Suzaku Observation of the Radio Halo Cluster Abell 2319: 
Gas Dynamics and Hard X-Ray Properties

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Abstract

We present the results of a Suzaku observation of the radio halo cluster Abell 2319 (A 2319). The metal abundance in the central cool region is found to be higher than the surrounding region, which was not resolved in former studies. We confirm that the line-of-sight velocities of the intracluster medium in the observed region are consistent with those of the member galaxies of the entire A 2319 and A 2319A subgroup for the first time, though no velocity difference within the region has been detected. On the other hand, we have not found any signs of gas motion relevant to the A 2319B subgroup. Hard X-ray emission from the cluster has clearly been detected, but its spectrum is likely to be thermal. Assuming a simple single-temperature model for the thermal component, we find that the upper limit of the non-thermal inverse Compton component becomes $2.6 \times 10^{-11}\, \text{erg s}^{-1}\, \text{cm}^{-2}$ in the 10–40 keV band, which means that the lower limit of the magnetic field is $0.19\, \mu\text{G}$ with a radio spectral index of 0.92. Although the results slightly depend on the detailed spectral modeling, it is robust that the upper limit of the power-law component flux and lower limit of the magnetic field strength become $3 \times 10^{-11}\, \text{erg s}^{-1}\, \text{cm}^{-2}$ and $0.2\, \mu\text{G}$, respectively. Considering the lack of a significant amount of very hot ($\sim 20\, \text{keV}$) gas and the strong bulk flow motion, it is more likely that the relativistic non-thermal electrons responsible for the radio halo are accelerated through intracluster turbulence rather than shocks.

Key words: galaxies: clusters: individual (Abell 2319) — magnetic fields — X-rays: galaxies: clusters

1. Introduction

Diffuse non-thermal synchrotron radio emission is found in a significant fraction of galaxy clusters (Giovannini & Feretti 2000; Kempner & Sarazin 2001), which indicates that there exist both relativistic electrons and a magnetic field as well as the thermal intracluster medium (ICM) in intracluster space. Some of such diffuse radio sources are located near the center, and cover the cluster entirely, which are called “radio halos”. Others are located at the periphery, and are called “radio relics”.

Although the origin of these non-thermal electrons is still unclear, some connections of radio halos and relics with dynamical motion of ICM have been reported. For example, they are rarely found in cool core clusters (Giovannini et al. 1999). The radio luminosity has a strong correlation with the X-ray luminosity and the ICM temperature (Liang et al. 2000). In addition, Buote (2001) has shown a correlation of the radio power with an asymmetry of the X-ray image.

It is likely that such non-thermal electrons are accelerated via shocks (Sarazin 1999; Takizawa & Naito 2000; Totani & Kitayama 2000; Miniati et al. 2001; Ryu et al. 2003; Takizawa 2002; Inoue et al. 2005) and/or turbulence (Roland 1981; Schlickeiser et al. 1987; Blasi 2000; Ohno et al. 2002; Fujita et al. 2003; Brunetti et al. 2004) in the ICM associated with cluster mergers. The magnetic field plays a crucial role in these acceleration processes. However, it is not so easy to determine cluster magnetic field strength and structures in an observational way. Faraday rotation measure observations of polarized radio sources in and/or behind clusters are often used for this purpose (Clarke et al. 2001; Vogt & Enßlin 2003; Govoni et al. 2006). However, the results strongly depend on the magnetic-field structures, themselves. Moreover, it can be applied for very limited regions where we have suitable polarized radio sources by chance, though this will be possibly resolved by using cosmic microwave background (CMB) as polarized sources (Ohno et al. 2003; Takizawa 2008). Therefore, it is very important to estimate the magnetic-field strength through another independent method.

GeV electrons in radio halos and relics are expected to emit non-thermal hard X-rays via an inverse Compton process of CMB photons. Comparing the synchrotron radio flux and inverse Compton hard X-ray flux (or its upper limit), we are able to estimate a volume-averaged magnetic field strength (or its lower limit). However, it is very difficult to detect such components, because of a large amount of thermal emission from the ICM. Although many efforts have been made to detect the non-thermal inverse Compton component from clusters of galaxies, the situation is still unclear. For example, the detection of non-thermal hard X-rays from the Coma cluster...
was reported from the Beppo-SAX PDS (Fusco-Femiano et al. 1999, 2005) and RXTE (Rephaeli et al. 1999; Rephaeli & Gruber 2002) data, but their reliability is still controversial (Rossetti & Molendi 2004; Fusco-Femiano et al. 2007). Recently, in addition, Wik et al. (2009) have shown a lower limit that conflicts with the former detection reports through a combined analysis of Suzaku and XMM. Therefore, firm detection or reliable upper limits of non-thermal components in the hard X-ray regime are highly desired by independent instruments.

Abell 2319 (A 2319) is one of the most well-known examples of merging clusters with a giant radio halo. Two subgroups, A 2319A and A 2319B, are recognized in the radial-velocity distribution of the member galaxies, which suggests that the merger axis is nearly along the line-of-sight and that the velocity difference between them is almost 3000 km s\(^{-1}\) (Oegerle et al. 1995). Markovitch (1996) has studied temperature structures on a relatively large scale, and has found that the temperature in the region corresponding to A 2319B is lower. Chandra observations revealed inhomogeneous temperature structures and a cold front in the central region, and showed that the position of the X-ray center is different from that of the cD galaxy (O’Hara et al. 2004; Govoni et al. 2004). Thus, it is obvious that the cluster is not dynamically relaxed. A 2319 has a giant radio halo, and the radio and thermal X-ray distributions are quite similar to each other (Feretti et al. 1997; Govoni et al. 2001). Observations in the hard X-ray band were performed by Beppo-SAX (Molendi et al. 1999), RXTE (Gruber & Rephaeli 2002), and Swift-BAT (Ajello et al. 2009), none of which reported any firm detection of non-thermal components.

The Hard X-ray Detector (HXD) aboard Suzaku (Mitsuda et al. 2007) is superior for investigating hard X-ray properties of galaxy clusters, because of its low detector background and narrow field of view (Kokubun et al. 2007; Takahashi et al. 2007). Indeed, an improved constraint for non-thermal components has been obtained for several clusters (Fujita et al. 2008; Kawano et al. 2009; Nakazawa et al. 2009; Wik et al. 2009), and very hot components (~20 keV) were found in RX J1347.5–1145 (Ota et al. 2008) and A 3667 (Nakazawa et al. 2009). In addition, the high spectral resolution of the X-ray Imaging Spectrometer (XIS: Koyama et al. 2007) aboard Suzaku makes it possible to constrain the bulk flow motion of the ICM, which is likely to be relevant to the particle-acceleration processes (Ota et al. 2007; Fujita et al. 2008).

In this paper, we present a Suzaku observation of the Abell 2319 cluster to investigate the dynamical status of the ICM and hard X-ray properties, which enable us to understand particle-acceleration processes and the origin of the radio halo. Canonical cosmological parameters of \(H_0 = 70\) Mpc\(^{-1}\) km s\(^{-1}\), \(\Omega_0 = 0.3\), and \(\lambda_0 = 0.7\) are used in this paper. Because the cluster mean redshift is \(z = 0.0557\), 1\(\circ\) corresponds to 62 kpc. Unless otherwise stated, all uncertainties are given at the 90\% confidence level.

The rest of this paper is organized as follows. In section 2 we describe the observation and data reduction. In section 3 we present spectral analysis results. In section 4 we discuss the results and their implications. In section 5 we summarize the results.

2. Observation and Data Reduction

We observed the central region of Abell 2319 with Suzaku on 2006 October 27–30 for an exposure time of 100 ks. The field of view (FOV) of Suzaku XIS, and that of HXD PIN in which the throughput of the fine-collimator becomes 50\% are shown in a ROSAT PSPC image (figure 1). An approximate position of the A 2319B subgroup is also shown. The observation was performed at HXD nominal pointing. As a result, most of the A 2319B is not within the XIS FOV. The XIS was operated in the normal full-frame clocking mode. The edit mode was 3 \times 3 and 5 \times 5, and we used combined data of both modes. Half of the 64 PINs of the HXD were operated at a nominal bias voltage of 500 V, and the others were at 400 V. All data were processed with Suzaku pipeline processing, version 2.0.6.13. We employed calibration data files (20081009). The XIS data were processed through standard criteria as follows. Events with a GRADE of 0, 2, 3, 4, 6 and STATUS with 0.524287 were extracted. We excluded data obtained at the South Atlantic Anomaly (SAA), within 436 s after the passage of SAA, and at low elevation angles from an Earth rim of < 5° and a Sun-lit Earth rim of < 20°. As a result, the effective exposure time was 99.5 ks for XIS. Non-X-ray background (NXB) spectra and images of XIS were generated using the tool “xisnxbgen” (Tawa et al. 2008). Figure 2 represents a 0.5–8.0 keV XIS image combined from those of the front-illuminated (FI) CCDs (XIS0, XIS2, XIS3). The images were corrected for exposure and vignetting effects after subtracting NXB, and smoothed by a Gaussian kernel with \(\sigma = 0.3\).

**Fig. 1.** ROSAT PSPC image of Abell 2319 overlaid with the field of view of Suzaku XIS CCDs (blue), and that of HXD PIN (magenta) in which the throughput of the fine-collimator becomes 50\%. An approximate position of the subgroup A 2319B is also represented by a dotted yellow circle. Image is shown in log scale, in counts s\(^{-1}\) pixel\(^{-1}\) (15 \times 15 arcsec\(^2\)).
The HXD data were also processed in a standard way. We excluded data obtained at SAA, within 500 s after the passage of SAA, within 180 s before entering SAA, at low elevation angles from an Earth rim of $<5\degree$, and at the location where the Cut-Off-Rigidity (COR) was lower than 6 GV. The resultant effective exposure time was 94.0 ks. As the NXB of the PIN, we used a public NXB model provided by the HXD team on the Suzaku website. The version of the model is “METHOD=LCFITDT”, or “tuned” (Fukazawa et al. 2009). The CXB level was estimated in the same way as Nakazawa et al. (2009) from the Lockman hole observation (Suzaku observation ID, 101002010). The detailed procedure is described in appendix 2 of Nakazawa et al. (2009). We defined the photon flux model as $N(E) = 8.7 \times 10^{-4} \times E^{-1.29} \times \exp(-E/40.0)$ in photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ FOV$^{-1}$, where $E$ is the photon energy in keV.

3. Spectral Analysis

For a spectral analysis of the XIS data, rmf and arf files were generated using the ftool “xisrmfgen” and “xissimarfgen”, respectively. The ROSAT PSPC image of A 2319 was used to make arf files, considering that the XIS FOV does not cover the cluster ICM emission entirely, and that Suzaku has only moderate spatial resolution. The cluster ICM emission in the XIS FOV is so bright that the background components from astrophysical origin, such as the CXB and Galactic diffuse components, are safely negligible.

We used an rmf file provided by the HXD team in the CALDB for PIN spectral analysis. A PIN arf file was made in the same way of Nakazawa et al. (2009); we calculated it by convolving the point-source arf while assuming that the spatial distribution of the emission is the same as that of the ROSAT PSPC image. A detailed description is given in subsection 2.4 of Nakazawa et al. (2009).

3.1. Temperature and Abundance Structures

Temperature and abundance structures can provide us with basic and crucial information about the ICM dynamics and its origin. To explore this, we divided the region observed with XIS into 15 regions presented in figure 3, and performed spectral analysis for each region. The sizes of the divided region were $3' \times 3'$ and $6' \times 6'$ for the cluster center and surrounding regions, respectively. FI CCD spectra and related response files for each region were summed, and FI and back-illuminated (BI) CCD spectra were fitted simultaneously. For the spectral fitting, we used the energy bands 0.6–10.0 keV and 0.6–8.0 keV for XIS FI and BI, respectively, though the energy band near the Si edge (1.7–1.9 keV) was ignored so as to avoid uncalibrated structures. Each spectrum was fitted by the photo-absorbed single-temperature APEC model ($W_{\text{ABS}} \times \text{APEC}$), assuming that $N_{\text{H}} = 7.93 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990) and that redshift $= 0.0557$ (Struble & Rood 1999). The fitting results are presented in table 1. In general, each data were fitted well with the above-mentioned model. Figures 4 and 5 show the resultant temperature and metal abundance for the regions presented in figure 3, respectively. The south–east of the X-ray center (regions 2, 3, and 4) tend to have a lower temperature and a higher abundance.

In order to confirm this trend of temperature and metal abundance distribution, we determined the X-ray spectra in annuli, whose center was located at the X-ray peak (RA, Dec) = (290°3000, +43°9458). The details of the spectral fitting procedure were similar in the two-dimensional analysis presented above. Figures 6 and 7 show the radial (not deprojected) profiles of the temperature and abundance, respectively.
Table 1. Best fit parameters for the XIS spectra of the regions presented in figure 3.

| Region | \( kT \) (keV) | \( Z / Z_\odot \) | \( \chi^2 / \text{d.o.f.} \) |
|--------|---------------|----------------|------------------|
| 1      | 11.5\( \pm 0.4 \) | 0.27\( \pm 0.04 \) | 977.3/892 |
| 2      | 9.7\( \pm 0.3 \)   | 0.31\( \pm 0.02 \) | 1540.0/1389     |
| 3      | 9.6\( \pm 0.3 \)   | 0.28\( \pm 0.03 \) | 967.9/982       |
| 4      | 9.6\( \pm 0.3 \)   | 0.29\( \pm 0.03 \) | 1198.3/1132     |
| 5      | 10.1\( \pm 0.3 \)  | 0.34\( \pm 0.02 \) | 1775.7/1610     |
| 6      | 10.5\( \pm 0.3 \)  | 0.24\( \pm 0.03 \) | 1117.3/990      |
| 7      | 11.7\( \pm 0.3 \)  | 0.23\( \pm 0.03 \) | 1162.3/1079     |
| 8      | 10.1\( \pm 0.3 \)  | 0.23\( \pm 0.03 \) | 953.6/902       |
| 9      | 11.1\( \pm 0.3 \)  | 0.25\( \pm 0.03 \) | 1219.0/1127     |
| 10     | 10.1\( \pm 0.3 \)  | 0.24\( \pm 0.03 \) | 1012.3/934      |
| 11     | 10.4\( \pm 0.3 \)  | 0.23\( \pm 0.05 \) | 501.3/449       |
| 12     | 10.4\( \pm 0.3 \)  | 0.16\( \pm 0.05 \) | 420.2/445       |
| 13     | 8.7\( \pm 0.3 \)   | 0.20\( \pm 0.06 \) | 283.0/282       |
| 14     | 8.9\( \pm 0.3 \)   | 0.21\( \pm 0.04 \) | 623.1/551       |
| 15     | 9.7\( \pm 0.3 \)   | 0.21\( \pm 0.07 \) | 362.8/251       |

Fig. 4. Temperature for the regions presented in figure 3.

It is clear that the ICM in the central regions has a lower temperature and a higher abundance.

3.2. Line-of-Sight Velocities of the ICM

Line-of-sight velocities of the ICM contain more direct information about the cluster dynamics than X-ray surface brightness and temperature structures. In general, however, more photons are necessary to determine the center of the Doppler-shifted lines with meaningful accuracy through a spectral fit of the XIS data than to determine the temperature and metal abundance, which means that we have to use larger regions. Thus, we divided the XIS FOV into the 11 regions shown in figure 8, and performed a spectral analysis for each region. The sizes of the regions were \( 3'' \times 3'' \) and \( 6'' \times 9'' \) for the central regions (from 1 to 6) and the outer parts (from 7 to 11), respectively. In order to determine the ICM line-of-sight velocities, we mainly used a Doppler-shifted He-like Fe K\( \alpha \) line (6.679 keV) and an H-like Fe K\( \alpha \) line (6.964 keV). Therefore, if the ICM motion is \( \sim 1000 \, \text{km s}^{-1} \), we have to resolve the...
energy shift of only $\sim 22$ eV. This is a challenging task considering that the energy resolution of XIS is 130 eV (FWHM).

To measure the energy scale of XIS accurately, we made a gain correction in a similar way as Fujita et al. (2008) with Mn Kα lines of the calibration sources on each XIS sensor. We obtained spectra of the calibration source region for each XIS sensor, and fit them with APEC plus two Gaussians, assuming that the abundance and redshift of APEC were equal to zero. A gain correction factor was defined as

$$ f_{\text{gain}} = \frac{E_{\text{fit}}(\text{Mn} - K\alpha)}{E_0(\text{Mn} - K\alpha)} $$

where $E_{\text{fit}}(\text{Mn} - K\alpha)$ and $E_0(\text{Mn} - K\alpha)$ are the energy values obtained from the fitting results and the expected one (5.895 keV), respectively. We evaluated the gain correction factor, $f_{\text{gain}}$, for each XIS sensor. Typically, we found $|f_{\text{gain}} - 1|$ to be $\sim 0.0005$, which corresponds to $\sim 150$ km s$^{-1}$. Then, the corrected redshift became

$$ z_{\text{cor}} = f_{\text{gain}}(z_{\text{fit}} + 1) - 1, $$

where $z_{\text{cor}}$ and $z_{\text{fit}}$ are the corrected redshift and that obtained from the fitting results, respectively.

Although the above-mentioned correction is obviously valid for regions near the calibration sources, the gain could depend upon the position on the same CCD chip, owing to the charge transfer inefficiency (CTI). As for this, an accuracy of 0.2% was reported over the CCD chips before spaced-row charge injection (SCI) was adopted (Ota et al. 2007). H. Matsumoto et al. (2007)$^1$ reported that CTI was almost zero just after the SCI was adopted. Since our observation was held at a timing very near to that of this report, we conclude that the systematic errors of the energy scale because of CTI are estimated to be 0.2%, which corresponds to $\sim 600$ km s$^{-1}$.

We fit the spectra of each XIS sensor with the APEC model in the energy band of 5.0–10.0 keV. The resultant values of $z_{\text{fit}}$ were corrected into $z_{\text{cor}}$ using equation (2), which were converted into line-of-sight velocities. We then calculated the arithmetic means of the results of all four XIS sensors.

Figure 9 shows line-of-sight velocities of the ICM for the regions presented in figure 8, where the red, green, and blue solid lines represent the mean line-of-sight velocities of the member galaxies for the entire A 2319, A 2319A subgroup, and A 2319B subgroup, respectively. The error bars stand for only statistical ones. Basically, the obtained ICM velocities lie between those of the entire A 2319 and A 2319A. No significant velocity difference was detected within the observed region. Taking account of the systematic errors because of CTI, we confirmed that the observed ICM velocities are consistent with those of the entire A 2319 and A 2319A subgroup, and did not find any signs of ICM motion associated with the A 2319B subgroup in the observed region.

As mentioned before, a cold front was found in the south–east of the X-ray center by Chandra observations (O’Hara et al. 2004; Govoni et al. 2004). In addition, we found that the region in the north–west of the cold front has lower temperature and higher abundance. This may mean that there exits a cold core that originated from a subcluster that infell in the past. Therefore, it is possible that the ICM in this region has a negligible relative velocity to the surrounding ICM. In order to examine this, we analyzed the spectra of the regions presented in figure 10, and measured the line-of-sight velocities in a similar way. The results are shown in figure 11. Again, no significant velocity difference was detected. The obtained ICM velocities lie between those of the entire A 2319 and A 2319A. It is also clear that there are no signs of ICM motion related to the A 2319B subgroup. The size of Region 1 in figure 10 is approximately $3' \times 5.5'$. Taking account of the
X-ray telescope response, we estimate that ~30% of photons detected in Region 1 originated from Region 2, and less than 10%, vice versa, respectively. Therefore, this contamination does not significantly affect our results.

3.3. Hard X-Ray Properties and Constraint of Non-Thermal Components

The PIN spectrum of this observation is shown in figure 12, where black, red, and green crosses represent the data, the NXB model, and the residual signals (data − NXB), respectively. A typical CXB model spectrum is also indicated by blue crosses. Hard X-ray emission from A 2319 was clearly detected in the energy region below ~40 keV. Therefore, we use the PIN spectrum in the energy band of 13.0–40.0 keV hereafter. We also checked the GSO spectrum and confirmed that the data are consistent with NXB. Thus, we do not use them.

First, we fit the PIN spectrum alone with the APEC or power-law model in the energy range of 13.0–40.0 keV. The metal abundance and redshift in the APEC model were fixed to be 0.3 and 0.0557, respectively, because it is very difficult to determine these parameters with only PIN data. The results of the fit are presented in table 2. It is obvious that the spectrum is better represented by a thermal APEC model than a non-thermal power-law one. The temperature determined from the PIN spectrum is similar to the values given in figure 4 determined from the XIS data.

Second, we performed a joint spectral analysis of PIN and XIS to investigate the hard X-ray properties. It should be noted that soft X-ray spectral information is essential to constrain the spectral components characteristic in the hard X-ray band, such as non-thermal power-law and/or very hot thermal ones. We used the XIS spectrum in the energy bands of 2.0–10.0 keV and 2.0–8.0 keV for FI and BI CCDs, respectively. The FI CCD spectra and associated response files were summed, and the FI, BI, and PIN spectra were fitted simultaneously. Systematic errors between XIS and PIN normalizations were taken into account properly.

We tried to fit the XIS + PIN spectra in a similar way, but for using XIS spectrum also below 2 keV. The fitting results were not acceptable if we adopted common $N_{\text{H}}$ for FI and BI CCDs, because significant residuals inconsistent between FI and BI CCDs were found in the soft band. We then tried to fit the spectra for each XIS sensor and PIN simultaneously, allowing that each XIS sensor has a different $N_{\text{H}}$ value. This improved the fitting results significantly. We suspect that this is possibly because the contamination correction of arf files is not very good in the case of regions as large as almost the entire XIS FOV, though we have no definitive idea about this problem at present. In addition, it is possible that this

![Fig. 10. Regions used in measuring the line-of-sight velocity around the cold front in figure 11.](image)

![Fig. 11. Same as figure 9, but for the regions presented in figure 10.](image)

![Fig. 12. PIN spectrum of this observation. Black, red, and green crosses show the spectrum of the data, NXB model, and residual signals (data − NXB), respectively. A typical CXB model spectrum is also indicated by blue crosses.](image)

| Model | $\Gamma$ or $kT$(keV) | $\chi^2$/d.o.f. |
|-------|-----------------------|-----------------|
| PL    | $3.1^{+0.1}_{-0.1}$   | 81.7/69         |
| $kT$  | $10.9^{+0.9}_{-0.9}$   | 67.7/69         |
kind of systematic error becomes apparent because the spectra have sufficiently good statistics. The difference of $N_{\text{H}}$ among four XIS sensors is typically $\sim 1-3 \times 10^{20}$ cm$^{-2}$, which is so small that it does not seriously affect the results of the spectral fit above 2.0 keV. Thus, we decided not to use XIS spectra below 2.0 keV so as to avoid this unsolved issue.

Since we are interested in both non-thermal inverse Compton and very hot components, the spectral models used here were a single-temperature APEC model ($kT$), a single-temperature APEC plus power-law model ($kT + \text{PL}$), a two-temperature APEC model ($2kT$), and a two-temperature APEC plus power-law model ($2kT + \text{PL}$). Again, we fixed both $N_{\text{H}} = 7.93 \times 10^{20}$ cm$^{-2}$ and a redshift of 0.0557, as in subsection 3.1. In the $2kT$ and $2kT + \text{PL}$ models, a relative normalization ratio between two APEC models was allowed not to be common between XIS and PIN, so as to compensate for any small ($\sim 10\%$) uncertainty in the arf generation. It is very difficult to constrain the power-law components in the XIS energy range because of a dominant presence of thermal emission, which could degrade the HXD fitting results. In order to avoid this, thus, a relative normalization ratio between APEC and the power-law models was also allowed not to be common between XIS and PIN. A photon index of the power-law component was also fixed, while assuming that it was emitted via an inverse Compton process of CMB from the same electron population that radiates the synchrotron radio region. Considering that the typical magnetic field strength of intracluster space is $\sim \mu$G, electrons that radiate inverse Compton hard X-rays of 20–40 keV emit relatively low-frequency synchrotron radio waves. We adopted 1.92 or 2.4 as the photon index of the power-law component, because 0.92 (408–610 MHz) and 1.4 (26–610 MHz) are reported to be the radio spectral index (Erickson et al. 1978; Harris & Miley 1978; Feretti et al. 1997).

Figures 13, 14, and 15 show the spectral fit results for the $kT$, $2kT$, and $kT + \text{PL}$ model with a photon index of 1.92, respectively. The best fit parameters of the $kT$ and $2kT$ models are listed in table 3. Although the reduced chi square is slightly improved in the $2kT$ model, the $kT$ model gives us sufficiently acceptable results. Thus, it is possible that there can be a little very hot component ($\sim 16$ keV), but it does not have to exist. The detailed fitting results of the $kT + \text{PL}$ and $2kT + \text{PL}$ models are also presented in tables 4 and 5, respectively. Clearly, adding a power-law component does not improve the fitting results significantly in both the $kT$ and $2kT$ models.

Our spectral modeling for the thermal components is somewhat too simple, considering that Chandra observations (O’Hara et al. 2004; Govoni et al. 2004) showed multi-temperature structures with a certain temperature range. In general, if multi-temperature spectra are forced to be fitted with a simple $kT + \text{PL}$ model, the power-law component tends to be overestimated. Thus, the derived upper limit of the power-law component can be regarded as being a relatively conservative one. In the case of $2kT$ modeling, on the other hand, the situation could be more complicated. The higher energy part of the spectra can be represented by both higher temperature and/or power-law components. It is not trivial how this increase in the degree of freedom of the model affects the actual fitting results.
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### Table 3. Best-fit parameters of the $1kT$ and $2kT$ models for the XIS and PIN spectrum.

| | $1kT$ | $2kT$ |
|---|---|---|
| $kT_{\text{low}}$ (keV) | $9.7^{+0.1}_{-0.1}$ | $6.5^{+0.5}_{-0.1}$ |
| $kT_{\text{high}}$ (keV) | $-1.0$ | $-1.0$ |
| $Z(Z_{\odot})$ | $0.26^{+0.01}_{-0.01}$ | $0.28^{+0.01}_{-0.01}$ |
| $N_{\text{low,XIS}}^{*}$ | $0.17^{+0.00}_{-0.00}$ | $8.5^{+1.1}_{-1.0} \times 10^{-2}$ |
| $N_{\text{low,PIN}}^{*}$ | $0.18^{+0.01}_{-0.01}$ | $0.14^{+0.04}_{-0.04}$ |
| $N_{\text{high,XIS}}^{*}$ | — | $9.2^{+1.1}_{-1.2} \times 10^{-2}$ |
| $N_{\text{high,PIN}}^{*}$ | — | $6.4^{+1.3}_{-1.3} \times 10^{-2}$ |
| $\chi^2/d.o.f.$ | 3215.6/2978 | 3136.6/2975 |

* Normalization in the apixe code, for the low and high temperature component, in each instrument.

### Table 4. Same as table 3, but for the $1kT + PL$ models, where the photon index of the power low component is fixed to 1.92 or 2.4.

| | $1kT + PL$ (1.92) | $1kT + PL$ (2.4) |
|---|---|---|
| $kT_{\text{low}}$ (keV) | $9.7^{+0.1}_{-0.1}$ | $9.7^{+0.1}_{-0.1}$ |
| $Z(Z_{\odot})$ | $0.26^{+0.01}_{-0.01}$ | $0.26^{+0.01}_{-0.01}$ |
| $N_{\text{low,XIS}}^{*}$ | $0.17^{+0.00}_{-0.00}$ | $0.17^{+0.00}_{-0.00}$ |
| $N_{\text{low,PIN}}^{*}$ | $0.16^{+0.02}_{-0.02}$ | $0.15^{+0.02}_{-0.02}$ |
| $\Gamma_{PL}$ | 1.92(fixed) | 2.4(fixed) |
| $N_{PL,XIS}$ | $0.0^{+0.7}_{-0.0} \times 10^{-3}$ | $0.0^{+0.3}_{-0.0} \times 10^{-3}$ |
| $N_{PL,PIN}$ | $3.8^{+2.8}_{-2.8} \times 10^{-3}$ | $2.2^{+1.5}_{-1.5} \times 10^{-2}$ |
| $\chi^2/d.o.f.$ | 3210.9/2976 | 3211.2/2976 |

In order to constrain an upper limit of a non-thermal power-law component, not only statistical errors, but also systematic errors of both CXB and NXB have to be taken into account properly. It is well-known that the CXB fluctuations can be modeled with $\sigma_{\text{CXB}}/I_{\text{CXB}} \propto \Omega_{e}^{-0.85} S_{e}^{-0.25}$, where $\Omega_{e}$ and $S_{e}$ are the effective solid angle and upper cutoff flux of a point source, respectively. From the HEAO-1 A2 results, $\sigma_{\text{CXB}}/I_{\text{CXB}} = 2.8\%$ with $\Omega_{e} = 15.8$ deg$^2$ and $S_{e} = 8 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ (Shafer 1983). Considering a rough estimate of the NXB uncertainties of PIN ($\sim 5 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$), we adopt a conservative upper cutoff flux, $S_{e} \sim 8 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$. Thus, the CXB fluctuation in the HXD PIN FOV is expected to be 18% at the 90% confidence level because of $\Omega_{e} = 0.32$ deg$^2$. Fukazawa et al. (2009) reported that the reproducibility of blank-sky observations separated into 10 ks exposures gave a distribution of 5.7% at the 90% confidence level, where the contribution from the statistical error of typically 3.3% or larger and the effect of CXB fluctuation (1.3% of the total background) were included. This means that the NXB systematic uncertainty is 4.5% (= $\sqrt{(5.7)^2 - (3.3)^2 - (1.3)^2}$) at the 90% confidence level.

In a joint spectrum analysis of PIN and XIS, the NXB and CXB components fluctuated at the 90% confidence level of the systematic uncertainty mentioned-above (4.5% and 18% for NXB and CXB, respectively). This caused changes of the best-fit parameters in the fits, and gave us systematic errors.

### Table 5. Same as table 4, but for the $2kT + PL$ models.

| | $2kT + PL$ (1.92) | $2kT + PL$ (2.4) |
|---|---|---|
| $kT_{\text{low}}$ (keV) | $6.5^{+0.3}_{-0.6}$ | $6.5^{+0.3}_{-0.6}$ |
| $kT_{\text{high}}$ (keV) | $15.7^{+0.9}_{-1.1}$ | $15.7^{+0.9}_{-1.1}$ |
| $Z(Z_{\odot})$ | $0.28^{+0.01}_{-0.01}$ | $0.28^{+0.01}_{-0.01}$ |
| $N_{\text{low,XIS}}^{*}$ | $8.6^{+1.1}_{-1.1} \times 10^{-2}$ | $8.6^{+1.1}_{-1.1} \times 10^{-2}$ |
| $N_{\text{low,PIN}}$ | $0.15^{+0.04}_{-0.04}$ | $0.15^{+0.04}_{-0.04}$ |
| $N_{\text{high,XIS}}^{*}$ | $9.2^{+1.2}_{-1.2} \times 10^{-2}$ | $9.2^{+1.2}_{-1.2} \times 10^{-2}$ |
| $N_{\text{high,PIN}}$ | $6.3^{+1.5}_{-2.5} \times 10^{-2}$ | $6.3^{+1.5}_{-2.5} \times 10^{-2}$ |
| $\Gamma_{PL}$ | 1.92(fixed) | 2.4(fixed) |
| $N_{PL,XIS}$ | $0.0^{+0.4}_{-0.0} \times 10^{-3}$ | $0.0^{+0.3}_{-0.0} \times 10^{-4}$ |
| $N_{PL,PIN}$ | $0.0^{+1.3}_{-0.0} \times 10^{-2}$ | $0.0^{+3.3}_{-0.0} \times 10^{-2}$ |
| $\chi^2/d.o.f.$ | 3136.7/2973 | 3136.7/2973 |

### Table 6. Flux of a power-law component in 10–40keV with statistical and systematic errors and its upper limit at the 90% confidence level for each model.

| Model | Flux (erg s$^{-1}$ cm$^{-2}$) | Upper limit (erg s$^{-1}$ cm$^{-2}$) |
|---|---|---|
| $1kT + PL$ (1.92) | $1.1^{+0.8+1.3}_{-0.8-1.1} \times 10^{-11}$ | $<2.6 \times 10^{-11}$ |
| $1kT + PL$ (2.4) | $1.5^{+1.2+1.9}_{-1.2-2.1} \times 10^{-11}$ | $<3.8 \times 10^{-11}$ |
| $2kT + PL$ (1.92) | $0.0^{+3.7+2.2}_{-0.0-0.0} \times 10^{-11}$ | $<4.3 \times 10^{-11}$ |
| $2kT + PL$ (2.4) | $0.0^{+2.2+3.9}_{-0.0-0.0} \times 10^{-11}$ | $<4.5 \times 10^{-11}$ |

Including both the statistical errors and the systematic ones of CXB and NXB, we derived an upper limit of the power-law component in 10–40 keV at the 90% confidence level for each model. The results are presented in table 6, where the former and latter errors of the flux are statistical and systematic ones, respectively. Although the results slightly depend on spectral modeling, all models give us an upper limit of $\sim 3 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$.

### 4. Discussion

#### 4.1. Temperature and Abundance Structures

Complex temperature structures were obtained in the central region of Abell 2319 by Chandra observations (O’Hara et al. 2004; Govoni et al. 2004). Basically, our results are consistent with theirs, though the FOVs of both observations are not perfectly overlapped with each other. There are high-temperature regions north–east of the X-ray center (region 1 and 7 in figure 3), and regions north–west of the cold front (region 2, 3, and 4 in figure 3) have lower temperatures. However, very high-temperature ($\sim 15$ keV) components in the Chandra data were not found in our two-dimensional spectral analysis of the XIS data alone. On the other hand, the $2kT$ model fitted to the XIS + PIN spectrum showed a strong 15 keV component, but this is likely to be an artifact from introducing a strong 6.5 keV component for a cluster with an average temperature of 9.7 keV. Since a spectral fit with only HXD prefers a temperature of less than 11.8 keV, and the
XIS + PIN wide-band spectrum is well fitted by a 9.7 keV single-temperature thermal model, we conclude that there is no strong evidence of a bright very hot component, as high as 15 keV in the Suzaku data. It should be noted that a temperature determination of a very hot gas with a temperature more than 10 keV is difficult for Chandra CCD without any sensitivity above 10 keV. It is also possible that our two-dimensional XIS results are significantly spatially smoothed because of the moderate spatial resolution of Suzaku.

Markevitch (1996) studied a larger scale temperature structure of A 2319 with ASCA. It revealed that the A 2319B region and the outer parts of the cluster have lower temperatures, which are without FOV of XIS, but partly within that of PIN. Our wide-band spectral analysis of the 2kT model shows that a relative ratio of normalizations between two APEC models in XIS and PIN is significantly different from each other. This results tell us that the lower temperature gas is more dominant in the PIN spectrum than XIS, which is not surprising and naturally expected from the above-mentioned ASCA results.

Our two-dimensional and projected radial spectrum analysis shows that the metal abundance in the central cool region is clearly higher than that in the surrounding region (see figures 5 and 7). Molendi et al. (1999) performed a similar analysis with Beppo-SAX, and showed that the metal abundance distribution is consistent with the homogeneous one within the statistical errors. Because of the large effective area and high sensitivity of XIS, the metal abundance inhomogeneity in A 2319 was clearly detected for the first time with Suzaku.

### 4.2. Bulk Flow Motion in the ICM

As written before, though no significant line-of-sight velocity difference within the observed region was detected, we found that their values are consistent with those of the entire A 2319 and A 2319A subgroup for the first time. In figure 9, the largest velocity difference is seen between region 4 and 8, which provides us with the value $940^{+1083}_{-1131}$ km s$^{-1}$. The sound velocity of 10 keV ICM is $\sim 1700$ km s$^{-1}$. Thus, it is probable that the internal motion of the ICM in the observed region is subsonic, though possibly it is close to the sound velocity. On the other hand, the difference between the observed region and A 2319B is nearly 3000 km s$^{-1}$. This means that a supersonic ICM collision is expected if the ICM associated with A 2319B has a velocity similar to that of the A 2319B member galaxies. Another possibility is that the A 2319B group is not gravitationally bound to A 2319, but located along the line-of-sight by chance. Please note that this possibility is not negligible from an orbital motion analysis with a two-body model in Oegerle et al. (1995).

### 4.3. Constraint of the Nonthermal Emission and Magnetic Field Strength

Let us constrain the magnetic field strength from the combined analysis of the radio synchrotron flux and an inverse Compton hard X-ray upper limit (Rybicki & Lightman 1979). The typical energy, $h\nu$, of photons scattered via inverse Compton processes by electrons with energy $y\sqrt{kT}$ is $h\nu \sim 4y^2h\nu/3$, where $h\nu$ is the photon energy before scattering. With the typical CMB photon energy ($h\nu \approx 2.3 \times 10^{-4}$ eV), the range of the electron’s relativistic Lorentz factor corresponding to the 10–40 keV inverse Compton hard X-rays becomes $3.3 \times 10^7 < y^2 < 1.3 \times 10^8$. On the other hand, a typical synchrotron radio frequency (or, a critical frequency) emitted by electrons with magnetic field strength $B$ is $(\nu_r/\text{MHz}) \approx 3.3y^2(B/\text{G})$, where a homogeneous pitch angle distribution is assumed. Therefore, the typical synchrotron radio frequency range emitted by the electrons in the above-mentioned energy range becomes $1.1 \times 10^8(B/\text{G}) < (\nu_r/\text{MHz}) < 4.3 \times 10^8(B/\text{G})$. It is reported that the radio flux of the A 2319 halo is 1.0 Jy at 610 MHz, and that its spectral index is 0.92 (408–610 MHz) or 1.4 (26–610 MHz) (Harris & Miley 1978; Feretti et al. 1997). Thus, the radio flux corresponding to the energy range of 10–40 keV inverse Compton hard X-rays has values as listed in table 7 for each spectral index, with a monochromatic approximation for a single electron’s spectrum and on the assumption of a single power-law electron energy distribution.

The flux of the inverse Compton scattering of CMB photons and synchrotron radiation from the same electron population has the following relationship:

$$\frac{F_{\text{IC}}}{F_{\text{syn}}} = \frac{U_{\text{CMB}}}{U_{\text{mag}}} = \frac{U_{\text{CMB}}}{B^2/(8\pi)},$$

where $U_{\text{CMB}}$ and $U_{\text{mag}}$ are the energy density of CMB photons and the magnetic field, respectively. With $U_{\text{CMB}} = 5.2 \times 10^{-15}$ erg cm$^{-3}$ at $z = 0.0557$ and the values in tables 6 and 7, the lower limit of the magnetic field strength for each model is obtained as in table 8. Although the detailed results slightly depend on the spectral modeling, basically the field strength tends to be more than $\sim 0.2 \mu G$.

A 2319 was observed by Beppo-SAX PDS in the hard X-ray band (Molendi et al. 1999). The obtained upper-limit flux of the power-law component in the energy band of 13–50 keV is $2.3 \times 10^{-11}$ or $2.0 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$, depending on the adopted radio spectral index of 0.92 (408–610 MHz) or 2.2 (610–1420 MHz), respectively. Different radio spectral indices were used, because the PDS results rely on a higher energy band than PIN. When these results are compared with ours, however, it should be noted that the Crab’s 20–80 keV flux derived from Beppo-SAX PDS is 21% smaller than that derived from Suzaku. Thus, the above-mentioned Beppo-SAX

### Table 7. Radio flux in the energy band corresponding to the 10–40 keV inverse Compton component.

| Photon index | Radio flux ($F_{\text{sync}}$) |
|--------------|-------------------------------|
|              | ($\text{erg s}^{-1}\text{cm}^{-2}$) |
| 1.92         | $2.3 \times 10^{-12}(B/\text{G})^{-0.08}$ |
| 2.4          | $5.1 \times 10^{-16}(B/\text{G})^{-0.4}$ |

### Table 8. Lower limit of the magnetic field strength for each model.

| Model          | $B$ (\mu G) |
|----------------|-------------|
| $1kT + \text{PL} (1.92)$ | $> 0.19$ |
| $1kT + \text{PL} (2.4)$  | $> 0.27$ |
| $2kT + \text{PL} (1.92)$ | $> 0.14$ |
| $2kT + \text{PL} (2.4)$  | $> 0.25$ |
results can be converted into Suzaku-equivalent fluxes of 2.9 \times 10^{-11} or 2.5 \times 10^{-11} \text{erg s}^{-1} \text{cm}^{-2} for a radio spectral index of 0.92 or 2.2, respectively. These results seem to be similar to our results for the \(kT + PL\) (1.92) model at first glance. However, we must note that HXD PIN FOV is much narrower than Beppo-SAX PDS, which is preferable in order to avoid contamination sources, but large enough to cover the A 2319 radio halo entirely.

Recently, Ajello et al. (2009) studied the hard X-ray properties of 10 galaxy clusters including Abell 2319 using Swift-BAT. The obtained upper limit of the power-law component in the energy band of 10–40 keV is 2.9 \times 10^{-12} or 1.7 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2} with a radio spectral index of 0.92 through Swift-BAT alone or the Swift-BAT + XMM-Newton analysis, respectively. Here, their original values at the 3\sigma confidence level in the energy band of 50–100 keV are converted into those at the 90% confidence level in the 10–40 keV band. Considering that A 2319 has a relatively high temperature (\sim 10 \text{keV}) and that Swift-BAT, with its long exposure, has better sensitivity in the higher energy band (\sim 100 keV) than Suzaku PIN, it is not so surprising that their results give a tighter constraint. Suzaku is superior for determining the thermal properties, thanks to its high sensitivity at around 20–40 keV. We note that their power-law “upper-limit” is quite low, much less than those inferred from the sensitivity. Their sensitivity plot shows \sim 1 \text{mCrab}, or \sim 1.6 \times 10^{-11} at 10–40 keV, as a 3-sigma sensitivity, or even worse above 100 keV. Thus, Swift-BAT is presenting \sim 2 or less \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2} upper-limit using a detector with a 90% confidence sensitivity of \sim 7 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2}. This is of course allowed in some cases, especially when the photon statistics favor a negative flux. In any case, our results, independently obtained, are consistent with theirs. We would also like to point out that the Swift alone analysis lacks soft X-ray spectral information which is important to determine the thermal component precisely, and that generally speaking cross-calibration between detectors aboard different satellites (such as XMM and BAT) is not so easy.

As we wrote before, ASCA results (Markevitch 1996) suggest that there is a lower temperature (\sim 8 \text{keV}) ICM in the outer region without XIS, but within PIN FOV, though this is not clear in Beppo-SAX results (Molendi et al. 1999). The existence of this cold ICM could affect any estimation of the upper limit of the power-law component. To evaluate this, we obtained the spectra while assuming that the outer region \(r \geq 10\) has 8 keV, and performed a joint spectrum analysis of XIS and PIN in a similar way as in subsection 3.3. The resultant flux of the power-law component in 10–40 keV increases by 10.4 \times 10^{-12} and 9.9 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2} for the \(kT + PL\) models with photon indices of 1.92 and 2.4, respectively. These values are smaller than both the statistical errors and those induced by background uncertainty, as listed in table 6. This effect should affect the Beppo-SAX PDS results as well.

### 4.4. Energy Budget of the Intracluster Space

From the observed results, we can obtain information about the energy densities of the thermal ICM, non-thermal electrons, and magnetic field in the intracluster space of A 2319, which are basic and important parameters for the cluster structure and evolution. For simplicity, we assume that the radio halo region is a sphere with a radius of 0.66 Mpc. With \(\beta\)-model parameters obtained by ROSAT (Trévese et al. 2000) and \(kT = 10 \text{keV}\), the energy density of the thermal ICM becomes \(U_{th} = 4 \times 10^{-6} \text{erg cm}^{-3}\). From the upper limit of an inverse Compton component of the \(kT + PL\) (1.92) model in table 6, we obtained the energy density of the relativistic electrons corresponding to 10–40 keV hard X-rays (or, \(5.7 \times 10^{-5} < y < 1.1 \times 10^{-4}\)) \(U_e < 2 \times 10^{-2} \text{eV cm}^{-3}\). Therefore, \(U_e/ U_{th} < 5 \times 10^{-3}\), though in this calculation we did not consider the contribution from relatively low-energy electrons, which could be dominant in the energy density of the non-thermal electron populations. With the lower limit of the magnetic field for the \(kT + PL\) (1.92) model in table 8, the energy density of the magnetic field becomes \(U_{mag} \geq 1 \times 10^{-3} \text{eV cm}^{-3}\), which means \(U_{mag}/U_{th} > 3 \times 10^{-5}\).

### 4.5. Particle Acceleration Scenario

In this subsection, let us discuss a particle-acceleration scenario of A 2319 implied by the XIS and HXD results mentioned above. The XIS results tell us two important points, as follows. First, the central cool region associated with the cold front has a higher metal abundance, which suggests that this might be an old remnant of a subcluster’s cool core that infell in the past. Second, the ICM velocity difference in the observed region is probably subsonic, which means that no definitive shocks are expected there. This is also supported by the fact that there is not a significant very hot component from the XIS + HXD analysis. On the other hand, the existence of subsonic turbulence (\(\Delta v \sim 500 \text{km s}^{-1}\)) can be allowed. Therefore, it is more likely that non-thermal electrons relevant to the radio halo of A 2319 are accelerated by intracluster turbulence rather than the shocks. The turbulence is probably excited by past merger activity, which is also responsible for the cold front and central cool core with a higher abundance. This picture is also consistent with the fact that numerical simulations show that turbulence motion is developed in the late phase of mergers (Takizawa 2005). Our discussion on the energy budget presented in the previous subsection shows that the magnetic-field energy density is likely to be much less than the hydrodynamical turbulence, which means that the magnetic turbulence can be easily excited (Roettiger et al. 1999; Asai et al. 2007; Takizawa 2008). Although a collision between subgroups A 2319A and A 2319B is likely to be supersonic, it does not seem to form sufficiently strong shocks to excite any radio halo activity. It is probable that they are not so close to each other such that sufficiently strong shocks would occur.

### 4.6. Future Prospects

We obtained only an upper limit of the ICM line-of-sight velocity difference. To resolve the intracluster turbulence (\(\Delta v \sim 500 \text{km s}^{-1}\)), a different type of X-ray spectrometer than CCD is highly desired. The ASTRO-H satellite (Takahashi et al. 2006), which is planned to be launched around 2013, will enable us to measure the line-of-sight velocity directly with X-ray microcalorimeters, and to provide us with useful information on the dynamical status of the ICM. ASTRO-H is also planned to have hard X-ray mirrors and an imager, which will enable us to obtain hard X-ray images at very high
sensitivity. This will give us very important clues to understand where and how the particle-acceleration processes occur in intracluster space.

5. Conclusions

We observed the central region of Abell 2319 with Suzaku. From an XIS analysis, we found that the central cool region north–west of the cold front has a higher metal abundance than the surrounding region for the first time. We measured the line-of-sight velocities of the ICM with XIS, and found that the velocity difference is less than \( \sim 2000 \, \text{km s}^{-1} \), which means that the ICM motion is probably subsonic. In addition, we showed that the velocities in the observed region are consistent with those of the entire A 2319 and A 2319A subgroup for the first time. No signs of ICM motion related to the A 2319B subgroup were found. If the ICM associated with the A 2319B subgroup has a similar velocity of A 2319B member galaxies, a supersonic collision is expected in the ICM. From an XIS + HXD wide-band spectral analysis, we searched for very hot and non-thermal inverse Compton components.

There can be a small amount of the very hot (\( \sim 16 \, \text{keV} \)) component, but it does not have to exist. No significant inverse-Compton component has been detected, and we derived its upper limit for several spectral models. Typically, it becomes \( < 3 \times 10^{-11} \, \text{erg s}^{-1} \, \text{cm}^{-2} \), which is consistent with the recent Swift-BAT results. Comparing the synchrotron radio flux and upper limit of the inverse Compton one, we obtained the lower limit of the magnetic field strength, \( B > 0.2 \, \mu \text{G} \), though the results slightly depend upon the spectral modeling. Taking into account the lack of the supersonic ICM motion, and a very hot component, we conclude that the relativistic electrons responsible for the radio halo of the Abell 2319 are more likely to be accelerated by the turbulence rather than shocks.

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