X-ray study of extended emission around M86 observed with Suzaku

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Abstract

We analyzed the Suzaku data of M86 and its adjacent regions to study the extended emission around it. The M86 core, the plume, and the tail extending toward the northwest were clearly detected, as well as the extended halo around them. From the position angle $\sim 45^\circ$ to $\sim 275^\circ$, the surface brightness distribution of the core and the extended halo was represented relatively well with a single $\beta$-model of $\beta \sim 0.5$ up to $15^\prime$–$20^\prime$. The X-ray spectra of the core was represented with a two-temperature model of $kT \sim 0.9$ keV and $\sim 0.6$ keV. The temperatures of the core and the halo have a positive gradient in the center, and reach the maximum of $kT \sim 1.0$ keV at $r \sim 7^\prime$, indicating that the halo gas is located in a larger scale potential structure than that of the galaxy. The temperatures of the plume and the tail were $0.86 \pm 0.01$ keV and $1.00 \pm 0.01$ keV. We succeeded in determining the abundances of $\alpha$-element separately, for the core, the plume, the tail, and the halo for the first time. Abundance ratios with respect to Fe were consistent with the solar ratios everywhere, except for Ne. The abundance of Fe was $\sim 0.7$ in the core and in the plume, while that in the tail was $\sim 1.0$, but the difference was not significant considering the uncertainties of the ICM. The abundance of the halo was almost the same up to $r \sim 10^\prime$, and then it becomes significantly smaller $(0.2–0.3)$ at $r > 10^\prime$, indicating the gas with low metal abundance still remains in the outer halo. From the surface brightness distribution, we estimated the gas mass ($\sim 3 \times 10^{10} M_\odot$) and the dynamical mass ($\sim 3 \times 10^{12} M_\odot$) in $r < 100$ kpc. The gas mass to the dynamical mass ratio was $10^{-3}$–$10^{-2}$, suggesting a significant fraction of the halo gas has been stripped.

Key words: Galaxies: individual: M86 — Galaxies: ISM — X-rays: galaxies: clusters

1 Introduction

M86 (NGC 4406) is a bright elliptical galaxy in the Virgo cluster, located about 1°26, or about 350 kpc in projection, from the Virgo cluster center M87. Its redshift is $z = -0.000747 \pm 0.000017$ (Cappellari et al. 2011), i.e., it is approaching us with the line-of-sight velocity of $224 \pm 5$ km $s^{-1}$. On the other hand, the redshift of M87 is $z = 0.004283 \pm 0.000017$, and it is going away from us with the line-of-sight velocity of $1284 \pm 5$ km $s^{-1}$. It is also reported that M86 is only about 1 Mpc more distance than M87 (Mei et al. 2007). Therefore, M86 is likely moving in the Virgo cluster with a relative line-of-sight velocity of about $1500$ km $s^{-1}$ with respect to the intracluster medium (ICM). This is much larger than the velocity dispersion of galaxies in the Virgo cluster ($\sim 700$ km $s^{-1}$) (Binggeli 1999), and hence, the direction of motion is considered close to the line-of-sight direction. Since the sound speed is 730 km $s^{-1}$ for the cluster ICM of $kT = 2$ keV, M86 is moving with a Mach number of $\gtrsim 2$. M86 is thought to be the dominant member of one
Table 1. Datasets used in the analysis.

| No. | ObsID    | Object          | Obs Date     | Exposure (ks) |
|-----|----------|-----------------|--------------|---------------|
| 1   | 803043010 | NGC 4406 (M86)  | 2009-06-19   | 102           |
| 2   | 808045010 | NGC 4438 Tail   | 2013-12-10   | 103           |
| 3   | 800017010 | NGC 4388        | 2005-12-24   | 124           |

of the subgroups within the Virgo cluster (e.g., Böhringer et al. 1994; Schindler et al. 1999). Therefore, M86 provides a good opportunity to study the interaction between the interstellar medium (ISM) and the ICM as well as the interaction between the subcluster and the ICM.

Characteristic features of M86 were reported by various authors, especially in the X-ray band, since it is sensitive to the hot ISM in the elliptical galaxies. Forman et al. (1979) discovered a plume of soft X-ray emission, which is thought to be stripped from M86 by ram-pressure with the Virgo ICM (see also White et al. 1991). Using ROSAT data, Rangarajan et al. (1995) showed that the temperatures of the galaxy and the plume are both \( \sim 0.8 \) keV. Using Chandra data, Randall et al. (2008) discovered a very long tail toward northwest, of 150 kpc in projection and the true length of \( \gtrsim 380 \) kpc. They also detected a discontinuity of the X-ray surface brightness, which was interpreted as the density jump due to the shock. M86 was also observed by XMM-Newton (Finoguenov et al. 2004; Ehlert et al. 2013). Ehlert et al. (2013) examined the temperature and abundance distributions in detail, and reported the existence of cool (\( \sim 0.6 \) keV) gas trailing to the northwest of M86 and, also to the east of M86 in the direction of NGC 4438.

In this paper, we report the results of our analysis of the Suzaku archival data of M86 and its adjacent regions, to study the extended emission around M86. We adopt a distance to the Virgo cluster of 16.5 Mpc, which gives a scale of 4.8 kpc per \( \prime \). All error ranges are 90% confidence intervals, and the \( F \)-test significance level is 1%, unless otherwise stated.

2 Data reduction

We used three datasets of Suzaku version 2.5 products, archived in Data ARchives and Transmission System (DARTS) at ISAS/JAXA. M86 was observed on 2009 June 19. Adjacent pointings aiming at NGC 4438 and NGC 4388 were also used. They are summarized in table 1.

HEAsoft 6.15.1 was used for data processing, extraction and analysis. The data were reprocessed using aepipeline v1.1.0, with CALDB version 20150105 for the dataset #1 (ObsID 803043010) and #2 (ObsID 808045010), and with CALDB version 20140520 for #3 (ObsID 800017010), following the standard screening criteria described in the Suzaku Data Reduction Guide\(^1\) Version 5.0. There were four independent XIS units (XIS0–3), but XIS2 was inoperative since 2006 November 9, and hence, XIS2 data were not available for the dataset #1 and #2. Event files of 5 \( \times \) 5 and 3 \( \times \) 3 editing modes were combined per sensor after the reprocessing. The regions which were illuminated by the calibration sources were discarded. The net exposure time of each observation is summarized in table 1. The average count rate of XIS1 in the 0.5–5 keV band was 2.0, 1.0, and 0.93 counts s\(^{-1}\), respectively. It was checked that there was no statistically significant variation in the light curves of the cleaned data.

Contribution of the particle background (Non-X-ray Background; NXB) of each XIS unit was estimated using xianxbgen tool and data taken when the satellite saw the night side of the Earth stored in the CALDB, by sorting them by the cutoff rigidity values, and properly weighting them by the exposure time ratio, based on the results by Tawa et al. (2008). The detector redistribution matrix files (RMFs) were generated with xissrfgen, using the appropriate calibration files at the time of the observation. On the other hand, responses of the X-ray telescopes were implemented into ancillary response files (ARFs), using ray-tracing based generator xissimarfgen (Ishisaki et al. 2007). Time- and position-dependent contamination in the optical path of each sensor was also considered by xissimarfgen. When the ARFs were generated, we assumed a uniform source distribution in a circle of 20’ radius.

3 Image analysis and results

A mosaic of the three pointings of the XIS in the 0.8–1.2 keV energy band is shown in figure 1. The energy range was selected to be sensitive to the hot gas of \( kT \sim 1 \) keV. Images in this energy band were extracted from the event files of XIS0, 1, 2, 3. They were rebinned by a factor of 8 (0’14), and were combined. The corresponding non-X-ray background images were generated using xianxbgen, and they were subtracted. Then, flat field images were generated, and the vignetting of the X-ray telescopes was corrected by dividing the XIS images with the flat field images. The mosaic was generated, the corresponding exposure map was generated using xisexpmapgen, and the mosaic was divided by the exposure map. Finally, it was smoothed with a Gaussian of \( \sigma = 0’42 \) (3 rebinned pixels).

As clearly seen in figure 1, an extended emission of a characteristic shape with two peaks was detected at the location of M86, together with two more relatively weak sources at the position of NGC 4388 and NGC 4438. The brightest peak is the M86 center. On the north side of it, a large plume of emission is seen, and an elongated tail extends toward the northwest. An extended halo of the X-ray emission is seen around the center of M86, which extends near NGC 4388 and NGC 4438. All these are consistent with the previously reported structures with high spatial resolution by ROSAT (Rangarajan et al. 1995), Chandra (Randall et al. 2008) and XMM-Newton (Ehlert et al.

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\(^1\) http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/abc/
Figure 1. (Left) Background-subtracted, vignetting-corrected mosaic of XIS images around M86 in the 0.8–1.2 keV energy band. Images of XIS0, 1, 3 were combined, and it was smoothed with a Gaussian of $\sigma$ corresponding to 0.42. (Right) X-ray contour map overlaid with an optical image. The optical image was taken from the Digitized Sky Survey.

2013 observations. Note that Randall et al. (2008) showed that the length of the tail in the plane of the sky is 150 kpc (0.51), but only a part of it was covered with the XIS field of view.

Figure 2 shows definition of the ten sector regions centered at the M86 center and surface brightness profiles of these regions. Among these, sector 1 is the brightest, while sectors 6–8 are the faintest. Sectors 7 and 8 contain NGC 4388 and an X-ray clump located near NGC 4388, respectively, and hence, the surface brightness profiles are complex. See section 5.3 for the X-ray clump. Except for them, the profiles are similar. In the eastern regions (sectors 1–4), the slopes of the surface brightness change at around 15’, and they become flatter outside it. In the southern regions (sectors 6–8), on the other hand, the slopes change at 10’–12’. Then, there is a contribution of NGC 4388. Outside $\sim 25’$ (sectors 7 and 8), the surface brightness becomes very low. At $r \gtrsim 25’$ in the eastern regions and $r \gtrsim 15’$ in the southern regions, it appears that the ICM of the Virgo cluster becomes dominant. Note that a factor of 2–3 difference in the ICM flux was reported around the M86 region (Rangarajan et al. 1995). The surface brightness variation of these regions is qualitatively consistent with their results.

To understand the surface brightness profiles more quantitatively, we fitted the profiles of sectors 2, 3, 4, and 6 with a $\beta$ model (Cavaliere & Fusco-Femiano 1976)

$$S(\theta) = S_0 \left(1 + \left(\frac{\theta}{b_0}\right)^2\right)^{-\frac{3+\beta}{2}} + \text{constant}, \quad (1)$$

where a constant was introduced to represent the ICM and other background and foreground components. The results are summarized in table 2 and the best fit models for sectors 2, 3, 4, and 6 are shown in figure 3. Since it was not possible to constrain the constant for sectors 3 and 4, it was fixed at the average value of sectors 2 and 6. The surface brightness of the Suzaku image can be represented relatively well with a single $\beta$-model of $\beta \sim 0.5$, up to $15’$–$20’$ in the eastern and southern regions.

4 Spectral analysis and results

As described in the previous section, the mosaic of the Suzaku XIS images showed structures of the X-ray emission from M86, i.e., emissions from the M86 core, the plume, the tail, and a diffuse emission around them. We defined regions as shown in figure 4, and performed a model fitting to the spectral data extracted from these regions. As an emission model from an optically-thin thermal plasma in collisional ionization equilibrium, we used the APEC (Astrophysical Plasma Emission Code) model (Smith et al. 2001), v2.0.2. It was used for the galaxy hot gas, the ICM, and the galactic foregrounds, i.e., the Local Hot Bubble (LHB) and the Milky Way Halo (MWH). The temperatures of the LHB and MWH were fixed at 0.11 keV (LHB) and 0.3 keV (MWH), respectively. The solar abundances ($Z$) by Lodders (2003) were adopted in the fitting, and those of LHB and MWH were assumed the same as the solar values ($1Z_\odot$). The Cosmic X-ray Background (CXB) was modeled with a power law function of a photon index 1.4 and a normalization corresponding to 9.7 photons s$^{-1}$ cm$^{-2}$ at 1 keV (Revnivtsev et al. 2005). The galactic hydrogen column density was fixed at $2.84 \times 10^{20}$ cm$^{-2}$ (Kalberla et al. 2005). Note that a constant ratio between the BI CCD data and the FI CCD data
were introduced. In all the fitting, it was in the acceptable range (\(~ 1.0 \pm 0.2\)).

4.1 Outer regions

First, we analyzed spectra of outer regions to the south-east and the south of M86 center. SE6 and S, respectively, to evaluate the ICM around M86. One or two APEC models were employed to represent the emission in these regions, in addition to two APEC models for the Galactic components (LHB and MWH) and a power law model for the CXB. When two APEC models were employed, their abundances were linked. The spectra and the best fit models are shown in figure 5, and the best fit parameters are summarized in table 3. Fitting was significantly improved by employing two APEC models. The 1σ-test provided the probability of 5.3 × 10⁻³ for region SE6 and 5.7 × 10⁻⁵ for region S, respectively. In both cases, the higher temperature component was dominant. The temperature was \( kT = 2.09^{+0.23}_{-0.16} \) keV and 1.71 ± 0.13 keV, respectively, and the abundance was \( N_{\text{H}} = 0.27Z_\odot \). The temperature of the other component was \( kT \sim 1 \) keV. Since the higher temperature component was dominant, and its temperature was \( \sim 2 \) keV, it was interpreted as the ICM emission. The lower temperature component was, on the other hand, considered a contribution of the extended emission of M86. Note that the normalizations of the LHB and the MWH were significantly different between the two regions, and their error bars were large. We compared them with those shown in Simionescu et al. (2015), who determined the spectral parameters of the LHB and the MWH using a set of 12 ROSAT All-sky Survey data beyond the virial radius of the Virgo cluster. After the unit conversion, the normalization of the MWH of region S was consistent with Simionescu et al. (2015) within an error range, while that of region SE6 was larger by a factor of \(~ 6\). The LHB normalizations were larger by about an order even for region S. We also compared the normalizations with those reported by Yoshino et al. (2009), who studied soft X-ray diffuse foreground emission with Suzaku. The normalizations of our results were within the variation range of those shown in Yoshino et al. (2009), except for the LHB normalization of region SE6. The foreground components of region SE6 might have been affected by solar activities.

A region around SE6 was observed with ROSAT and Chandra. According to Rangarajan et al. (1995), the ICM temperature of the ROSAT South East quadrant was 1.76 keV, while Randall et al. (2008) reported that the spectrum of their R18 region was represented with \( kT = 1.085 \) keV and 2.107 keV APEC models. These were close to the temperatures of the 1T model and the 2T model shown in table 3, respectively. Therefore, we judged that the results were in agreement with each other. On the other hand, the ICM temperature of ROSAT South West quadrant was 2.09 keV (Rangarajan et al. 1995), which was not consistent with the temperatures of our region.

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**Table 2. Best-fit parameters of the β model fit for sectors 2, 3, 4, and 6.**

| Parameter | Unit | Sector 2 | Sector 3 | Sector 4 | Sector 6 |
|-----------|------|----------|----------|----------|----------|
| \( \beta \) | | 0.51 ± 0.03 | 0.49 ± 0.01 | 0.44 ± 0.01 | 0.46 ± 0.03 |
| \( \theta_0 \) | (arcmin) | 2.7 ± 0.3 | 2.7 ± 0.2 | 1.8 ± 0.2 | 1.6 ± 0.2 |
| \( S_0 \) | \( \times 10^{-2} \text{ c s}^{-1} \text{ arcmin}^{-2} \) | 1.20 ± 0.06 | 1.06 ± 0.06 | 1.28 ± 0.10 | 1.48±0.14 |
| constant | \( \times 10^{-4} \text{ c s}^{-1} \text{ arcmin}^{-2} \) | 6.3 ± 0.5 | 6.0 (fixed) | 6.0 (fixed) | 5.7 ± 0.5 |
Surface brightness
Sector 2
0.1 1 10
0.8 1 1.2
ratio
Angular distance from M86 center (arcmin)

Surface brightness
Sector 3
0.1 1 10
0.8 1 1.2
ratio
Angular distance from M86 center (arcmin)

Surface brightness
Sector 4
0.1 1 10
0.8 1 1.2
ratio
Angular distance from M86 center (arcmin)

Surface brightness
Sector 6
0.1 1 10
0.8 1 1.2
ratio
Angular distance from M86 center (arcmin)

Fig. 3. The best fit models for the surface brightness profiles of sectors 2, 3, 4, and 6.

Table 3. Best fit parameters for the spectra of the outer regions SE6 and S.

| Component   | Parameter | Unit     | Region SE6 | Region S |
|-------------|-----------|----------|------------|----------|
|             |           |          | 1T model   | 2T model |
| APEC1       | $kT$      | (keV)    | 1.887$^{+0.098}_{-0.101}$ | 2.089$^{+0.284}_{-0.157}$ |
|             | $Z$ (solar) |          | 0.199$^{+0.063}_{-0.051}$ | 0.273$^{+0.107}_{-0.079}$ |
|             | Norm ($\times 10^{-2}$) |          | 4.191$^{+0.287}_{-0.272}$ | 3.586$^{+0.400}_{-0.384}$ |
| APEC2       | $kT$      | (keV)    | 0.922$^{+0.346}_{-0.230}$ | 0.922$^{+0.346}_{-0.230}$ |
|             | $Z$ (solar) |          | = APEC1 : Z | = APEC1 : Z |
|             | Norm ($\times 10^{-3}$) |          | 3.327$^{+1.753}_{-1.598}$ | 3.327$^{+1.753}_{-1.598}$ |
| APEC (LHB)  | $kT$      | (keV)    | 0.11 (fixed) | 0.11 (fixed) |
|             | Norm ($\times 10^{-3}$) |          | 8.138$^{+2.382}_{-2.352}$ | 10.333$^{+2.638}_{-2.616}$ |
| APEC (MWH)  | $kT$      | (keV)    | 0.3 (fixed) | 0.3 (fixed) |
|             | Norm ($\times 10^{-4}$) |          | 8.567$^{+5.036}_{-5.056}$ | 4.083$^{+6.685}_{-4.083}$ |

$\chi^2$/d.o.f.
333.37/279 320.99/277 494.53/424 472.16/422

The abundances of LHB and MWH were fixed at 1 solar. The normalizations of the APEC components are in units of $10^{-14} \int n_e n_H dV$ per 400$\pi$ arcmin$^2$, where $D_A$ is the angular diameter distance to the source (cm), $n_e$ and $n_H$ are the electron and hydrogen densities (cm$^{-3}$).
S. In the following analysis, the 2T model parameters for region SE6 was regarded as representative of the ICM emission, and the abundance of the ICM was assumed to be $0.27Z_\odot$. It is consistent with the number (26%) adopted by Randall et al. (2008). Note that the metallicity of the Virgo cluster at the same radius from M87 was also reported to be $Z \sim 0.3Z_\odot$ (Urban et al. 2011; Ehlert et al. 2013).

4.2 M86 center and halo regions

Secondly, the M86 center and the halo regions were analyzed. The regions used for the analysis were the center and 5 annular sectors (SE1–5, EX1–3) shown in figure 4. The center region is a circle of 1.5 radius at the M86 center. This is smaller than $\theta_0$ shown in table 2, and surface brightness can be regarded approximately constant in this radius. Annular sectors SE1–5 were defined from the position angle 95° to 150°, to avoid contamination from NGC 4438 and NGC 4388. The radius of the five regions were 1’5–3’5, 3’5–6’, 6’0–8’5, 8’5–12’, and 12’–16’, respectively. The dataset #1 was used for the inner three regions (SE1–3), while the dataset #2 was used for the outer two regions (SE4, 5). To examine the abundance distribution, wider regions were needed from the statistical point of view. Hence, we also defined annular sectors EX1–3 for this purpose. The radius of the three regions were 1’5–5’, 5’–10’, and 10’–16’. The dataset #1 was used for EX1 and EX2, while the dataset #2 was used for EX3.

We fitted the spectra with a single-temperature (1T) model and a two-temperature (2T) model, represented by one or two vAPEC model(s), which is an APEC model with variable abundances, in addition to the background and foreground components described in the previous section. An additional power law was added to the center region, to represent the contribution of unresolved low mass X-ray binaries. The photon index was fixed at 1.5 (e.g., Sarazin et al. 2003). To avoid the normalizations of the galactic components varying region by region, we first fitted the center and SE1–6 regions simultaneously to determine the normalizations of the galactic components, and fixed them at the values obtained in the simultaneous fitting. The fitting results of the 1T model and the 2T model are shown in table 4 for the center and SE1–5 regions, and in table 5 for EX1–3 regions. The spectra and the best-fit models of the 1T fit are shown in figure 6 for the center and SE1–5, and in figure 7 for EX1–3. Since there was an uncertainty in the normalizations of the LHB and the MWH as described in section 4.1, we investigated how the results of the 1T fit were affected if these normalizations were fixed at the numbers obtained by Simionescu et al. (2015). When we fixed the normalization of the MWH at $1.9 \times 10^{-4}$, i.e., 1/10 of the number shown in table 4 and 5, the best-fit parameters were unchanged within a statistical error range even in SE4 and SE5. When we fixed the normalization of the LHB at $0.16 \times 10^{-3}$, i.e., 1.6% of the number shown in table 4 and 5, the temperature of the vAPEC component of SE5 decreased, the Fe abundances of SE4 and SE5 decreased, and the normalizations of SE4 and SE5 increased, while other parameters were unchanged within a statistical error range. In these cases, however, reduced $\chi^2$ increased by 0.05 for SE4 and 0.11 for SE5. When another APEC component was added, the temperature became close to that of the LHB. Therefore, a larger normalization of the LHB or equivalent was needed to represent the Suzaku spectra.

4.2.1 Temperatures

The temperatures of the 1T fit were about 0.8–1.0 keV. As shown in the upper panel of figure 8, the temperatures of the inner regions (center and SE1) were lower, while they were almost constant or slightly decreasing toward the outer regions (SE2–6). When the 1T fit and the 2T fit were compared, the $F$-test probabilities were $8.5 \times 10^{-4}$, $9.0 \times 10^{-4}$, $2.1 \times 10^{-3}$, $1.5 \times 10^{-3}$, $6.5 \times 10^{-3}$, and 0.37, for the center and the SE1–5 regions, respectively. Thus, the improvement of the fit was reasonable except for SE5.

In the center region, the temperature of the main component was $0.88^{+0.03}_{-0.04}$ keV while that of the second component was $\sim 0.6$ keV, when the 2T model was employed. The normalization of the second component was about 0.3 times that of the first component. When the ICM temperature was made free in the 1T fit, it resulted in $\sim 0.6$ keV, rather than staying around 2 keV. Thus, the spectral data preferred the existence of a cold component. Matsushita (2001) showed that the temperature of the central region (< 2’6) was 0.69 keV, while Randall et al. (2008) reported existence of cold clumps around the core. Ehlert et al. (2013) pointed the presence of $\sim 0.6$–0.7 keV gas
Fig. 5. Spectra of the outer regions SE6 and S, and the best-fit models. The red and black crosses show the data points of BI and FI CCD data, and the red and black solid curves are the best fit models for them. The green, magenta, and gray curves are the high-$T$ component, the low-$T$ component, and the backgrounds/foreground components (CXB, LHB, MWH), respectively. Only the components for the BI model are shown.

Table 4. Best-fit spectral parameters for the center and SE regions obtained from the 17’ fit and the 27’ fit.

| Component | Parameter | Unit | Center | SE1 | SE2 | SE3 | SE4 | SE5 |
|-----------|-----------|------|--------|-----|-----|-----|-----|-----|
| 17’ model |           |      |        |     |     |     |     |     |
| vAPEC     | $kT$      | keV  | 0.800±0.009 | 0.813±0.016 | 0.933±0.022 | 0.984±0.022 | 0.957±0.024 | 0.982±0.016 |
|           | $Z_O$     | solar | 0.666±0.271 | 0.738±0.486 | 0.919±0.691 | 0.537±0.101 | 0.236±0.042 | <0.089 |
|           | $Z_{NO}$  | solar | 2.683±0.666 | 2.319±1.224 | 1.480±1.088 | 2.751±2.601 | 0.964±0.964 | 1.454±1.518 |
|           | $Z_{MG}$  | solar | 0.810±0.139 | 0.662±0.275 | 0.696±0.356 | 0.976±0.806 | 0.387±0.244 | <0.084 |
|           | $Z_{Si}$  | solar | 0.646±0.100 | 0.540±0.191 | 0.552±0.230 | 0.733±0.159 | 0.260±0.178 | 0.238±0.239 |
|           | $Z_{S}$   | solar | 0.896±0.228 | 0.526±0.314 | 0.853±0.410 | 0.695±0.637 | 0.614±0.496 | <0.084 |
|           | $Z_{Fe}$  | solar | 0.663±0.097 | 0.561±0.168 | 0.571±0.229 | 0.707±0.523 | 0.425±0.261 | 0.248±0.283 |
| APEC (ICM)| $kT$      | keV  | 16.288±2.573 | 1.2±0.192 | 9.293±1.992 | 4.253±1.097 | 2.123±0.851 | 1.883±0.631 |
|           | $Z$       | solar | 1.830±0.623 | 0.629±0.469 | 2.962±0.469 | 3.066±0.424 | 2.934±0.299 | 3.205±0.238 |
| Power law (LMXB)| $\Gamma$ | 1.5 (fixed) | 0.27 (fixed) | 2.1 (fixed) | 3.156 (fixed) | – | – | – |
|           | Norm $(\times 10^{-2})$ | – | 671.48±640 | 394.74±151 | 408.06±401 | 393.65±393 | 354.09±329 | 405.31±371 |
| 27’ model |           |      |        |     |     |     |     |     |
| vAPEC1    | $kT$      | keV  | 0.876±0.029 | 0.810±0.016 | 0.833±0.029 | 0.934±0.034 | 0.997±0.038 | 0.843±0.084 |
|           | $Z_O$     | solar | 0.647±0.036 | 0.841±0.457 | 0.991±0.808 | 0.698±1.081 | 0.106±0.351 | 0.122±0.849 |
|           | $Z_{NO}$  | solar | 2.277±0.695 | 2.118±0.776 | 1.786±1.213 | 4.389±2.233 | 0.356±0.709 | 1.538±2.199 |
|           | $Z_{MG}$  | solar | 0.874±0.213 | 0.700±0.125 | 0.856±0.289 | 1.165±0.981 | 0.290±0.182 | 0.087±0.385 |
|           | $Z_{Si}$  | solar | 0.715±0.150 | 0.581±0.172 | 0.673±0.295 | 0.807±0.585 | 0.243±0.110 | 0.332±0.279 |
|           | $Z_{S}$   | solar | 0.921±0.205 | 0.538±0.236 | 0.937±0.456 | 0.796±0.634 | 0.463±0.234 | 0.427±0.518 |
|           | $Z_{Fe}$  | solar | 0.745±0.162 | 0.635±0.169 | 0.700±0.320 | 0.832±0.657 | 0.234±0.117 | 0.339±0.327 |
| APEC2     | $kT$      | keV  | 12.097±2.078 | 12.14±2.149 | 8.227±1.802 | 2.466±0.959 | 1.554±0.863 | 3.339±1.001 |
|           | $Z$       | solar | 0.852±0.059 | 1.819±0.215 | 1.252±0.381 | 1.719±0.407 | 5.58±0.975 | 1.875 |
| Power law (LMXB)| $\Gamma$ | 1.5 (fixed) | 0.27 (fixed) | 2.1 (fixed) | 3.156 (fixed) | – | – | – |
|           | Norm $(\times 10^{-2})$ | – | 3.048±1.902 | 0.027±0.290 | 1.252±0.381 | 1.719±0.407 | 5.58±0.975 | 1.875 |
| APEC (ICM)| $kT$      | keV  | 3.625±1.025 | 0.126±1.450 | 3.273±2.396 | 1.656±0.791 | 1.155±0.514 | 0.522±0.325 |
|           | $Z$       | solar | 1.5 (fixed) | 0.27 (fixed) | 2.1 (fixed) | 3.156 (fixed) | – | – | – |
| Power law (LMXB)| $\Gamma$ | 1.5 (fixed) | 0.27 (fixed) | 2.1 (fixed) | 3.156 (fixed) | – | – | – |
|           | Norm $(\times 10^{-3})$ | – | 4.280±1.564 | 0.145±1.485 | 3.7920±394 | 395.73±399 | 380.85±391 | 343.36±327 |

In all the cases, APEC models for LHB ($kT = 0.11$ keV, $Z = 1Z_{\odot}$, Norm = 9.6×10^{-3}) and MWH ($kT = 0.3$ keV, $Z = 1Z_{\odot}$, Norm = 1.9×10^{-3}), and a power law model for CXB ($\Gamma = 1.4$, Norm = 1.063×10^{-3}) were included. The normalizations of the APEC components are in units of $10^{-15} \text{erg s}^{-1} \text{cm}^{-2} \text{arcmin}^{-2}$, where $D_{A}$ is the angular diameter distance to the source (cm), $n_{e}$, and $n_{H}$ are the electron and hydrogen number densities (cm^{-3}). The normalizations of the power law are in units of photons keV^{-1} cm^{-2} s^{-2} at 1 keV per 400π arcmin^{-2}.
Fig. 6. Spectra of the center and SE1–6, and the best-fit models of the 1σ fit. The red and black crosses show the data points of BI and FI CCD data, and the red and black solid curves are the best fit models for them. The blue, green, yellow, and gray curves are the vAPEC component, the ICM, the LMXBs, and the backgrounds/foreground components (CXB, LHB, MWH), respectively. Only the components for the BI model are shown.
Table 5. Best-fit spectral parameters for EX 1–3 regions obtained from the 1T fit and the 2T fit.

| Component | Parameter | Unit | Region EX1 | Region EX2 | Region EX3 |
|-----------|-----------|------|------------|------------|------------|
|           |           |      | 1T model   | 2T model   | 1T model   | 2T model   |
| vAPEC1    | $kT$      | (keV)| 0.829 ± 0.009 | 0.954 ± 0.028 | 0.968 ± 0.011 | 0.889 ± 0.046 | 0.819 ± 0.026 | 0.944 ± 0.054 |
|           | $Z_{O}$   | (solar)| 0.594 ± 0.019 | 0.697 ± 0.219 | 0.530 ± 0.103 | 0.514 ± 0.320 | 0.228 ± 0.233 | 0.263 ± 0.189 |
|           | $Z_{Ne}$  | (solar)| 2.652 ± 0.441 | 1.639 ± 0.441 | 2.749 ± 1.033 | 1.940 ± 0.103 | 0.967 ± 0.374 | 0.577 ± 0.372 |
|           | $Z_{Mg}$  | (solar)| 0.736 ± 0.103 | 0.819 ± 0.143 | 1.137 ± 0.327 | 1.390 ± 0.327 | 0.267 ± 0.224 | 0.291 ± 0.122 |
|           | $Z_{Si}$  | (solar)| 0.531 ± 0.090 | 0.653 ± 0.099 | 0.909 ± 0.720 | 1.076 ± 0.227 | 0.278 ± 0.082 | 0.308 ± 0.087 |
|           | $Z_{S}$   | (solar)| 0.589 ± 0.145 | 0.619 ± 0.146 | 1.123 ± 0.295 | 1.214 ± 0.321 | 0.350 ± 0.222 | 0.361 ± 0.208 |
|           | $Z_{Fe}$  | (solar)| 0.547 ± 0.061 | 0.724 ± 0.101 | 0.825 ± 0.211 | 1.024 ± 0.390 | 0.211 ± 0.054 | 0.260 ± 0.064 |
|           | Norm      | ($\times 10^{-2}$)| 6.823 ± 0.080 | 5.128 ± 0.704 | 1.662 ± 0.350 | 1.056 ± 0.445 | 1.768 ± 0.255 | 1.343 ± 0.440 |
| APEC (I CM)| $kT$      | (keV)| 2.1 (fixed) | 6.820 ± 0.061 | 5.128 ± 0.704 | 1.662 ± 0.350 | 1.056 ± 0.445 | 1.768 ± 0.255 | 1.343 ± 0.440 |
|           | Z         | (solar)| 0.27 (fixed) | 0.27 (fixed) | 0.27 (fixed) | 0.27 (fixed) | 0.27 (fixed) | 0.27 (fixed) |
|           | $\chi^2$/d.o.f. | | 3.582 ± 0.234 | 3.314 ± 0.274 | 3.148 ± 0.174 | 2.662 ± 0.333 | 2.793 ± 0.099 | 2.708 ± 0.130 |

In all the cases, APEC models for LHB ($kT = 0.11$ keV, $Z = 1Z_{\odot}$, Norm $= 9.6 \times 10^{-3}$) and MWH ($kT = 0.3$ keV, $Z = 1Z_{\odot}$, Norm $= 1.9 \times 10^{-3}$), and a power law model for CXB ($\Gamma = 1.4$, Norm $= 1.063 \times 10^{-3}$) were included. The normalizations of the APEC components are in units of $\int n_e n_H dV/400 \pi \text{arcmin}^2$, where $D_A$ is the angular diameter distance to the source (cm), $n_e$, and $n_H$ are the electron and hydrogen number densities (cm$^{-3}$). The normalizations of the power law are in units of photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV per 400$\pi$ arcmin$^2$.

Fig. 7. Spectra of the center and EX1–3, and the best-fit models of the 1T fit. The red and black crosses show the data points of BI and FI CCD data, and the red and black solid curves are the best fit models for them. The blue, green, and gray curves are the vAPEC component, the ICM, and the backgrounds/foreground components (CXB, LHB, MWH), respectively. Only the components for the BI model are shown.
reasonable for EX1 and 2. The second temperature of EX1 was between M86 and NGC 4438. Our result was qualitatively consistent with them.

For SE1, the temperature of the main component was almost unchanged while the second temperature was $1.82^{+0.22}_{-0.25}$ keV. The normalization of the ICM, however, became 0, which was unrealistic. If the ICM temperature was made free in the $1T$ model, the results suggested that the ICM temperature is located between them, but it was not possible to further constrain them. For SE4, the second temperature was too high to constrain.

As a conclusion, the $2T$ model is better for the center, while the $1T$ model is enough for SE1 but the ICM temperature could be as low as 1.6 keV. For SE2 and SE3, the ICM temperature may also be lower than 2.1 keV, while that of SE4 may be slightly higher.

Note that the temperatures of EX1–3 showed a similar characteristics. When the $1T$ fit and $2T$ fit were compared, the $F$-test probabilities were $6 \times 10^{-19}$, $2 \times 10^{-10}$, and 0.023, for EX1, 2, 3, respectively. Thus, the improvement of the fit was reasonable for EX1 and 2. The second temperature of EX1 was 0.61$^{+0.06}_{-0.09}$ keV, which may be the cooler component either located at the center or in the region between M86 and NGC 4438. The results of EX2 may indicate that the ICM temperature is lower than what was assumed.

4.2.2 Normalizations, density and mass of the core
The normalizations of the $1T$ fit were plotted as a function of radius from the center, in the lower panel of figure 8. When the profile was fitted with a $\beta$-model, the best-fit parameters were $\beta = 0.42^{+0.17}_{-0.09}$, $\theta_0 = 2.0^{+2.1}_{-1.3}$, and $S_0 = 0.18^{+0.09}_{-0.05}$. $\beta$ and $\theta_0$ were consistent with those of sector 4 shown in table 2 within an error range.

From the normalization of the APEC model, the emission measure can be obtained. Assuming the center region as a uniform sphere of $1.5$ (7.2 kpc) radius, the number density of hydrogen $n_H$ became $\sim 7.1 \times 10^{-3}$ cm$^{-3}$, and the mass of the sphere $M$ became $\sim 3.9 \times 10^3 M_\odot$, where mean molecular weight of hydrogen was assumed to be 1.4. When the normalization of the $2T$ model was adopted, the results were unchanged ($n_H \sim 6.2 \times 10^{-3}$ cm$^{-3}$ and $M \sim 3.4 \times 10^5 M_\odot$). Note that they are consistent with what was obtained by Randall et al. (2008) ($n_{\text{core}} \approx 6.2 \times 10^{-3}$ cm$^{-3}$ and $M_{\text{core}} \approx 7.4 \times 10^5 M_\odot$ within a sphere of radius 9.6 kpc).

4.2.3 Abundances
Figure 9 shows the radial distributions of the abundances of O, Ne, Mg, Si, and Fe of the center and EX1–3 regions. $1T$ fit results of SE1–5 regions are also shown. The distributions were consistent with each other, although the errors of SE1–5 were large. Within $r \lesssim 10''$, the abundances were relatively large and roughly constant, while outside $r \gtrsim 10''$ the abundances became significantly smaller ($0.2-0.3 Z_\odot$).

Figure 10 shows the abundance ratios of elements with respect to Fe. O/Fe, Mg/Fe, Si/Fe, S/Fe are consistent with 1, while Ne/Fe is 2–4. When the $2T$ model was adopted, the abundances were generally slightly higher, by $\sim 0.1 Z_\odot$, but the over-abundance of Ne was unchanged.

4.3 Plume and tail
Thirdly, we fitted the spectra of the plume and the tail regions with $1T$ model. The results are summarized in table 6 as case 1 (ICM temperature fixed at 2.1 keV) and case 2 (ICM temperature free), and the best-fit models of case 1 are shown in figure 11. The $F$-test probabilities between case 1 and case 2 were $9.3 \times 10^{-3}$ and 0.20 for the plume and the tail, respectively. The improvement was reasonable for the plume, but the ICM temperature was $> 3.2$ keV in case 2, which seemed too high as the ICM temperature. On the other hand, the abundances of the tail were high ($\sim 1.3 Z_\odot$) when the ICM temperature was fixed at 2.1 keV (case 1). The ICM temperature slightly higher than
Fig. 9. Radial distributions of the abundances of O, Ne, Mg, Si, S, and Fe, as a function of angular distance from the M86 center. Black crosses and green squares are $1\sigma$ fit and $2\sigma$ fit results of the center and EX1–3 regions, respectively. $1\sigma$ fit results of SE1–5 are also shown with gray crosses.
The abundance of Fe, especially in the tail region, was seen in both case 1 and 2, i.e., the abundances of O, Mg, Si, S, Fe were close to each other, while that of Ne was about 2.5 times larger.

The abundance of Fe, especially in the tail region, was slightly higher than that of the center. In the tail region, the surface brightness was relatively low, and the abundance (also the normalization) was affected by the normalization and the temperature of the ICM. Figure 12 shows a confidence contour between the Fe abundance and the ICM normalization when the ICM temperature was fixed at 2.1 keV, and a confidence contour between the Fe abundance and the ICM temperature when both the ICM temperature and normalization were free. There is a positive correlation with the ICM normalization and a negative correlation with the ICM temperature. The 90% lower limit of the Fe abundance is 0.9 if the ICM temperature is 2.44 keV. Therefore, we cannot conclude that the abundances in the tail region is higher than those of the center region from the Suzaku data.

If we assume a uniform prolate spheroid of the equatorial radius of 1.2 and the polar radius of 2.7 for the plume, the hydrogen number density becomes \( n_{\text{plume}} \approx 6.4 \times 10^{-3} \text{ cm}^{-3} \) and the total mass is \( M_{\text{plume}} \approx 4.0 \times 10^{6} M_{\odot} \). This is consistent with the numbers obtained by Randall et al. (2008) within a factor of 2. If we assume a uniform cylinder of 1.7 radius and 4.1 height for the tail region, the hydrogen number density becomes \( n_{\text{tail}} \approx 3.1 \times 10^{-3} \text{ cm}^{-3} \) and the total mass is \( M_{\text{tail}} \approx 4.5 \times 10^{6} M_{\odot} \). The mass is about 1/4 of that estimated by Randall et al. (2008). Major difference is that our data only covered part of the tail.

### Table 6. Best-fit parameters of the plume and the tail regions.

| Component | Parameter | Unit | Case 1 | Case 2 | Case 1 | Case 2 |
|-----------|-----------|------|--------|--------|--------|--------|
|           | \( kT \) (keV) |      | 0.861+0.010 | 0.862+0.011 | 0.994+0.010 | 0.999+0.010 |
| vAPEC     | \( Z_{O} \) (solar) |      | 0.751+0.033 | 0.574+0.229 | 1.295+1.026 | 1.014+1.013 |
|           | \( Z_{Ne} \) (solar) |      | 2.663+0.173 | 2.063+0.155 | 3.634+2.030 | 3.781+1.081 |
|           | \( Z_{Mg} \) (solar) |      | 2.181+0.164 | 0.999+0.160 | 2.173+0.526 | 1.372+0.399 |
|           | \( Z_{Si} \) (solar) |      | 0.813+0.131 | 0.692+0.091 | 1.241+0.499 | 1.022+0.408 |
|           | \( Z_{S} \) (solar) |      | 0.940+0.117 | 0.715+0.121 | 1.376+0.583 | 1.084+0.603 |
|           | \( Z_{Fe} \) (solar) |      | 0.940+0.117 | 0.715+0.121 | 1.376+0.583 | 1.084+0.603 |
|            | Norm \((×10^{-2})\) | 1.230+1.513 | 1.075+1.405 | 12.856+5.214 | 4.186+1.190 | 5.340+2.007 |
| APEC (ICM) | \( kT \) (keV) |      | 2.1 (fixed) | >3.2 | 2.1 (fixed) | 2.728+0.861 |
|           | Norm \((×10^{-2})\) | 2.095+0.497 | 0.508 | 0.862+0.180 | 0.927 | 0.576 | 2.113+1.301 |
|           | - \( \chi^{2}/\text{d.o.f.} \) | 600.13/566 | 592.98/565 | 441.24/422 | 439.52/421 |

In all the cases, APEC models for LHB \((kT = 0.11 \text{ keV}, Z = 1Z_{\odot}, \text{Norm}= 9.6 \times 10^{-3})\) and MWH \((kT = 0.3 \text{ keV}, Z = 1Z_{\odot}, \text{Norm}= 1.9 \times 10^{-3})\), and a power law model for CXB \((\Gamma = 1.4, \text{Norm}= 1.063 \times 10^{-5})\) were included. The normalizations of the APEC components are in units of \(\text{cm}^{−2} \text{ keV} \), where \(\int n_{e} n_{H} dV \text{ per } 4000 \text{ arcmin}^{2}, \text{where } D_{A} \text{ is the angular diameter distance to the source (cm), } n_{e} \text{ and } n_{H} \text{ are the electron and hydrogen number densities (cm}^{-3}).\) The normalizations of the power law are in units of photons \text{keV}^{−1} \text{ cm}^{−2} \text{ s}^{−1} \text{ at } 1 \text{ keV per } 4000 \text{ arcmin}^{2}.\)

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**Fig. 10.** Abundance ratios of O, Ne, Mg, Si, and S with respect to Fe. Triangles, circles, and squares represent the center, SE1–5, and EX1–3, respectively.

2.1 keV is preferred for both the plume and the tail. When we employed a 2\( T \) model, the temperature of the second component became too high to constrain. Therefore, 2\( T \) model was not meaningful for these regions.

A similar abundance pattern to that of the center region was seen in both case 1 and 2, i.e., the abundances of O, Mg, Si, S, Fe were close to each other, while that of Ne was about 2.5 times larger.

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### 5 Discussion

#### 5.1 Core, plume, and tail

As shown in the previous section, the temperatures of the core were \(kT = 0.88^{+0.10}_{-0.04} \text{ keV} \) and \(\sim 0.6 \text{ keV} \) (2\( T \) fit), while those of the plume and the tail were \(0.86\pm0.01 \text{ keV} \) and \(1.00\pm0.01 \text{ keV} \), respectively. Thus, the temperature of the tail was slightly higher. This is generally consistent with those reported by Randall et al. (2008) and Ehler et al. (2013). There was a tendency that the abundances became slightly larger in the order of the core, the plume, and the tail. However, we concluded that the difference was not significant, thinking about statistical errors and also about systematic errors due to variation of
the ICM temperature and normalization. Randall et al. (2008) pointed that the temperature structure of the tail is consistent with a ram-pressure stripping model, i.e., the hotter, higher entropy group gas is stripped first, followed by the cooler, lower entropy M86 ISM. Our results strongly support it, since the temperature of SE3 (0.98$^{+0.02}_{-0.03}$ keV) and the Fe abundance (0.7–0.8$Z_{\odot}$) are close to those of the tail.

We determined the abundances of O, Ne, Mg, Si, S, and Fe separately, and also showed that all the spectra of the different regions had a very similar abundance pattern, i.e., O/Fe, Mg/Fe, Si/Fe, and S/Fe were basically consistent with the solar ratio, while Ne/Fe was larger by a factor of 3–4. Konami et al. (2014) analyzed Suzaku data of M86 as a whole, i.e., including the core, the plume, and part of the tail together, and reported that Ne/Fe was about 3. Our analysis showed that it was the case with the center, the plume, the tail, and also the halo. The spectra of these regions (figure 6 and 11) showed a peak at around 0.9 keV and a hump slightly above 1 keV. They were caused by a forest of Fe L lines, and Ne X Ly\(\alpha\) lines at 1022 eV (Ne X 2p \(\rightarrow\) 1s), respectively, when the temperature was 0.8 keV. The peak energy due to the forest of Fe L lines rises as the temperature rises. Therefore, the spectral shape in this energy region is mainly determined by the temperature and the abundances of Fe and Ne. The Ne abundance by Lodders (2003) is about 60% of that provided by Anders & Grevesse (1989) or Grevesse & Sauval (1998). In the recent solar abundances provided by Lodders (2010), the Ne abundance is much closer to Anders & Grevesse (1989) or Grevesse & Sauval (1998). Even if the new value were adopted, Ne overabundance would be still significant, by a factor of 2–3. This common abundance pattern, which is derived from the very similar spectral shapes, is one evidence that the hot gas in the plume and the tail regions has the same origin as that in the core.

Konami et al. (2014) reported that the large Ne/Fe ratio
cannot be explained by any mixture of SNe type Ia and core-collapse SNe, and concluded that Ne abundance may have intrinsically large systematic errors because their emission lines are hidden by prominent Fe-L lines. We further investigated it. To check model uncertainties, we fitted the center data with SPEX 3.0 (Kaastra et al. 1996). When the temperature was fixed at the same number, the abundances differed by ~30%. However, the difference of Ne/Fe was only about 5%, and hence, there was no significant difference between the results based on APEC and SPEX. According to AtomDB, there is an Fe L line (Fe XXI 2p^34d^1 → 2p^6) at 1023 eV. In addition, there is a strong Fe L line (Fe XXI 2p^33d^1 → 2p^2) at 1009 eV, whose emissivity is comparable to the summation of two Ne X Lyα lines when the temperature is ~0.8 keV, and reaches the maximum when the temperature is ~1.1 keV. Therefore, it may be difficult to determine the abundance of Ne precisely in this temperature range unless Ne X Lyα lines are separated from strong Fe L lines. Note that Ji et al. (2009) showed high-resolution spectra of M86 obtained with XMM-Newton reflection grating spectrometers (RGS), and the Fe XXI 2p^33d^1 → 2p^2 line seemed to be resolved. However, the neon abundance was not reported.

5.2 Extended halo

5.2.1 Characteristics of the halo gas

The extended emission around M86 was clearly detected with Suzaku. According to the XIS mosaic shown in figure 1, it extends over 15′ (72 kpc) from the center in the east direction, and over 10′ (48 kpc) in the south-west direction. With the moderate spatial resolution of Suzaku, the surface brightness profile of the core and the extended halo was represented with a single β model of β ~ 0.5, as described in section 3, and it indicated that the emission spreads to ~20′ (~100 kpc). This picture is consistent with the the spectral fit of SE6 region (r = 16′–20′), which showed the existence of a component of kT = 0.9 keV. If the surface brightness extends to a certain distance following a β model, the actual extent of the gas must be significantly larger. Therefore, our results strongly suggest that the halo of M86 extends over 100 kpc, at least in the east direction.

Using the effective radius r_e of 1.74 (de Vaucouleurs et al. 1991), Suzaku detected X-ray emission up to ~11.5r_e in SE1–6 regions. The ratio of the temperature at 4–8r_e to that at <1r_e was kT(4–8r_e)/kT(<1r_e) = 1.21^{+0.05}_{-0.06}, showing the positive temperature gradient in the central region. Nagino & Matsushida (2009) denoted galaxies with the temperature ratio >1.3 as X-ray extended galaxies and others as X-ray compact galaxies. According to their criteria, M86 is located in the boundary area. The ratio of the stellar velocity dispersion to the gas temperature $\beta_{\text{spec}} \equiv \mu m_p \sigma^2 / kT$, where $\mu$ is the mean molecular weight in terms of the proton mass $m_p$, is $\beta_{\text{spec}} = 0.47$, for the gas temperature of 0.9 keV and the stellar velocity dispersion of 256 km s$^{-1}$ (Roberts et al. 1991). This is close to the typical number of the X-ray extended elliptical galaxies (Matsushita 2001). These results suggest that the halo gas is located in a larger scale potential structure than that of the galaxy, such as a galaxy group (Matsushita 2001; Nagino & Matsushida 2009).

5.2.2 Estimation of the gas mass and the dynamical mass

In section 3, we showed the surface brightness distribution is represented by a β model of β ~ 0.5. In this section, we estimate the gas mass assuming the β model obtained in section 3. The β model was valid from the position angle ~45° to ~275°, covering about 64% of the whole area, and hence, we used only this region.

In section 4.2.2, we estimated that the hydrogen number density in the core was (6–7) × 10^{-3} cm^{-3}, assuming a uniform sphere of 1.5 radius. We first calculated the total emission measure along the line-of-sight through the M86 center (r < 1.5) assuming the β model parameters shown in table 2, and derived the density at r = 0. It became (4.0–6.3) × 10^{-3} cm^{-3}. In the following discussion, we assume that the hydrogen number density at r = 0 is 5 × 10^{-3} cm^{-3}.

If the β model for the surface brightness distribution is valid to infinity, the density is given by the following function:

$$n(r) = n_0 \left(1 + \left(\frac{r}{r_0}\right)^2\right)^{-\frac{3}{2}}. \quad (2)$$

Since the hydrogen number density at the center is 5 × 10^{-3} cm^{-3}, the density at r ~ 100 kpc is ~ 2 × 10^{-4} cm^{-3}. According to Urban et al. (2011), the electron density of the Virgo ICM is ~ 2 × 10^{-4} cm^{-3} at about 350 kpc from the center of the Virgo cluster. Hence, the densities of the halo gas and the ICM are comparable at around r = 100 kpc.
where $R$ is the radius of the gas, $\Delta \theta_i$ is the angle of the $i$-th sector, $\rho_i(r)$ is the mass density at $r$ of the $i$-th sector. The gas mass thus obtained is shown in figure 13 as a function of radius. The mass of the halo gas in $r < 100$ kpc became $\sim 3 \times 10^{12} M_\odot$.

We further estimated the dynamical mass assuming the hydrostatic equilibrium. The halo must be affected by the motion of M86 in the Virgo cluster, and also by the ram-pressure stripping, and hence, the hydrostatic equilibrium will not be a good approximation. However, we think it is still useful to discuss the condition of M86. We calculated the dynamical mass using the following equation:

$$M_{dyn}(r) = \frac{kT_r}{\mu m_H G} \left( \frac{d \ln \rho}{d \ln r} + \frac{d \ln T}{d \ln r} \right) \simeq \frac{3 \beta kT_r}{\mu m_H G} \frac{r^2}{r_0^2}$$

assuming the temperature is almost constant. The dynamical mass thus obtained is also shown in figure 13. It became $\sim 3 \times 10^{12} M_\odot$ for $r < 100$ kpc. Then the ratio of the gas mass to the dynamical mass $M_{gas}/M_{dyn}$ became $\sim 0.01$.

Böhringer et al. (1994) decomposed the X-ray surface brightness distribution obtained with ROSAT into several components, and estimated the total mass within 280 kpc is $(1–3) \times 10^{12} M_\odot$. If we use their number, $M_{gas}/M_{dyn}$ becomes only $\sim 10^{-3}$. If we extend our calculation to 230 kpc (difference of the distance corrected) assuming the same $\beta$ models are valid, the gas mass becomes $\sim 1 \times 10^{11} M_\odot$, and the ratio is $\sim 10^{-2}$. Schindler et al. (1999) reported that the galaxy mass within 240 kpc from M86 center is $6 \times 10^{11} M_\odot$, and the ratio of the galaxy mass to the total mass is 2–6%. Therefore, depending on the actual spread of the gas, the ratio of the gas mass to the galaxy mass also significantly differs, from $\sim 0.1$ to $\sim 1$.

According to Sasaki et al. (2015), the gas mass fractions of clusters to the hydrostatic mass are about 0.02–0.1. They also found that the ratio is $10^{-3}$ for several subhalos in the Coma cluster, indicating significant fraction of the gas was removed due to interaction with the ICM, such as ram-pressure stripping. Our results implicate that the gas mass to the dynamical mass ratio of M86 is $10^{-3}–10^{-2}$, suggesting it is also significantly affected by the interaction with the ICM.

### 5.2.3 Timescales of Ram-pressure stripping in M86

According to Forman et al. (1979), the ram-pressure stripping occurs when the ram-pressure of the cluster gas exceeds the force holding the gas in the galaxy:

$$\rho_{ICM} v^2 > \rho_{ISM} \sigma_{gal}^2$$  \hspace{1cm} (5)

where $\rho_{ICM}$ and $\rho_{ISM}$ are the ICM and ISM densities, and $\sigma_{gal}$ is the galaxy velocity dispersion (See also Gunn & Gott 1972). At the core of M86, the ram-pressure is $\sim 6$ eV cm$^{-3}$ and $\rho_{ISM} \sigma_{gal}^2$ is $\sim 5$ eV cm$^{-3}$, for $n_{ICM} = 2 \times 10^{-4}$ cm$^{-3}$, $n_{ISM} = 5 \times 10^{-3}$ cm$^{-3}$, $v = 1500$ km s$^{-1}$, and $\sigma_{gal} = 256$ km s$^{-1}$.

Therefore, the ram-pressure stripping condition is satisfied even in the core.

According to Frank et al. (1992), the mean free path $\lambda_\perp$ of the Coulomb collisions of two protons that causes the large deflection ($\sim 90^\circ$) is given by:

$$\lambda_\perp \approx \frac{m_p v^4}{4 \pi e^4 n}$$  \hspace{1cm} (6)

and the time needed for the particle to travel the mean free path is given by:

$$t_\perp = \frac{\lambda_\perp}{v} \approx \frac{m_p v^3}{4 \pi e^4 n}$$  \hspace{1cm} (7)

They were calculated for the core and the halo and are shown in table 7. The mean free path is comparable to the diameter of the core and the halo, and hence, the close Coulomb collisions occur with a large probability. In fact, there are much more distant scatterings, and the mean free path and the travel time will be shortened by a factor of the Coulomb logarithm ($\sim 10$).

|           | Center | Halo |
|-----------|--------|------|
| Number density $n_{ISM}$ (cm$^{-3}$) | $5 \times 10^{-3}$ | $2 \times 10^{-4}$ |
| Mean free path $\lambda_\perp$ (kpc) | 8.6 | 215 |
| Travel time (y) | $5.6 \times 10^{6}$ | $1.4 \times 10^{6}$ |

Time needed to strip all the halo gas is simply estimated by the total number of the halo gas divided by the flux of the ICM, i.e.,

$$t_{strip} \approx \frac{4 n_{ISM} R^3}{3 n_{ICM} R^2 v} = \frac{4 n_{ISM} R}{3 n_{ICM} v}$$  \hspace{1cm} (8)

It becomes $\sim 3 \times 10^{6}$ y in the core, and $\sim 2 \times 10^{5}$ y in the outer halo. Since the distance between M86 and M87 is 350 kpc in projection, the crossing time is

$$t_{cross} \geq \frac{2R}{v} \sim 4 \times 10^8 \ [y].$$  \hspace{1cm} (9)

Therefore, $t_{strip} \lesssim t_{cross}$, and hence, most of the gas in the core and in the halo will be stripped if M86 passes through the Virgo cluster center once.

We showed that the gas of low metal abundance still remains in the outer halo. On the other hand, it was indicated that the gas mass to the dynamical mass ratio is $10^{-3}–10^{-2}$, which suggests significant fraction of the halo gas has been stripped. The M86 group is experiencing the stripping by the Virgo cluster system.

### 5.3 X-ray clump near NGC 4388

As shown in section 3, a faint X-ray clump was detected near NGC 4388. The temperature of the gas was $\sim 1$ keV and its flux in the 0.5–2 keV band was $\sim 4 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. We could not find any literature mentioning it. We checked the NASA/IPAC Extragalactic Database (NED)$^2$ to see if there

$^2$ http://ned.ipac.caltech.edu/.
are any associations with known background groups or clusters. One cluster WHL J122512.2+142722 at $z = 0.4264$ and one group SDSSCGB 65849 were found near the XIS field of view, but it is unlikely that either of them is an optical counterpart. Next, we looked for galaxies with known redshift and X-ray sources in NED. The results are summarized in figure 14. Among them, IC 3303 is located near the brightest part of the X-ray clump. The redshift of this galaxy is $-0.000627 \pm 0.000077$ (Conselice, Gallagher & Wyse 2001), which is very close to that of M86. Therefore, this clump might be part of the M86 subgroup gas, though it is separated from the extended emission around M86. Further study is needed.

6 Summary

We analyzed the Suzaku data of M86 and its adjacent regions to study the extended emission around it. The M86 core, the plume, and the tail extending toward the northwest were clearly detected, as well as the extended halo around them. From the position angle $\sim 45^\circ$ to $\sim 275^\circ$, the surface brightness distribution was represented relatively well with a single $\beta$-model of $\beta \sim 0.5$ up to $15^\circ$--$20^\circ$.

The Suzaku XIS spectra of the M86 center, the extended halo, the plume, and the tail were explained with one- or two-temperature plasma model, in addition to the Virgo ICM of $kT \approx 2.1$ keV and other background/foreground components. The temperatures of the center were $0.88^{+0.03}_{-0.04}$ keV and $\sim 0.6$ keV. The temperatures of the core and the halo have a positive gradient, and reach the maximum of $kT \sim 1.0$ keV at $r \sim 7'$ or $\sim 4r_e$. Outside it, it is almost constant or slightly decreasing toward the outer regions. The temperature of the plume and the tail were $0.86 \pm 0.01$ keV and $1.00 \pm 0.01$ keV, respectively. Therefore, the temperature of the tail is slightly higher than the core and the plume. These were qualitatively consistent with the previous Chandra and XMM-Newton results (Randall et al. 2008; Ehlert et al. 2013).

We succeeded in determining the abundances of O, Ne, Mg, Si, S, and Fe separately, for the core, the plume, the tail, and the halo for the first time. The best-fit values of the Fe abundance in the core and in the plume were $\sim 0.7$, while that in the tail was slightly higher ($\sim 1.0$). However, we cannot conclude that the abundance in the tail is higher, thinking about the normalization and the temperature variation of the ICM. The abundance of the halo is almost the same up to $\sim 10'$, and then it becomes significantly smaller (0.2–0.3) at $r \gtrsim 10'$. This means that the gas in the outer halo is less polluted by the metals produced in the galaxy. In all the regions, the abundance ratios of O, Mg, Si, and S to Fe were $\sim 1$, while Ne/Fe showed a significantly larger number (2–4). This Ne overabundance is coming from the spectral features at around 1 keV, and is another evidence that the plume and the tail have the same origin as the core. However, the overabundance by a factor of 2–4 cannot be explained by the uncertainty of the abundances, or mixture of known SNe nucleosynthesis models. Ne abundance may have intrinsically large systematic errors as suggested by Konami et al. (2014).

Our results suggest that the halo of M86 extends over 100 kpc, at least in the east direction. The temperature at the center is slightly lower, and the ratio of the stellar velocity dispersion to the gas temperature is only 0.47. These features indicate that the extended halo gas is located in a larger scale potential structure than that of the galaxy, such as a galaxy group (Nagino & Matsushita 2009; Matsushita 2001). Using the $\beta$ models for sectors, we estimated the gas mass from the position angle $\sim 45^\circ$ to $\sim 275^\circ$ (64% of the whole area). It was $\sim 3 \times 10^{12} M_\odot$ in $r < 100$ kpc. If we further assume the hydrostatic equilibrium, the dynamical mass in the same region was $\sim 3 \times 10^{12} M_\odot$, giving the ratio of the gas mass to the dynamical mass $M_{\text{gas}}/M_{\text{dyn}} \sim 0.01$. If we adopt the dynamical mass within 230 kpc provided by Böhringer et al. (1994), the ratio becomes $\sim 10^{-3}$. These ratios suggest the halo of M86 is significantly affected by the interaction with the Virgo ICM. Simple estimation of the ram-pressure stripping length scales and timescales showed that the mean free path is comparable to the size of the core or the halo, and the stripping timescale is comparable or shorter than the crossing time through the Virgo center. Therefore, most of the gas in the core and in the halo will be stripped if M86 passes through the Virgo center once. The fact that the low metal gas still remains in the outer halo indicates that the M86 group is experiencing the stripping by the Virgo ICM right now.

Acknowledgments

We thank Prof. Kyoko Matsushita for her valuable comments on X-ray properties of the elliptical galaxies and interaction with the ICM. We also
acknowledge Dr. Toru Sasaki, who supported our analysis. We are grateful to the anonymous referee, who provided useful comments to improve our manuscript.

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