H}_0} \) [cm\(^{-3}\)] | \( S \) [keV cm\(^2\)] |
| 0' < r < 3'    | \( 1.03 \pm 0.05 \) \times 10\(^{-2}\) | 395 \pm 89       | \( 9.11 \pm 0.58 \) \times 10\(^{-4}\) | 423 \pm 116       |
| 3' < r < 6'    | \( 6.63 \pm 0.23 \) \times 10\(^{-4}\) | 394 \pm 52       | \( 5.65 \pm 0.28 \) \times 10\(^{-4}\) | 585 \pm 98\(^a\)  |
| 6' < r < 9'    | \( 3.71 \pm 0.15 \) \times 10\(^{-4}\) | 866 \pm 161      | \( 5.85 \pm 0.29 \) \times 10\(^{-4}\) | 324 \pm 43        |
| 9' < r < 12'   | \( 2.85 \pm 0.19 \) \times 10\(^{-4}\) | 385 \pm 80       |                           |                  |
| 12' < r < 15'  | \( 3.00 \pm 0.13 \) \times 10\(^{-4}\) | 1508 \pm 373     |                           |                  |
| 15' < r < 18'  | \( 2.65 \pm 0.12 \) \times 10\(^{-4}\) | 611 \pm 103      |                           |                  |

Notes. \(^{a}\) Values obtained from region 3' < r < 9' in A76 West.

5. Summary

We have performed X-ray spectral analysis of the LSB cluster A76, which is characterized by extremely low X-ray surface brightness. We constructed the profiles of gas temperature, density, entropy from the Suzaku satellite data, and out to large radii (0.6\(r_{200}\) in A76 East and 0.4\(r_{200}\) in A76 West data) for the first time. The central gas entropy (∼400 keV cm\(^2\)) is one of the highest among the known nearby clusters and significantly higher than what is predicted from the mean \( S \) – \( T \) relationship. Given that the gas density is extremely low for the observed high temperature of 3–4 keV, and because the gas distribution in the cluster is irregular and clumpy, we suggest that A76 is at an early stage of cluster formation and that gas compression caused by potential confinement is lagging behind the gas heating. Currently A76 is the only LSB cluster to be analyzed using Suzaku data. To further clarify the nature of LSB clusters and their thermodynamic evolution, we consider that many more galaxy clusters must be sampled and analyzed.

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