Suzaku Observations of Metal Distributions in the Intracluster Medium of the Centaurus Cluster

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Abstract

We report the first observations of metal distributions in the intracluster medium of the Centaurus cluster up to \( \sim 0.17r_{180} \) with Suzaku. Radial profiles of the O, Mg, Si, S, Ar, Ca, and Fe were determined at the outer region of the cluster, and their variations appear to be similar to each other. Within the cool core region \((r < 0.045r_{180})\), all of the metal distributions sharply increased toward the center. In the central region \((r < 0.015r_{180})\), the abundances of Si, S, Ar, Ca, and Fe were 1.5–1.8 solar, while those of O and Mg were approximately 1 solar. The derived abundance ratios of O and Mg to Fe were slightly lower than those of a set of other clusters. In contrast, the calculated mass-to-light ratios (MLRs) for O, Mg, and Fe were larger than those of the other clusters. For the outer region of the cool core \((r > 0.07r_{180})\), all of the abundances were almost constant at 0.5 solar. The derived MLRs were comparable to those of the other clusters. This suggests that the cD galaxy of the Centaurus cluster efficiently supplies more Fe than the other clusters.

Key words: galaxies: clusters: individual (Centaurus cluster) — X-rays: galaxies: clusters — X-rays: ICM

1. Introduction

The metal abundances of the intracluster medium (ICM) provide important information regarding the chemical history and evolution of clusters. The metals in the ICM were primarily produced by supernovae (SNe) in early-type galaxies (Arnaud et al. 1992; Renzini et al. 1993). Si and Fe are synthesized both in SNe Ia and SNe II, while O and Mg are synthesized predominantly in SNe II. O and Mg abundances, and therefore are crucial for understanding the history of massive stars in clusters of galaxies.

Because the Fe-K lines are prominent in the spectra of the ICM, the Fe abundances of the ICM have been studied in detail. ASCA has first shown the Fe distribution in the ICM (Fukazawa et al. 1998, 2000; Finoguenov et al. 2000, 2001; Ezawa et al. 1997). De Grandi and Molendi (2002) derived the Fe distribution and its gradient from Beppo-SAX observations. Recently, XMM-Newton and Chandra observations have been used to study the spatial distribution of Fe up to 0.3–0.4\(r_{180}\) (Vikhlinin et al. 2005; Baldi et al. 2007; Maughan et al. 2008; Leccardi & Molendi 2008; Matsushita 2011). Within the cool core regions, the Fe abundance in clusters decreases sharply toward the outer region. Matsushita (2011) found that outside the cool cores both cD and non-cD clusters have similar Fe abundance profiles, which are flatter than expected from numerical simulations. A simple explanation is that a significant fraction of Fe was synthesized in an early phase of cluster evolution.

XMM-Newton provided the means to study the O and Mg abundances in the brightest cool cores of clusters and groups of galaxies (Finoguenov et al. 2002; Matsushita et al. 2003; Tamura et al. 2003; Matsushita et al. 2007b). However, a higher background level and a strong instrumental Al line of the MOS detector onboard XMM-Newton can cause problems in measuring the O and Mg abundances outside cool cores. The X-ray Imaging Spectrometer (XIS) instrument (Koyama et al. 2007) onboard Suzaku (Mitsuda et al. 2007) offered an improved line spread function below 1 keV coupled with a lower background level. With the Suzaku satellite, the O and Mg abundances of the ICM outside the cool cores of several clusters and groups of galaxies were measured up to 0.2–0.3\(r_{180}\) (Matsushita et al. 2007a; Komiyama et al. 2009; Sato et al. 2007a, 2008, 2009a, 2009b, 2010). Within the cool cores, the derived abundance patterns of O/Mg/Si/Fe are comparable to the solar ratio, obtained by adopting the solar abundance by Lodders (2003). Combining the Suzaku results with SNe nucleosynthesis models, Sato et al. (2007b) showed the number ratios of SNe II to Ia to be \(\sim 3.5\), and that Fe was synthesized mainly by SNe Ia. A slight increase in O/Fe and Mg/Fe with increasing radius was detected in Abell 1060 (Sato et al. 2007a) and AWM 7 (Sato et al. 2008), although the error bars were reasonably large. MLR, the ratios of metal mass in the ICM to the total galaxy (stellar) luminosity, is important for studying the origin of metals, because metals are synthesized in stars. The integrated values of the Fe mass-to-light ratio (MLR) profiles of the \(kT = 2–3\) keV clusters, such as Abell 262, and AWM 7 observed with Suzaku increased outward from 0.1\(r_{180}\) to 0.3–0.4\(r_{180}\). These results imply that Fe in the ICM extends farther than stars in the outer regions. These results also indicate early metal enrichment process in the ICM.

The Centaurus cluster (Abell 3526) is a nearby X-ray bright cluster with a cool core (Allen & Fabian 1994; Ikebe et al. 1999; Sanders et al. 2008; Takahashi et al. 2009) at a redshift of \(z = 0.0104\). At the cluster center, the cD galaxy NGC 4696 is associated with the low-power radio source PKS 1246–410.
One offset and three central regions of the Centaurus cluster were observed in 2005 December and 2007 by Suzaku. The observed regions range to 23\r180 in number. We use the Hubble constant $H_0 = 70$ km s\(^{-1}\) Mpc\(^{-1}\). The luminosity distance to the Centaurus cluster is $D_L = 44.9$ Mpc, which \( r_{180} \) corresponds to 13 kpc. The virial radius, $r_{180} = 1.95 h_{100}^{-2} \sqrt{(kT)/10}$ keV (Markevitch et al. 1998; Evrard et al. 1996), is approximately 1.74 Mpc for the average temperature of $\langle kT \rangle = 3.88$ keV with ASCA (Furusho et al. 2001). Unless otherwise specified, the errors are within the 90% confidence region for a single parameter of interest.

### Table 1. Suzaku observations of the Centaurus cluster and the background region.

| Target name            | Sequence number | Date     | Coordinates (J2000.0) | Exposure (ks) |
|------------------------|-----------------|----------|----------------------|---------------|
| CENTAURUS_CLUSTER      | 800014010       | 2005-Dec-27 | 192\(^{\circ}\)2054 41\(^{\circ}\)3111 | 36.3          |
| CENCL_OFFSET1          | 800015010       | 2005-Dec-28 | 192\(^{\circ}\)2054 41\(^{\circ}\)4440 | 44.7          |
| CENCL_OFFSET2          | 800016010       | 2005-Dec-29 | 192\(^{\circ}\)2054 41\(^{\circ}\)1780 | 43.0          |
| CEN 45                 | 802008010       | 2007-Dec-24 | 192\(^{\circ}\)5119 41\(^{\circ}\)3865 | 58.2          |
| LOCKMANHOLE            | 100046010       | 2005-Nov-14 | 163\(^{\circ}\)4063 57\(^{\circ}\)6108 | 77.0          |
| LOCKMANHOLE            | 101002010       | 2006-May-17 | 162\(^{\circ}\)9366 57\(^{\circ}\)2557 | 80.4          |
| LOCKMANHOLE            | 102018010       | 2007-May-03 | 162\(^{\circ}\)9257 57\(^{\circ}\)2581 | 96.1          |
| LOCKMANHOLE            | 103009010       | 2008-May-18 | 162\(^{\circ}\)9369 57\(^{\circ}\)2546 | 83.4          |

Fig. 1. XIS 0 image (0.5–4 keV) of the Centaurus cluster. The images obtained with the four pointing observations are superposed. The exposure was corrected, but the NXB and CXB were not subtracted. The image was smoothed by a Gaussian of $\sigma = 10$ pixels. The unit of color bar is counts pixel\(^{-1}\) s\(^{-1}\). The circles indicate the annular regions as mentioned in the spectral analysis.

2. Observation and Data Reduction

One offset and three central regions of the Centaurus cluster were observed in 2005 December and 2007 by Suzaku. The observed regions range to 23\r180, which corresponds to $\sim 0.17 r_{180}$, from the cD galaxy NGC 4696 at the center. The Cen 45 field corresponds to the subcluster, the Cen 45 region. The observation logs are given in table 1, and an XIS image in the 0.5–4 keV band is shown in figure 1. We used only the XIS data in this study. The XIS instrument consists of four sets of X-ray CCD (XIS 0, 1, 2, and 3). XIS 1 is a back-illuminated (BI) sensor, while XIS 0, 2, and 3 are front-illuminated (FI) sensors. XIS 2, however, has not been available since 2006 November; hence, the Cen 45 observation was carried out only by XIS 0, 1, and 3. The XIS was operated in the normal clocking mode with standard 5 x 5 or 3 x 3 editing modes.

The analysis was performed with HEAsoft version 6.7 and XSPEC 12.5.1. We used the standard data selection,\(^1\) and the CALDB files version 2009-04-02. Because the energy resolution slowly degraded after the launch because of radiation damage, this effect was included in the redistribution matrix file generated by the “xisrmfgen” Ftools task. We generated an Ancillary Response File (ARF) for the spectrum of each annular sky region, which assumed an $r = 25\rarcmin$ circle size of the surface brightness profile, which is the sum of two $\beta$-models, $\beta_1 = 0.57$, $r_c = 7.3$ and $\beta_2 = 0.92$, $r_{c2} = 9.2$ derived from ASCA and ROSAT results (Ikebe et al. 1999) by the “ixissrmarfgen” Ftools task (Ishisaki et al. 2007). We also included the contamination effect on the optical blocking filter of the XIS in the ARFs. We employed the night Earth database generated by the “xissnbgen” Ftools task to subtract non-X-ray background (NXB).

\(^{1}\)(http://www.astro.isas.ac.jp/suzaku/process/v2changes/criteria_xis.html)
3. Spectral Analysis

3.1. Estimation of the Cosmic X-Ray Background and Galactic Foreground

We estimated the cosmic X-ray background (CXB) using four Lockman hole observations with Suzaku, as shown in table 1. Because the observed emissions in our observation were dominated by the ICM emission from the Centaurus cluster, we could not estimate the CXB level in our observation. Thus, we used the Lockman hole data for the background estimation. We fitted the spectra from the Lockman hole data with an absorbed power-law model. The resultant parameters are given in table 2. The weighted average of the photon index, $\Gamma = 1.47$, and Norm = 9.9 photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$ at 1 keV were used.

The galactic emissions mainly arise from the local hot bubble (LHB) and the Milky Way halo (MWH). We used a two-temperature model (apec: Smith et al. 2001) for these emissions. The version 1.3.1 of the APEC code is used through this paper. For the outermost region (15$'$–23$'$), we fitted the spectra with the model formula apec$_{LHB}$ + wabs * (apec$_{MWH}$ + power-law$_{CXB}$ + apec$_{ICM}$), as described in Sato et al. (2007a) and Komiyama et al. (2009). Here, we fixed the LHB temperature at 0.1 keV, which was typical value of XMM result (Lumb et al. 2002), while the MWH temperature was a free parameter. The normalizations of the LHB and MWH were allowed to vary. We also assumed a solar abundance and zero redshift for the LHB and MWH components. The resultant parameters are given in table 2. The derived values were consistent with those of Yoshino et al. (2009).

Using these parameters, we generated mock spectra including the CXB, the LHB, and the MWH components as the background. In a spectral analysis of the inner (0$'$–15$'$) regions, we subtracted the mock spectra as the background from the observed spectra for each sensor. The CXB and galactic components in the 15$'$–23$'$ region were included as models in the spectral fits. As a result, the temperature and the abundances in the ICM did not change within the statistical errors when we examined the systematic errors of our results by changing the background normalization by $\pm$10%, as mentioned in subsection 4.5.

3.2. ICM Component

We extracted spectra from six annular regions of 0$'$–2$'$, 2$'$–4$'$, 4$'$–6$'$, 6$'$–9$'$, 9$'$–15$'$, and 15$'$–23$'$, centered on the peak of X-ray intensity at $(RA, Dec) = (192^\circ 2058, \sim 41^\circ 3042)$ (Ota et al. 2007). The annular spectra are shown in figure 2. Each spectrum was carefully binned so as to observe details in the metal lines, especially below $\sim 1$ keV. Each spectral bin contained 50 or more counts. We fitted the spectra in 0.5–9.0 keV at XIS 0, 2, 3, and 0.4–9.0 keV at XIS 1. We excluded the narrow energy band around the Si-K edge (1.82–1.84 keV) because of an anomalous response.

We assumed a single- or two-temperature (hereafter, 1T or 2T, respectively) model (vapec: Smith et al. 2001), and fitted the spectra of all detectors simultaneously for each region. We also examined a three-temperature (3T) model at the innermost region within 2$'$, because the Chandra result suggested that at least a 3T model was needed to represent the spectra in the central region (Sanders & Fabian 2006).

The metal abundances of He, C, N, and Al were fixed to a solar value, while the other nine elements were allowed to vary. Note that the Ne-K and Ni-L lines could not be resolved from the Fe-L lines. Therefore, we do not report on the Ne and Ni abundances in this paper. The galactic absorption for neutral hydrogen $N_H$ was also allowed to vary in the spectral fits. This is because the galactic latitude of the Centaurus, 21$^\circ 7$, is relatively low, and there may be systematic uncertainties in the adopted galactic absorption, which is a weighted average of those of positions within 1$^\circ$ from the cD galaxy. In addition, a systematic uncertainty in the thickness of the contaminant on the optical filter of the XIS also causes a systematic uncertainty in the $N_H$.

| Sequence number | $\Gamma$ | Norm$^*$ | $\chi^2$/d.o.f. |
|-----------------|---------|----------|-----------------|
| 100046010       | 1.53$^{+0.03}_{-0.03}$ | 14.2$^{+0.6}_{-0.5}$ | 1120/945 |
| 101002010       | 1.41$^{+0.04}_{-0.04}$ | 9.3$^{+0.4}_{-0.4}$ | 831/765 |
| 102018010       | 1.43$^{+0.05}_{-0.05}$ | 8.8$^{+0.4}_{-0.4}$ | 662/617 |
| 103009010       | 1.49$^{+0.05}_{-0.05}$ | 9.0$^{+0.5}_{-0.5}$ | 670/529 |

Galactic

| $kT_{MWH}$ (keV) | Norm$_{MWH}^{\dagger}$ | $kT_{LHB}$ (keV) | Norm$_{LHB}^{\dagger}$ | $\chi^2$/d.o.f. |
|------------------|------------------------|------------------|------------------------|-----------------|
| 0.16$^{+0.03}_{-0.03}$ | 3.1$^{+1.7}_{-1.3}$ | 0.1 (fixed) | 0.0$^{+1.3}_{-0.0}$ | 535/561 |

$^*$ The units of photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$ at 1 keV.

$\dagger$ Normalization of the apec component divided by the solid angle, $\Omega^2$, assumed in the uniform-sky ARF calculation (20$'$ radius), Norm = $\int n_{eH1}dV/[4\pi (1 + z^2)D_A^2]/\Omega^2 \times 10^{14}$ cm$^{-5}$ 400sr arcmin$^{-2}$, where $D_A$ is the angular distance to the source.
Fig. 2. Panels show the observed spectra for the annular regions of the Centaurus cluster. The data are plotted by black, red, and blue crosses for XIS 1 spectra of the CENTAURUS CLUSTER, CENCL OFFSET1, and CENCL OFFSET2 region in $0^\circ–9^\circ$, while CEN45, CENCL OFFSET1, and CENCL OFFSET2 in $9^\circ–23^\circ$, respectively. The estimated NXB, CXB, and galactic components were subtracted from the spectra in the $0^\circ–15^\circ$ region. In $15^\circ–23^\circ$, the CXB component is a fixed Lockmanhole value and galactic components are included as the models. The yellow lines show the best-fit model for XIS 1. The XIS 1 spectra of the ICM components are shown in magenta, orange, and light blue lines. The energy range around the Si-K edge (1.82–1.84 keV) was ignored in the spectral fits. The lower panels show the fit residuals in units of $/\text{ESC}$. 

Fig. 3. Data-to-model ratios of the fits of the XIS 1 spectra with the 1T (black), 2T (red), and 3T (blue) models.

4. Results

4.1. Fitting Results

Table 3 and figures 3, 4, and 5 summarize the resultant parameters of the fits. The data-to-model ratios of the fits are also shown in figure 3. Within $2^\circ$, or $r < 0.015 r_{180}$, the reduced $\chi^2$ with the 1T model is much larger than unity, and the error ranges of the parameters are not represented. The 2T model significantly improved the resultant $\chi^2$ of the fit compared to that with the 1T model. The fit with the 3T model is even better than that with the 2T model, particularly around 0.8 keV (figure 3). At $2^\circ–4^\circ$, or $0.015–0.03 r_{180}$, the 2T model also improved the fits at around 0.9–1.1 keV. Beyond $4^\circ$, or $r > 0.03 r_{180}$, the 2T model is significantly better than the 1T model, considering only the statistical errors, and the data-model ratio improved by several percent at around 1.1 keV. However, considering possible systematic uncertainties in the Fe-L modeling, the 1T model fits still represent the spectra fairly well.

4.2. Temperature Profile of the ICM

The radial temperature profile and the ratios of the normalizations of the hotter and cooler ICM components from the cluster center to $r \sim 0.17 r_{180}$ are shown in figure 4 and table 3. The ICM temperatures of the three components at the central region, within $0.015 r_{180} \simeq 2^\circ$, were $\sim 3.8$, $\sim 1.7$, and $\sim 0.8$ keV, respectively, and the two higher temperatures with the 3T model appear to be similar to the hot and cool ICM temperatures with the 2T model in the $2^\circ–4^\circ$ ($0.015 < r < 0.03 r_{180}$) region. Our results for the 3T model are consistent with the previous Chandra result (Sanders et al. 2006). For the outer region ($r > 0.015 r_{180}$) the ICM temperature of the hotter component with the 2T model slightly increased to $\sim 4.6$ keV in the outermost region, while that of the cooler component was almost constant at $1.7$ keV. The resultant temperatures with the 1T model were consistent with the previous XMM-Newton result with the 1T model (Matsushita et al. 2007b). A comparison of the normalization ratios of the hotter and cooler components for the 2T and 3T models is shown in figure 4. The ratios reached a peak at $\sim 0.04 r_{180}$, and...
then decreased to approximately one fourth of its peak value in the outermost region.

4.3. Abundance Profiles of ICM

Radial abundance profiles of O, Mg, Si, S, Ar, Ca, and Fe up to \(r \approx 0.17 r_{180}\) are summarized in table 3 and figure 5. All of the abundances lie over a solar abundance at the central region, and decrease toward the outer region.

Within the cool core region (\(r < 0.045 r_{180} \approx 6\)) the abundances sharply increased toward the center. The Fe abundance reached a maximum value of \(\approx 1.83\) solar within \(0.015 r_{180}\) with the 3T model. The Si, S, Ar, and Ca abundances showed the same behavior as the Fe profile. The O and Mg abundances were approximately 1 solar within \(0.015 r_{180}\).

For the outer region (\(r > 0.045 r_{180}\)), the 1T and 2T models gave similar O, Mg, Si, S, Ca, and Fe abundances, although the 2T model gave slightly higher abundances for Ar. All of the abundances were nearly constant at \(\approx 0.5\) solar. Fe decreased to approximately one fourth of the central value in the outer region. The ratio of O and Mg to Fe also decreased to approximately half of the central value. In the outermost region (\(0.11 < r < 0.17 r_{180}\)), the fits gave only the upper limit of the O abundance with 90% error. This was the first time to derive the Mg abundance to \(0.17 r_{180}\). The derived abundances are consistent with those from XMM and Chandra data (Sanders et al. 2006; Matsushita et al. 2007b), but the error bars are small, particularly outside the cool core.

### 4.4. Profiles of ICM Abundance Ratios

The radial profiles of the abundance ratios of O, Mg, Si, S, Ar, and Ca to Fe abundance are shown in figure 6. Excluding the central region, the 1T and 2T models gave similar abundance ratios of O/Fe, Mg/Fe, Si/Fe, and S/Fe, whereas the 2T model yielded higher Ar/Fe and Ca/Fe ratios by several
Fig. 4. (a) Radial temperature profile derived from the spectral fits with the 1T (black cross), 2T (red diamond), and 3T (blue diamond) models. (b) Ratios of the normalization of the hotter to the cooler ICM components obtained from the spectral fits with the 2T (red diamond) and 3T (blue diamond) models.

Fig. 5. (a) Radial neutral hydrogen column density ($N_{\text{H}}$) profile derived from the spectra. Black dashed lines show the galactic $N_{\text{H}}$ of $8.56 \times 10^{20}$ cm$^{-2}$ from Kalberla et al. (2005). Black crosses, red and blue diamonds correspond to the results with the 1T, 2T, and 3T models, respectively. (b)–(h) Radial abundance profiles are plotted similar to that in (a).
tens of a percent. The abundance ratios of O/Fe and Mg/Fe are \( \approx 0.5 \) solar ratio within \( 0.03 r_{180} \) and \( \approx 0.7–1 \) solar ratio beyond the radius. The other abundance ratios of Si/Fe, S/Fe, Ar/Fe, and Ca/Fe are \( \approx 1 \) solar ratio in the entire region. The weighted averages of the abundance ratios were calculated for three radial regions, and are shown in Table 4.

### 4.5. Uncertainties

In order to estimate the systematic errors, we varied the normalizations of the NXB spectra and the mock spectra including the CXB, LHB, and MWH by \( \pm 10\% \) in the spectral fits. The systematic errors due to the background estimation were almost negligible, and the resultant temperatures and abundances did not change within the statistical errors by changing the background level. We also note that the Ne abundance is not reliably determined because of an overlap with the strong and complex Fe-L line emissions. However, these abundances were allowed to vary freely during the spectral fits.

### 5. Discussion

#### 5.1. ICM Abundance Pattern and Contributions from SN Ia and SN II

Figure 7 summarizes the abundance pattern of the O/Fe, Mg/Fe, Si/Fe, S/Fe, Ar/Fe, and Ca/Fe ratios within \( 0.05 r_{180} \), \( 0.05–0.1 r_{180} \), and beyond \( 0.1 r_{180} \) of the Centaurus, AWM 7, Abell 262, and the Perseus clusters with those of the four groups of galaxies and the Fornax cluster. Within \( 0.1 r_{180} \), the Centaurus cluster has the smallest error bars for O/Fe and Mg/Fe ratios compared to the other clusters and groups of galaxies.

Outside the cool core, beyond \( 0.05 r_{180} \), the O/Fe, Mg/Fe, and Mg/Fe ratios of these groups and clusters of galaxies are close to the solar ratio. The Mg/Fe ratio might be caused by uncertainties in the Fe-L atomic data, because the Mg-K lines are surrounded by the Fe-L lines. The Centaurus cluster and the Perseus cluster have similar Ar/Fe and Ca/Fe ratios. There is no significant difference in the abundance pattern between the clusters and groups of galaxies.

Within \( 0.05 r_{180} \), or the cool core region, Mg/Fe ratio of the Centaurus cluster shows the lowest value of 0.5 in units of the solar ratio. The Mg/Fe ratio of the other systems scatters around unity, i.e., the solar ratio. The O/Fe ratio of the Centaurus cluster is the same as those of other clusters and groups of galaxies, although the error bars of the other clusters and groups are fairly large. In contrast, the Si/Fe and S/Fe ratios of the Centaurus clusters and other systems agree well.

#### 5.2. Mass-to-Light Ratios

The metal MLR is a useful measure to study the ICM chemical evolution, because metals in the ICM are all synthesized in galaxies. We calculated the B-band and K-band ratios.
Fig. 7. Weighted averages of the abundance ratios of O, Mg, Si, Ar, and Ca to Fe for the three regions (a) $r < 0.05 \, r_{180}$, (b) $0.05 \, r < 0.1 \, r_{180}$, and (c) $r > 0.1 \, r_{180}$. We used the abundance ratio derived from the 3T model within $0.015 \, r_{180}$ and the 2T model for the outer regions. The abundance ratios of other clusters, AWM 7 (Sato et al. 2008), Abell 262 (Sato et al. 2009b), the Perseus cluster (Tamura et al. 2009), NGC 5044 (Komiyama et al. 2009), NGC 1550 (Sato et al. 2010), HCG 62 (Tokoi et al. 2008), NGC 507 (Sato et al. 2009a), and the Fornax cluster (Matsushita et al. 2007a) are also plotted in the panels. SN II yields by Nomoto et al. (2006) refer to an average of the Salpeter initial mass function of stellar masses from 10 to 50 $M_\odot$ with a progenitor metallicity of $Z = 0.02$. The SN Ia yields were taken from the W7 model (Iwamoto et al. 1999).

luminosity profiles to estimate the MLRs. The $K$-band luminosity of a galaxy correlates more than the $B$-band with the stellar mass. The $B$-band luminosities were used to compare previous studies.

To derive a $B$-band luminosity profile, we integrated the luminosities of the member galaxies from Jerjen and Dressler (1997), deprojected the profile assuming spherical symmetry, and derived a three-dimensional profile of $L_B$. Jerjen and Dressler (1997) optically studied the Centaurus cluster, and identified 296 member galaxies whose apparent magnitudes are brighter than 21.5 in the $B$-band. The brightest cluster galaxy, NGC 4696, has an apparent magnitude of $m_B = 7.298$ or $L_B = L_B = 11.2$ using 44.9 Mpc and the foreground galactic extinction, $A_B = 0.492$ (Schlegel et al. 1998), from the NASA/IPAC Extragalactic Database (NED).

To derive a $K$-band luminosity profile, we used the luminosity of galaxy data in a box of $10^5 \times 10^5$ centered at the peak of the X-ray intensity from the Two Micron All Sky Survey (2MASS). The brightest cluster galaxy, NGC 4696, has an apparent magnitude of $m_K = 7.298$ or $L_K = L_K = 11.7$, using the foreground galactic extinction, $A_K = 0.42$ (Schlegel et al. 1998), from NED. Figure 8 shows the galaxies detected with 2MASS within $0.2 \, r_{180}$ from the cD galaxy. The average surface brightness in the region of $140' < r < 300' \ (r_{180} 

http://www.ipac.caltech.edu/2mass/).
we deprojected the brightness profiles of the LB cluster (Mieske et al. 2005). Therefore, excluding NGC 4709, the integrated mass profiles indicate that NGC 4709 is located in front of the Centaurus cluster. Within 0.1 r180, where the central galaxies dominate the integrated L_K profiles, the IMLR, OMLR, and MMLR of the Centaurus cluster tend to be higher than those of the other systems by a factor of 1.5–2. In contrast, at 0.1–0.17 r180, MLRs of the Centaurus cluster become consistent with those of the other systems.

5.3. Metal Enrichment Histories outside the Cool Core

Outside the cool core, from 0.05 r180 to ~0.17 r180, the observed Fe abundance profile of the Centaurus cluster agrees well with those of the weighted average of the nearby cD clusters observed with XMM (Matsushita 2011). At this radial range, the IMLR, OMLR, and MMLR of the Centaurus cluster are also similar to those of AWM 7, Abell 262, and NGC 1550 observed with Suzaku, considering the difference in the integrated values within 0.05 r180. The abundance patterns of O/Mg/Si/S/Fe of these systems are almost similar, although the Mg/Fe ratio of the AWM 7 cluster at 0.05–0.1 r180 tends to be higher. These results indicate that outside the cool core regions of clusters, the metals in the ICM may be universal in clusters of galaxies, and clusters of galaxies may have universal metal enrichment histories.

The observed abundance pattern of O/Mg/Si/S/Ar/Ca/Fe beyond 0.05 r180 is between those of SN II and SN Ia from nucleosynthesis models (figure 7). Therefore, both SN Ia and SN II products have been mixed into the ICM. The observed solar-abundance pattern of O to Fe indicates that a large quantity of Fe was synthesized by SN Ia, and that the number of Fe ratio of SN II to SN Ia is estimated to be 3–4 (Sato et al. 2007b, 2008). The similarity of the abundance pattern of these clusters and groups of galaxies outside the cool cores indicates that the contributions of the two types of SN to the metals in the ICM are similar.

Renzini (2005) found that the OMLR of the ICM is a very sensitive function of the slope of the initial mass function (IMF). Adopting a Salpeter IMF, the expected value is ~0.1 M_⊙/L_⊙, and an increase in the slope of the IMF decreases the value of the OMLR. In contrast, the integrated OMLR at 0.17 r180 of the Centaurus cluster, excluding NGC 4709, is 0.01–0.04 M_⊙/L_⊙. We expect the OMLR to become 0.02–0.04 M_⊙/L_⊙, assuming that the ratio of O and Mg is constant, since within the radius the abundance ratio of the O and Mg is consistent with a constant. This value is smaller than the expected value obtained with the Salpeter IMF by a factor of 3–5. Considering that the observed MLRs of AWM 7 and Abell 262 increase with radius, the observed

![Fig. 9. Integrated mass of the hot gas (magenta), O (green), Mg (red), and Fe (black). Integrated K-band luminosities of galaxies L_K (blue) and B-band luminosities of galaxies L_B (light blue) are also plotted in the panel. Integrated luminosities excluding NGC 4709 are shown with dashed lines (in the right ends).](https://academic.oup.com/pasj/article-abstract/63/sp3/S979/2898239)

![Fig. 8. Identified objects from the Two Micron All Sky Survey (2MASS) in K-band (black open circle). The red (near center) and blue (left slightly lower) crosses denote the coordinates of the cD galaxy (NGC 4696: Ota et al. 2007) and NGC 4709, respectively.](https://academic.oup.com/pasj/article-abstract/63/sp3/S979/2898239)
values give lower limits of the OMLRs in all of the clusters. Therefore, to study the slope of the IMF in clusters of galaxies we need measurements of MLRs at outer regions of these systems.

5.4. Metal Enrichment from the cD Galaxy

The metals in the cool core of clusters are a mixture of those in the ICM and the supply from the cD galaxy, which contains those synthesized by SN Ia and those coming from stars through stellar mass loss. The metal abundances in the ISM of elliptical galaxies provide important information regarding current metal supply into the ICM. In these galaxies, the O and Mg abundances in the ISM should be equal to those in mass-losing stars, because these elements are not substantially synthesized by SN Ia. The Fe abundance of the ISM is a sum of the stellar metallicity and the SN Ia contribution,

Table 5. Summary of B-band and K-band metal mass-to-light ratios of the Centaurus cluster.

|          | B-band |          |          |          |          |
|----------|--------|----------|----------|----------|----------|
|          |        | r [arcmin] | $L_B$ [$10^{11} L_\odot$] | $M_{\mathrm{gas}}$ [$10^{11} M_\odot$] | IMLR ($M_\odot/L_\odot$) | OMLR ($M_\odot/L_\odot$) | MMLR ($M_\odot/L_\odot$) |
|          |        | ($r_{180}$) |         |          |          |          |          |
| 2°/0.15  | 1.5    | 0.21     | 3.0$^{+0.03}_{-0.03}$ | 0.80$^{+0.06}_{-0.06}$ | 0.89$^{+0.04}_{-0.04}$ |
| 4°/0.30  | 1.5    | 0.91     | 10.3$^{+0.1}_{-0.1}$ | 3.0$^{+0.2}_{-0.2}$ | 2.7$^{+0.2}_{-0.2}$ |
| 6°/0.045 | 1.5    | 2.0      | 17.4     | 5.7$^{+0.6}_{-0.5}$ | 5.1$^{+0.4}_{-0.4}$ |
| 9°/0.068 | 1.5    | 4.3      | 28.2$^{+0.3}_{-0.4}$ | 10.6$^{+1.2}_{-1.1}$ | 9.1$^{+0.8}_{-0.8}$ |
| 15°/0.11 | 1.8    | 11.4     | 49$^{+1}_{-1}$ | 19$^{+4}_{-4}$ | 19$^{+2}_{-2}$ |
| 22°/0.17 | 2.9    | 22.0     | 51$^{+2}_{-2}$ | 19$^{+16}_{-8}$ | 27$^{+5}_{-4}$ |
|          |        |          |          |          |          |          |          |
| B-band (excluding NGC 4709) |        |          |          |          |          |          |          |
| 15°/0.11 | 1.8    | 11.4     | 48$^{+1}_{-1}$ | 19$^{+4}_{-4}$ | 19$^{+2}_{-2}$ |
| 22°/0.17 | 2.4    | 22.0     | 63$^{+2}_{-3}$ | 23$^{+20}_{-19}$ | 33$^{+6}_{-5}$ |

|          |          | r [arcmin] | $L_K$ [$10^{11} L_\odot$] | $M_{\mathrm{gas}}$ [$10^{11} M_\odot$] | IMLR ($M_\odot/L_\odot$) | OMLR ($M_\odot/L_\odot$) | MMLR ($M_\odot/L_\odot$) |
|----------|----------|----------|-----------------|-----------------|-----------------|-----------------|-----------------|
|          |          | ($r_{180}$) |      |      |      |      |      |
| 2°/0.15  | 5.4      | 0.21     | 0.85$^{+0.01}_{-0.01}$ | 0.22$^{+0.02}_{-0.02}$ | 0.25$^{+0.01}_{-0.01}$ |
| 4°/0.30  | 5.4      | 0.91     | 2.83$^{+0.02}_{-0.02}$ | 0.80$^{+0.06}_{-0.06}$ | 0.75$^{+0.05}_{-0.05}$ |
| 6°/0.045 | 5.4      | 2.0      | 4.88$^{+0.04}_{-0.06}$ | 1.6$^{+0.2}_{-0.1}$ | 1.43$^{+0.11}_{-0.11}$ |
| 9°/0.068 | 5.4      | 4.3      | 8.04$^{+0.10}_{-0.09}$ | 3.0$^{+0.3}_{-0.3}$ | 2.6$^{+0.2}_{-0.2}$ |
| 15°/0.11 | 6.1      | 11.4     | 14.7$^{+0.3}_{-0.3}$ | 5.7$^{+1.1}_{-1.1}$ | 5.7$^{+0.7}_{-0.7}$ |
| 22°/0.17 | 10.3     | 22.0     | 14.6$^{+0.5}_{-0.5}$ | 5.5$^{+4.5}_{-2.2}$ | 7.8$^{+1.3}_{-1.2}$ |
|          |          |          |          |          |          |          |          |
| K-band (excluding NGC 4709) |          |          |          |          |          |          |          |
| 15°/0.11 | 6.1      | 11.4     | 14.6$^{+0.3}_{-0.3}$ | 5.6$^{+1.1}_{-1.1}$ | 5.6$^{+0.7}_{-0.7}$ |
| 22°/0.17 | 7.7      | 22.0     | 19.4$^{+0.7}_{-0.7}$ | 7.3$^{+6.1}_{-3.0}$ | 10.4$^{+1.7}_{-1.7}$ |
which is proportional to $M_{\text{Fe}}^{\text{SN}}/\alpha_*$ (see Matsushita et al. 2003 for details). Here, $M_{\text{Fe}}^{\text{SN}}$ is the Fe mass synthesized in one SN Ia, $\theta_{\text{SN}}$ is the SN Ia rate, and $\alpha_*$ is the stellar mass-loss rate.

Figure 11 compares the central abundance pattern of the Centaurus cluster within $r_180$ with those of early-type galaxies observed with Suzaku. The O/Fe and Mg/Fe ratios of the Centaurus cluster, 0.5–0.6 solar ratio, are systematically smaller than those of the galaxies at 0.8–1.0 solar ratio. The stellar metallicity of NGC 4696, the $b$-band galaxy of the Centaurus cluster, calculated from the gradient of optical Mg$_2$ indexes within the effective radius, is similar to those of NGC 720, NGC 4636, and NGC 5044 plotted in figure 11 (Kobayashi & Arimoto 1999). Therefore, the difference in the abundance ratios may be caused by a difference in the contribution from SN Ia, and the metals in the center of the Centaurus cluster are not simple accumulations of hot ISM in ellipticals. Because the abundance pattern outside the cool core regions of clusters is similar to those of ISM in elliptical galaxies, the metals in the center of the Centaurus cluster may not be a simple mixture of those in the ICM and the current ISM in elliptical galaxies.

The difference between the Centaurus cluster and elliptical galaxies is the accumulation time scale of metals from stars. The IMLR using $B$-band luminosity of elliptical galaxies observed with ASCA is $10^{-5} - 10^{-4} M_{\odot}/L_{B, \odot}$ (Makishima et al. 2001), which is a factor of 3–30 smaller than that within $r_180$ (0.015$r_{180}$) of the Centaurus cluster. The enrichment timescale of excess Fe in the center of the Centaurus cluster is at least several Gyr (Böhringer et al. 2004), whereas the enrichment time scales of hot ISM in elliptical galaxies are smaller than 1 Gyr (Matsushita et al. 2000; Matsushita 2001). Therefore, a simple interpretation is that a longer time scale indicates that the ratio of the SN Ia rate to stellar mass loss rate was higher in the past.

Another interpretation is that SN Ia products in the ISM in elliptical galaxies are lost to intergalactic space by their buoyancy, as discussed in Matsushita et al. (2000), based on ASCA observations of early-type galaxies. Tang and Wang (2010) simulated the evolution of hot SN Ia ejecta, and found that they quickly reach a substantially higher outward velocity than the ambient medium. In the center of the Centaurus cluster, these ejecta can mix with the surrounding medium because of the long enrichment time.

The central value of Fe abundance of the Centaurus cluster is highest among nearby cool core clusters (Sanders & Fabian 2006; De Grandi & Molendi 2009; Matsushita 2011) within 0.03$r_{180}$: the Fe abundance of the Centaurus cluster is a factor of two higher than the average of the other clusters with cool cores. Within the cool core, the slope of the Fe abundance of the Centaurus cluster is the steepest, while those of the other nearby clusters with the cool cores are similar (Matsushita 2011).

With XMM observations of the Centaurus, Virgo, Perseus, and Abell 1795 clusters, Böhringer et al. (2004) found that the enrichment time for the central 20 kpc of the Centaurus cluster is a factor of two greater than those of the Virgo and Perseus clusters and a factor of 5 greater than that of the Abell 1795 cluster. We found that the integrated IMLR of the Centaurus cluster is a factor of two higher than that of Abell 262 and AWM 7 clusters. Furthermore, the central O/Fe and Mg/Fe ratios of the Centaurus cluster tend to be smaller than those of the other groups and clusters of galaxies (figure 7). These results indicate that the central regions of the Centaurus cluster contain more SN Ia yields than the other clusters.

With Chandra observations, Fabian et al. (2005) found that the core of the Centaurus cluster is complicated with bubbles and filaments, and sloshing motions of the gas within the central potential well or the central active galactic nuclei may cause the central structure of the ICM. The dynamics of the ICM in the cool core, particularly turbulent motions, have been used to explain the lack of cool X-ray emitting gas in the cool cores. The turbulent motion in the core of the Centaurus cluster is loosely constrained as $<1400 \text{ km} \text{s}^{-1}$ from the Suzaku/XIS analysis of Fe-line width for the Doppler broadening (Ota et al. 2007) and $<1100 \text{ km} \text{s}^{-1}$ from the XMM/RGS observations (Sanders et al. 2011). Graham et al. (2006) derived the limit of 400 km s$^{-1}$ in the central 25 kpc of the cluster based on an argument that strong turbulence would smear out, via diffusion, the observed abundance gradient. A tighter constraint will be attained with the future high-resolution spectrometer onboard the ASTRO-H (Mitsuda et al. 2010; Takahashi et al. 2010). The larger contribution from SN Ia limits mixing in the cool core in the center of the Centaurus cluster, compared to that in the other cool cores.

6. Summary and Conclusion

The abundance patterns of O, Mg, Si, S, Ar, Ca, and Fe were derived up to the outermost radius $0.17 r_{180}$ with Suzaku observations. Outside the cool core ($r > 0.07 r_{180}$), all elements have almost the same value of 0.5 solar, and the abundance pattern is approximately 1 solar ratio. The integrated IMLR is similar to other clusters of galaxies. The similarity of the abundances and MLRs indicates that clusters of galaxies may have universal metal enrichment histories outside the cool
cores. Within the cool core ($r < 0.05r_{180}$) the abundances suddenly increase toward the center. The Si, S, Ar, Ca, and Fe abundances have a value of 1.5–2 solar, while the O and Mg abundances have a value of ~1 solar. The highest central Fe abundance and IMGM and smaller O/Fe and Mg/Fe ratios compared to the other clusters limit the mixing in the cool core in the Centaurus cluster.

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