METAL-MASS-TO-LIGHT RATIOS OF THE PERSEUS CLUSTER OUT TO THE VIRIAL RADIUS

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ABSTRACT

We analyzed XMM-Newton data of the Perseus cluster out to ∼1 Mpc, or approximately half the virial radius. Using the flux ratios of Lyα lines of H-like Si and S to Ka line of He-like Fe, the abundance ratios of Si/Fe and S/Fe of the intracluster medium (ICM) were derived using the APEC plasma code v2.0.1. The temperature dependence of the line ratio limits the systematic uncertainty in the derived abundance ratio. The Si/Fe and S/Fe ratios in the ICM of the Perseus cluster show no radial gradient. The emission-weighted averages of the Si/Fe and S/Fe ratios outside the cool core are 0.91 ± 0.08 and 0.93 ± 0.10, respectively, in solar units according to the solar abundance table of Lodders. These ratios indicate that most Fe was synthesized by supernovae Ia. We collected K-band luminosities of galaxies and calculated the ratio of Fe and Si mass in the ICM to K-band luminosity, iron-mass-to-light ratio (IMLR), and silicon-mass-to-light ratio (SMLR). Within ∼1 Mpc, the cumulative IMLR and SMLR increase with radius. Using Suzaku data for the northwest and east directions, we also calculated the IMLR out to ∼1.8 Mpc, or about the virial radius. We constrained the SMLR out to this radius and discussed the slope of the initial mass function of stars in the cluster. Using the cumulative IMLR profile, we discuss the past supernova Ia rate.

Key words: galaxies: clusters: individual (the Perseus cluster) – galaxies: clusters: intracluster medium

Online-only material: color figures

1. INTRODUCTION

Clusters of galaxies are the largest gravitationally bound objects in the universe. The intracluster medium (ICM) contains a large amount of metals, synthesized by supernovae (SNe) in cluster galaxies. Thus, the distribution of metals in the ICM provides important information on the chemical history and evolution of clusters.

Because metals were synthesized in galaxies, the ratios of metal mass in the ICM to the total light from galaxies in clusters or groups (i.e., metal-mass-to-light ratios) are key parameters in investigating the chemical evolution of the ICM. Using Einstein and Ginga data, Arnaud et al. (1992) and Tsuru (1992) derived ratios of Fe mass in the ICM to the total light from galaxies, which is the iron-mass-to-light ratio (IMLR). To account for the observed IMLR, either the past average rate of SNe Ia was at least higher by a factor of 10 than the present rate or massive stars in clusters formed with a very flat initial mass function (IMF; Renzini et al. 1993). With ASCA observations, the derived IMLR within a radius where the ICM density falls below 3 × 10⁻⁴ cm⁻³ is nearly constant in rich clusters and decreases toward poorer systems (Makishima et al. 2001). With Suzaku, Chandra, and XMM satellites, the IMLR of several medium-sized clusters and groups of galaxies was measured out to 0.5r₁₈₀ (Matsushita et al. 2007b; Komiyama et al. 2009; Sato et al. 2007, 2008, 2009a, 2009b, 2010; Rasmussen & Ponman 2009; Sakuma et al. 2011) and that of the Coma cluster was derived out to 0.5r₁₈₀ (Matsushita et al. 2013). Suzaku first measured the Fe abundance of the ICM beyond 0.5r₁₈₀ (Fujita et al. 2008; Simionescu et al. 2011). With Suzaku, Sato et al. (2012) derived the IMLR profile of the Hydra A cluster out to r₁₈₀. Here, r₁₈₀ is the radius in which matter at 180 times the critical density of the universe is contained. In individual clusters, the IMLR is lower around the center, indicating that Fe in the ICM extends farther than stars. Therefore, to derive the total Fe mass in the ICM, we need observations out to the virial radius.

Since Fe is synthesized by both SNe Ia and by core-collapse SNe (hereafter SNecc), we need measurements of abundances of various elements to constrain contributions from the two types of SNe. The ASCA satellite first studied the Si abundance in the ICM (Fukazawa et al. 1998, 2000; Finoguenov et al. 2000, 2001). Fukazawa et al. (1998) reported that the Si/Fe ratio in the ICM increases with ICM temperature, and Finoguenov et al. (2000) reported that the Si/Fe ratio increases with radius in several clusters. Using Chandra data of groups out to r₅₀₀, Rasmussen & Ponman (2007) reported that the SNecc contribution increases with radius and completely dominates at r₅₀₀. XMM-Newton and Suzaku observations have also been used to study the Si/Fe ratio of the ICM in clusters and groups of galaxies. (e.g., Matsushita et al. 2003, 2007b, 2007a; Tamura et al. 2004; de Plaa et al. 2007; Rasmussen & Ponman 2007; Sato et al. 2007, 2008; Komiyama et al. 2009; Simionescu et al. 2009; de Grandi & Molendi 2009; Sato et al. 2009a, 2009b, 2010; Sakuma et al. 2011). With Suzaku observations of clusters and groups with ICM temperatures lower than ∼4 keV, the derived values of Si abundance are close to those of Fe out to 0.2r₁₈₀–0.5r₁₈₀, with a small scatter when using the solar abundance table by Lodders (2003). On the basis of the abundance ratios of Si and Fe, the contributions from SNe Ia and SNecc have been estimated. However, excluding cool-core regions, the error bars in the Si/Fe ratio of hotter clusters are very large (Tamura et al. 2004). Matsushita et al. (2013) derived the Si/Fe ratio in the ICM of the Coma cluster from the flux ratios of the Lyα line of H-like Si and the Ka line of He-like Fe. The temperature dependence of the line ratio above several keV is relatively small and limits the systematic uncertainty in the derived abundance ratio. The derived Si/Fe ratio of the Coma cluster is approximately 1 solar according to the same solar abundance table, with no radial gradient out to 0.5r₁₈₀.

The Perseus cluster is the brightest cool-core cluster, with a redshift of 0.018. With Chandra observations, the cool core of the Perseus cluster shows complicated features such as ripples
and shocks around radio bubbles (Fabian et al. 2006). With XMM, Tamura et al. (2004) derived the Si/Fe ratio outside the cool core of the Perseus cluster, (50–200 km s^{-1} kpc) to be 0.77 ± 0.25 in solar units using the solar abundance table by Lodders (2003). Here, the Hubble constant is H_{0} = 100h_{100} km s^{-1} Mpc^{-1}. With Suzaku data, Tamura et al. (2009) derived the abundance distribution of Mg, Si, S, Ar, Ca, Cr, Mn, Fe, and Ni of the central region of the Perseus cluster. Simionescu et al. (2011) derived the electron density and Fe abundance profiles out to the virial radius toward the northwest (NW) and east (E) directions observed with Suzaku. Simionescu et al. (2012) studied the large-scale motions of the ICM of the Perseus cluster using ROSAT, XMM, and Suzaku data.

In this paper, we study the Si/Fe and S/Fe ratios in the ICM of the Perseus cluster observed with XMM out to 1.1 Mpc. We collect the K-band luminosity of galaxies and calculated the ICM temperature from the Fe line, most of the continuum comes from non-X-ray background (NXB). As a result, a small uncertainty in the abundance of the Fe lines may affect the derived Fe abundance. To derive the strength of the Si line accurately and to derive S and Fe line abundances, the model and the derived abundances from the PN and MOS detectors differ by a factor of two. When we restricted energy ranges around H-like lines of Si and S and refitted the spectra, the derived abundances strongly depend on the adopted energy range.

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To derive the strength of the Si line accurately and to obtain suitable statistics, we fitted the raw (without background subtraction) MOS and PN spectra of each annular region outside 60 kpc (0.03 r_{180}/\text{LT}) to 1090 kpc (0.5 r_{180}/\text{LT}) simultaneously with a sum of the vAPEC code v2.0.1, two Gaussians for the Lyα line of H-like Si, a power-law model with Γ = 1.4 for the cosmic X-ray background, and a power-law model that is not folded through the auxiliary response file (ARF) for the NXB. Here, we used an energy range of 1.8–2.1 keV, the Si abundance of the vAPEC model was fixed at 0, and the abundance of the other metals was assumed to have a same value, which was left free. Above 1.8 keV, a systematic uncertainty caused by a strong instrumental fluorescence line at λ~1.7 keV of the MOS detector does not affect the derived Si abundance. To derive S and Fe line strengths, we fitted the spectra in the same manner but used an energy range of 2.3–2.8 keV and 6.0–7.2 keV, respectively. We added a 6.4 keV Gaussian for an instrumental background line. We did not use the region within 60 kpc where the temperature structure is rather complicated because of the cool core (Fabian et al. 2006). Tables 2 and 3 show the results of the spectral fits. We obtained reasonable χ^2 values and, as shown in Figure 2, the spectra around Si, S, and Fe lines of the MOS and PN were well reproduced by the model.

Within 0.5 r_{180}/\text{LT}, we derived the ICM temperature from the line ratio of Lyα of H-like Fe to Kα of He-like Fe using the APEC model. However, the derived abundance strongly depends on the adopted energy range.

Table 1

| ObsID* | (R.A., Decl.)* | Date* | Exposures (ks)* |
|--------|---------------|-------|----------------|
| 0085110101 | 03^h 19^m 48^s 36 | 2001 Jan 30 | 49, 51, 48 |
| 0085592001 | 03^h 19^m 45^s 12 | 2001 Feb 10 | 42, 40, 38 |
| 0131560101 | 03^h 16^m 39^s 07 | 2003 Feb 26 | 25, 25, 18 |
| 0204720201 | 03^h 21^m 33^s 80 | 2004 Feb 4 | 15, 15, 12 |
| 0204720201 | 03^h 23^m 18^s 92 | 2004 Feb 4 | 25, 25, 21 |
| 0305720301 | 03^h 22^m 16^s 00 | 2005 Aug 3 | 20, 21, 16 |
| 0305720101 | 03^h 18^m 01^s 94 | 2005 Sep 1 | 13, 13, 10 |
| 0305690101 | 03^h 17^m 58^s 31 | 2005 Feb 10 | 26, 27, 26 |
| 0305690001 | 03^h 19^m 45^s 91 | 2005 Feb 11 | 20, 16, 18 |
| 0305690001 | 03^h 21^m 49^s 07 | 2005 Feb 11 | 27, 27, 25 |
| 0405410101 | 03^h 21^m 04^s 82 | 2006 Aug 3 | 18, 16, 12 |
| 0405410201 | 03^h 18^m 44^s 75 | 2006 Aug 3 | 17, 26, 9 |

Notes.

* XMM-Newton observation identifier.
** In 12000.0.
*** Date of start of the observation.
**** Exposure times of MOS1, MOS2, and PN, respectively, after screenings.

2. OBSERVATIONS

We analyzed the archival data of the XMM-Newton observations of the Perseus cluster using PN, MOS1, and MOS2 detectors. In this study, we used SASv12.0, but the details of observations, event selection, and background subtraction are the same as those in Matsushita (2011). The observation log is summarized in Table 1. We included three observations in the archive in addition to those in Matsushita (2011). The exposure-corrected combined MOS image of the Perseus cluster within an energy range of 0.5–4.0 keV is shown in Figure 1. Spectra were accumulated in concentric annular regions centered on the X-ray peak of the Perseus cluster. The spectra from MOS1 and MOS2 were added.

3. DATA ANALYSIS AND RESULTS

3.1. Abundance Ratios of Si/Fe and S/Fe out to 0.5 r_{180}/\text{LT}

Figure 2 shows representative MOS and PN spectra around the Lyα lines of H-like Si and S and Kα line of He-like Fe. Although the Si and S lines are clearly seen in the spectra, the peak level of the lines in the spectra is only several percentage points above that of the continuum. For the spectra beyond several hundred kpc, around the Fe line, most of the continuum comes from non-X-ray background (NXB). As a result, a small systematic uncertainty in the response matrix and background can cause a large systematic uncertainty in the abundance of these elements. For example, when we fitted MOS and PN spectra at 0.1–0.2 r_{180}/\text{LT} using an energy range of 0.5–10.0 keV with a vAPEC model (Smith et al. 2001), there are discrepancies of a few percent around the Si and S lines between the data and the model and the derived abundances from the PN and MOS detectors differ by a factor of two. When we restricted energy ranges around H-like lines of Si and S and refitted the spectra, the derived abundances strongly depend on the adopted energy range.

To derive the strength of the Si line accurately and to obtain suitable statistics, we fitted the raw (without background subtraction) MOS and PN spectra of each annular region outside 60 kpc (0.03 r_{180}/\text{LT}) to 1090 kpc (0.5 r_{180}/\text{LT}) simultaneously with a sum of the vAPEC code v2.0.1, two Gaussians for the Lyα line of H-like Si and the Kα line of He-like Si, a power-law model with Γ = 1.4 for the cosmic X-ray background, and a power-law model that is not folded through the auxiliary response file (ARF) for the NXB. Here, we used an energy range of 1.8–2.1 keV, the Si abundance of the vAPEC model was fixed at 0, and the abundance of the other metals was assumed to have a same value, which was left free. Above 1.8 keV, a systematic uncertainty caused by a strong instrumental fluorescence line at λ~1.7 keV of the MOS detector does not affect the derived Si abundance. To derive S and Fe line strengths, we fitted the spectra in the same manner but used an energy range of 2.3–2.8 keV and 6.0–7.2 keV, respectively. We added a 6.4 keV Gaussian for an instrumental background line. We did not use the region within 60 kpc where the temperature structure is rather complicated because of the cool core (Fabian et al. 2006). Tables 2 and 3 show the results of the spectral fits. We obtained reasonable χ^2 values and, as shown in Figure 2, the spectra around Si, S, and Fe lines of the MOS and PN were well reproduced by the model.
at solar Si

line ratios of Si and S to Fe are close to theoretical expectations of He-like Fe plotted against the ICM temperature. The derived Fe, or 6.0–7.2 keV.

expectation by APEC v2.0.1.

v2.0.1 plasma code to reduce systematic uncertainties caused by e ICM temperature derived from the spectral fitting within energy range of d Fe abundance derived from the flux ratio of Kα Fe abundance.

The ICM temperature derived from the Fe line ratios using the theoretical expectation by Matsushita2011. The derived ICM temperatures are shown in Table2.

Figure 1. Exposure-corrected combined MOS image of the Perseus cluster (0.5–4.0 keV). The circles have radii of 0.03, 0.06, 0.1, 0.2, 0.3, and 0.5130(kpc). The numbers below the color bar have units of counts s−1 pixel−1.

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

Table 2

Results of the Spectral Fitting around Kα Line of Fe

| Radius (kpc/r180(kT)) | F6.9/F6.0+ | kTb (keV) | χ2/dfc | Fed (solar) |
|-----------------------|------------|-----------|--------|-------------|
| 60–130/0.03–0.06      | 0.23 ± 0.01| 5.9 ± 0.1 | 76/93  | 0.63 ± 0.01 |
| 130–220/0.06–0.1      | 0.30 ± 0.02| 6.5 ± 0.2 | 77/93  | 0.54 ± 0.03 |
| 220–440/0.1–0.2       | 0.27 ± 0.03| 6.2 ± 0.2 | 128/124| 0.47 ± 0.03 |
| 440–650/0.2–0.3       | 0.23 ± 0.05| 5.9 ± 0.5 | 59/52  | 0.38 ± 0.04 |
| 650–1090/0.3–0.5      | ···         | 5.6 ± 0.6 | 45/52  | 0.48 ± 0.07 |

Notes.

a Ratio of flux in units of photons cm−2 s−1 of Lyα line of H-like Fe and Kα line of He-like Fe.
b The ICM temperature derived from the Fe line ratios using the theoretical expectation by APEC v2.0.1.
c χ2 and degrees of freedom of the spectral fitting around the Kα line of He-like Fe, or 6.0–7.2 keV.
d Fe abundance derived from the flux ratio of Kα line of He-like Fe and the continuum at 3.5–6.0 keV.
e ICM temperature derived from the spectral fitting within energy range of 0.8–7.3 keV, considering 10% systematic error.

v2.0.1 plasma code to reduce systematic uncertainties caused by those in the response matrix and background. At 0.3–0.5r180(kT), we used deep sky observations as a background, and fitted the background-subtracted spectra within an energy range of 0.8–7.3 keV with an APEC model and a power law without ARF for a possible remaining NXB component. Furthermore, we added an 10% systematic error in the derived ICM temperature at 0.3–0.5r180(kT) considering the systematic uncertainties in the response matrix and background (Matsushita 2011). The derived ICM temperatures are shown in Table 2.

Figure 3 shows the ratio of Lyα of H-like Si or S to the Kα line of He-like Fe plotted against the ICM temperature. The derived line ratios of Si and S to Fe are close to theoretical expectations at solar Si/Fe and S/Fe ratios, respectively, by APEC v2.0.1 (Figure 3). These two line ratios show a similar temperature dependence: Above 5 keV, the line ratios are relatively flat at fixed Si/Fe or S/Fe ratios. The weak temperature dependence can minimize the effect of uncertainties in the temperature structure of the ICM. At a given ICM temperature and abundance ratio, the theoretical expectations obtained by the MEKAL and APEC codes differ by approximately 10%. The APEC v1.3 code gave almost the same line ratios with APEC v2.0.1. Therefore, any systematic effect due to the plasma codes is expected to be insignificant.

Using the APEC v2.0.1 code, we converted the derived line ratios to the abundance ratio of Si/Fe and S/Fe assuming the single temperature structure. Table 3 and Figure 4 summarize the derived Si/Fe and S/Fe ratios. The derived Si/Fe and S/Fe ratios show no radial gradient out to ~1100 kpc, or 0.5r180(kT).

Since the temperature dependence of the flux ratio of these lines is relatively flat above several keV, the derived abundance ratios should not change as a result of underestimating the ICM temperature. In contrast, if the ICM temperature is overestimated or if there is an emission component with a lower temperature, the same flux ratio yields a lower ICM abundance. As a result, the Si/Fe and S/Fe ratios should not be much greater than unity in solar units. The emission-weighted averages of the Si/Fe and S/Fe ratios outside the cool core, 130–1090 kpc, or 0.06–0.5r180(kT), are 0.91 ± 0.08 and 0.93 ± 0.10, respectively, in units of the solar ratio.

To derive the Fe abundance, we used the flux ratio of the Kα line of He-like Fe and the continuum at 3.5–6.0 keV (see Matsushita 2011 for details). Here, we used the APEC v2.0.1 code and the temperatures shown in Table 2. The results are shown in Table 2. The derived Fe abundances are almost the same as in Matsushita (2011). Figure 5 shows the radial profiles of Si, S, and Fe abundances. Beyond 220 kpc (0.1r180(kT)) from the center, the Si and S abundances have flat radial profiles at ~0.4 solar.

Figure 3 shows the ratio of Lyα of H-like Si or S to the Kα line of He-like Fe plotted against the ICM temperature. The derived line ratios of Si and S to Fe are close to theoretical expectations at solar Si/Fe and S/Fe ratios, respectively, by APEC v2.0.1.
3.2. K-band Luminosity of Galaxies

Because the K-band luminosity of a galaxy correlates well with the stellar mass, we calculated the luminosity profile of the K band. We collected K-band magnitudes of galaxies in a 10 × 10 deg² box centered on the center of the Perseus cluster from the Two Micron All Sky Survey (2MASS). Figure 6 shows the galaxies detected by 2MASS. In the Perseus cluster, the distribution of galaxies is elongated in an east–west direction. We selected galaxies above the completeness limit of 2MASS, $K_s = 13.5$ in apparent magnitude. We corrected the foreground Galactic extinction of $A_K = 0.06$ (Schlegel et al. 1998) by using the NASA/IPAC Extragalactic Database. The K-band surface brightness profile of the selected galaxies centered on the cD galaxy is shown in Figure 7. The average surface brightness in the region at $1.0r_{180<kT}> < r < 2.0r_{180<kT}>$ (100’ < r < 200’) was subtracted as the background. Next, we deprojected the brightness profile assuming a spherical

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4 See http://www.ipac.caltech.edu/2mass/releases/second/doc/explsup.html
The numbers on the plots show the Si/Fe or S/Fe ratios in solar units.

Table 3
Line Ratios of the Lyα of H-like Si and S to Kα to He-like Fe and Si/Fe and S/Fe Ratios

| Radius (kpc/r_{180(kt)}) | F_{Si}/F_{Fe}^{a} | Si/Fe^{b} (solar ratio) | \(\chi^{2}\)/dof^{c} | F_{Si}/F_{Fe}^{a} | S/Fe^{b} (solar ratio) | \(\chi^{2}\)/dof^{d} |
|--------------------------|-------------------|------------------------|-----------------|-------------------|------------------------|-----------------|
| 60–130/0.03–0.06         | 0.33 ± 0.03       | 0.99±0.08               | 22/22           | 0.23 ± 0.02       | 1.02±0.09              | 80/71           |
| 130–220/0.06–0.1          | 0.27 ± 0.04       | 0.87±0.14               | 22/22           | 0.23 ± 0.03       | 1.11±0.16              | 49/71           |
| 220–440/0.1–0.2           | 0.28 ± 0.03       | 0.88±0.10               | 16/22           | 0.17 ± 0.03       | 0.76±0.14              | 38/46           |
| 440–650/0.2–0.3           | 0.37 ± 0.05       | 1.15±0.17               | 11/22           | 0.16 ± 0.05       | 0.69±0.21              | 54/46           |
| 650–1090/0.3–0.5          | 0.26 ± 0.08       | 0.77±0.23               | 19/22           | 0.22 ± 0.06       | 0.97±0.26              | 45/46           |

Notes.

a Ratio of flux in units of photons cm\(^{-2}\) s\(^{-1}\) of Lyα line of H-like Si or S to Kα line of He-like Fe.

b The Si/Fe or S/Fe abundance ratios in units of solar ratio derived from the line ratio using the theoretical expectation by APEC v2.0.1.

c \(\chi^{2}\) and degrees of freedom of the spectral fitting around the Lyα line of H-like Si, or 1.8–2.1 keV.

d \(\chi^{2}\) and degrees of freedom of the spectral fitting around the Lyα line of H-like S, or 2.3–2.8 keV.

Table 4
Cumulative Values of K-band Luminosity (\(L_{K}\)), Gas Mass (\(M_{gas}\)), IMLR, and SMLR Derived with XMM

| Radius (kpc/r_{180(kt)}) | \(L_{K}\) (10^{12} L_{⊙}) | \(M_{gas}\) (10^{45} M_{⊙}) | IMLR (10^{-4} M_{⊙}/L_{⊙}) | SMLR (10^{-4} M_{⊙}/L_{⊙}) |
|--------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 130/0.06                 | 2.0                         | 3.2                         | 12.5±0.2                    | 7.0±0.1                     |
| 220/0.1                  | 2.9                         | 6.6                         | 16.0±0.4                    | 8.5±0.2                     |
| 440/0.2                  | 4.3                         | 21                          | 29±1                        | 15±1                        |
| 650/0.3                  | 6.0                         | 39                          | 34±2                        | 20±1                        |
| 1090/0.5                 | 6.9                         | 82                          | 64±5                        | 32±2                        |

3.3. Gas-mass, Si-mass, and Fe-mass Profiles

To estimate the integrated gas- and Fe-mass profiles, we accumulated MOS spectra in concentric annular regions with width of 1′–2′ out to 50′, or 0.5\(r_{180(kt)}\). We subtracted those of deep sky observations accumulated over the same detector regions as background. We fitted these spectra within an energy range of 1.6–5.0 keV with an APEC model to avoid uncertainties in the background. Here, the temperature and Fe abundance were restricted within the error bars shown in Table 2. We fitted the radial profile of the derived emission measures from the spectral fits per area with a sum of two \(\beta\)-models. The profile is well represented with the model and we calculated the electron density profile. We integrated the electron density profiles observed with XMM in this way out to 0.5\(r_{180(kt)}\) and Suzaku toward E and NW directions by Simionescu et al. (2011) of the Perseus cluster of \(-25.09±0.29\) (Lin et al. 2004). Integrating the luminosity function with the assumption of the Schechter function, the contribution of fainter galaxies below the 2MASS limit is a few percent.
out to $\sim r_{200\text{[HE]}}$ and derived the integrated gas-mass profiles (Figure 8 and Table 4). Because of gas sloshing and cold front at 700 kpc in the E direction, the integrated gas mass toward this direction is higher than that of the NW direction. The gas-mass profile with XMM falls between the profiles of the two directions with Suzaku out to 0.5$r_{180\text{[kT]}}$. With the integrated K-band luminosity and gas-mass profiles with XMM and weighted average for the two directions with Suzaku, we calculated the radial profiles of cumulative gas-mass-to-light ratio. In spite of differences in the observed azimuthal directions and in the analysis methods, as shown in Figure 9, the Suzaku and XMM gave similar radial profiles for the gas-mass-to-light ratio. The ratio increases with radius out to the virial radius.

We used the Si and Fe abundance profiles from XMM-Newton data and derived integrated mass profiles of Fe and Si in the ICM.

We also integrated the Fe mass using the weighted average of the Fe abundance profiles for the E and NW directions observed with Suzaku (Simionescu et al. 2011). The radial profiles of the cumulative IMLR and SMLR are shown in Figure 10 and Table 4. The error bars of the mass-to-light ratio include only the errors in abundance. These profiles continue to increase with radius out to 1800 kpc, $\sim r_{200\text{[HE]}}$.

4. DISCUSSIONS

4.1. The Abundance Pattern and Contribution of SNe Ia and SNecc

The derived Si/Fe and S/Fe ratios in the ICM of the Perseus cluster show no radial gradient out to 1.1 Mpc, or 0.5$r_{180\text{[kT]}}$. The emission-weighted averages of the Si/Fe and S/Fe ratios within 0.06–0.5$r_{180\text{[kT]}}$ are $0.91 \pm 0.08$ and $0.93 \pm 0.10$, respectively,
in solar units. These values are consistent with the emission-weighted average of the Si/Fe ratio of 0.99 ± 0.13 in solar units of the Coma cluster within 0.5$r_{180}(kT)$. They are also consistent with the values of ~0.8 in solar units of those in clusters and groups observed with Suzaku with ICM temperature less than several keV (e.g., Matsushita et al. 2007b; Sato et al. 2007, 2008, 2009a, 2009b, 2010; Komiyama et al. 2009; Sakuma et al. 2011).

Based on the abundance ratios including Si and Fe, the contribution from SNe Ia and SNecc were derived (e.g., Finoguenov et al. 2000; de Plaa et al. 2007; Rasmussen & Ponman 2007; Sato et al. 2007; de Grandi & Molendi 2009; Simionescu et al. 2009; Matsushita et al. 2013). Since Si and Fe were synthesized by both SNe Ia and SNecc, the contribution of the two types of SNe strongly depends on the adopted nucleosynthesis model of SNe Ia. With the yields of SNecc with metallicity $= 0.02$ by Nomoto et al. (2006), they found that by using the classical deflagration model, W7 (Iwamoto et al. 1999), and a delayed detonation (DD) model, WDD3 (Iwamoto et al. 1999), for the theoretical SN Ia yield, over a half of the Fe and a few tens of percent of Si in the ICM were synthesized in SNe Ia. By adopting another DD model, WDD1 (Iwamoto et al. 1999), they found that approximately half of the Si and most of the Fe come from SNe Ia. Suzaku enabled us to measure O and Mg abundances in the ICM outside cool cores of clusters and groups of galaxies with ICM temperatures smaller than several keV. Sato et al. (2007, 2009b, 2010) found that the mixture of yields of the W7 model and SNecc gave better fits of the observed abundance pattern of O, Mg, Si, S, and Fe in the ICM observed with Suzaku than for the WDD1 model and SNecc. The number ratio of SNecc and SNe Ia to synthesize metals in the ICM was also estimated with Suzaku and XMM data (e.g., de Plaa et al. 2007; de Grandi & Molendi 2009; Simionescu et al. 2009; Sato et al. 2007, 2009b, 2010). Using the Suzaku results including O and Mg, the number ratio of SNecc to SNe Ia was estimated to be $\sim 3.5$ and $\sim 2$, using the W7 and WDD1 models, respectively.

We also calculated yields mixtures of nucleosynthesis models. By adopting an Si/Fe ratio of 0.91 ± 0.08 in solar units in the ICM of the Perseus cluster, and using the W7 model, we find that 65%–74% and 23%–30% of Fe and Si, respectively, were synthesized by SNe Ia. Using the WDD1 model, 80%–91% and 56%–75% of Fe and Si, respectively, originated from SNe Ia. Here, we also used the yields of SNecc with metallicity $= 0.02$ by Nomoto et al. (2006). The difference in the Si/Fe ratios in the yields of SNecc assuming a Salpeter IMF and a top-heavy IMF and different nucleosynthesis models.
by Chieffi & Limongi (2004) and Woosley & Weaver (1995) are relatively small, within \( \sim 10\% \).

From the Si/Fe ratio of the Perseus cluster, we also derived the number ratio of the SNecc to SNe Ia to contribute metals in the ICM. Using the W7 and WDD1 models, the derived number ratios are 3.2–4.8 and 0.8–2.0, respectively. The number ratio from the Si/Fe ratio strongly depends on the adopted nucleosynthesis model, as found by previous studies.

The average S/Si ratio of the ICM in the Perseus cluster is \( 1.02 \pm 0.14 \) in solar units. The S/Fe ratio of the theoretical yield of SNcc by Nomoto et al. (2006) with metallicity = 0.02 and the Salpeter IMF is 0.83 in solar units. The yields of the W7 model and the WDD models are approximately 1.1–1.2 in solar units. Therefore, the observed S/Si ratio of the Perseus cluster is consistent with the yields of both SNe Ia and SNcc.

4.2. Si-mass-to-light Ratios and Initial Mass Function of Stars

The integrated SMLR using the \( K \) band at \( 0.5 \langle f_{180} \rangle \) of the Perseus cluster is \( \sim 0.003 M_\odot /L_{K,\odot} \). When we assume that the Si/Fe ratio beyond \( 0.5 \langle f_{180} \rangle \) is the same as that within the radius, the SMLR out to \( 0.86 \langle f_{180} \rangle \) becomes 0.004–0.005 \( M_\odot /L_{K,\odot} \) (Figure 10). The Si abundance is not expected to increase with radius because gas is more extended than stars. Then, assuming that the Si abundance beyond \( 0.5 \langle f_{180} \rangle \) is 0.4 solar, which is the Si abundance at 0.1–0.5 \( \langle f_{180} \rangle \), the SMLR becomes 0.005 \( M_\odot /L_{K,\odot} \). The clumping of the gas is significant (Simionescu et al. 2011) and the gas fraction at the virial radius is close to the value of the Wilkinson Microwave Anisotropy Probe 7 (Komatsu et al. 2011), the cumulative SMLR out to \( 0.86 \langle f_{180} \rangle \) is overestimated by 20%–30%. To summarize, the expected value of the SMLR at \( 0.86 \langle f_{180} \rangle \) is 0.003–0.005 \( M_\odot /L_{K,\odot} \). Adopting the W7 and WDD1 models for the SN Ia nucleosynthesis model, the SMLR synthesized by SNcc becomes 0.002–0.004 \( M_\odot /L_{K,\odot} \) and 0.001–0.002 \( M_\odot /L_{K,\odot} \), respectively.

The O, Mg, and Si abundances in the hot interstellar medium (ISM) in early-type galaxies reflect stellar metallicity because the ISM is thought to come from stellar mass loss. The abundances of these elements in the hot ISM in bright early-type galaxies observed with Suzaku are approximately 0.5–2 solar (Konami et al. 2012). Extrapolating the observed gradient of the Mg index in optical spectra of elliptical galaxies, Kobayashi & Arimoto (1999) calculated that the mean stellar metallicity [Fe/H] of individual galaxies ranges from \( -0.8 \) to \( +0.3 \) and correlates with stellar luminosity. They also found that typical [Mg/Fe] is approximately \( +0.2 \). These results indicate that the Si abundance in stars in giant cluster galaxies is approximately 0.5–2 solar. Using \( K \) band, the stellar mass-to-light ratio in bright early-type galaxies is approximately unity (Nagino & Matsushita 2009). As a result, the SMLR in stars should be \( 0.0005–0.002 M_\odot /L_{K,\odot} \). The estimated value of the total SMLR in the Perseus cluster (i.e., the sum of the SMLR in the ICM and in stars) is \( 0.004–0.008 M_\odot /L_{K,\odot} \).

Theoretical models predict that the oxygen-mass-to-light ratio and SMLR of a cluster are very sensitive functions of the slope of the IMF (Renzini 2005). Here, the oxygen and silicon mass are a sum of that trapped in stars and that in the ICM. Adopting a Salpeter IMF with a slope of 2.35, and difference in the stellar mass-to-light ratio between the \( B \) band and the \( K \) band equal 5, we find that the expected value of the SMLR from SNcc is \( \sim 0.02 M_\odot /L_{K,\odot} \). This value is close to the sum of the SMLR in stars and ICM from SNcc, adopting the nucleosynthesis yield of WDD1 model. Using the W7 yields, the SMLR from SNcc corresponds to a slope of \( \sim 2 \) based on the calculation by Renzini (2005). A top-heavy IMF with a slope of 1.35 overproduces metals more than that with a factor of 20. Therefore, the expected value of the SMLR out to the virial radius does not need the top-heavy IMF.

4.3. Fe Mass and Past SN Ia Rate

The solar Si/Fe abundance ratio in the ICM of the Perseus cluster indicates that most of the Fe was synthesized by SNe Ia. The estimate of the current SN Ia rate in present early-type galaxies is \( 0.1–0.3 \) SN Ia/(100 yr)/(10\(^10\) \( L_\odot \)) (Cappellaro et al. 1997, 1999; Turatto et al. 1999; Sharon et al. 2007; Mannucci et al. 2008). We adopted the Fe mass by one SN Ia rate of 0.75 \( M_\odot \) by W7 model (Iwamoto et al. 1999) and \( L_K/L_B \sim 5 L_K/L_B \) for early-type galaxies (Nagino & Matsushita 2009). Then, accumulating the present SN Ia rate over the Hubble time, 13.7 Gyr, the expected IMLR from SNe Ia becomes \( (2–6) \times 10^{-4} M_\odot /L_{K,\odot} \). This value is over an order of magnitude smaller than the observed IMLR (6–7) \( \times 10^{-2} M_\odot /L_{K,\odot} \) and \( (7–9) \times 10^{-2} M_\odot /L_{K,\odot} \) within \( 0.5 r_{180} \) and \( \sim 0.86 r_{180} \), respectively.

The increase of the radial profile of the IMLR with radius of clusters indicates that Fe in the ICM extends farther than stars, at least out to \( 0.5 r_{180} \). Leccardi & Molendi (2008) and Matsushita (2011) discovered that the Fe abundance profiles of the ICM within \( r_{500} \) are flatter than expected from the numerical simulations by Fabjan et al. (2008), without active galactic nucleus feedback. These results indicate that a significant fraction of Fe is synthesized in an early phase of cluster evolution, because if metal enrichment occurs after the formation of clusters, the metal distribution is expected to follow the stellar distribution. Considering that most Fe is synthesized by SNe Ia, the lifetimes of most of SN Ia are much shorter than the Hubble time, and the SN Ia rate in cluster galaxies was much higher in the past. If the IMF is close to that in our Galaxy and if most of stars in our Galaxy and clusters were already formed before a few Gyr ago, the abundance pattern (including the ICM and stars in cluster galaxies) should naturally be similar to the solar abundance pattern.

4.4. Comparison of Radial Profiles of IMLR with other Systems

Figure 11 compares the cumulative IMLR profile of the Perseus cluster with those of clusters of galaxies observed with Suzaku or XMM out to 0.5–1.0 \( r_{180} \) including Coma (8 keV; Matsushita et al. 2013), A262 (2 keV; Sato et al. 2009b), AWM 7 (3.6 keV; Sato et al. 2008), and the Hydra A (3.0 keV; Sato et al. 2012) clusters. The IMLR profiles of three cool-core clusters at a similar redshift, A262, AWM 7, and the Perseus cluster, agree very well with each other at 0.2–0.5 \( r_{180} \), whereas the Coma cluster has a lower IMLR at 0.5 \( r_{180} \). There is no significant temperature dependence on the derived IMLR profiles. Since the IMLR profiles increase with radius, comparison of the total IMLR values requires observations of IMLR profiles of clusters out to the virial radii.

At a given radius in units of \( r_{180} \), the Hydra A cluster has a factor-of-two-higher IMLR than the Perseus cluster. Because of the higher redshift of the Hydra A cluster and lower ICM temperature, the number of galaxies detected in Hydra A might not be sufficient to deproject the luminosity profiles in the \( K \) band. However, at \( r_{180} \), where systematic uncertainties due to the limited number of galaxies are relatively small, the cumulative IMLR of the Hydra A and the Perseus clusters agree well.
No systematic dependence on the ICM temperature is evident for these two clusters with temperatures of 3 keV and 6 keV.

At the center, within 0.1$r_{180(kT)}$, the Perseus cluster and the Hydra A cluster have much higher IMLR than the other systems, which is due to the very bright cool core of these two clusters. Within this radius, the cD galaxies dominate the K-band luminosity and the systematic uncertainties in the K-band luminosity should be small. The IMLR within 0.1$r_{180(kT)}$ of the Perseus and Hydra A clusters are about (1.5–2) $\times 10^{-3} M_{\odot}/L_{K,\odot}$, which is a factor 3–10 higher than the expected IMLR from SNe Ia assuming the present SN Ia rate over the Hubble time. The higher IMLR in these two clusters reflect higher gas-mass-to-light ratio in 0.1$r_{180(kT)}$, since the Fe abundance of these two clusters is not higher than those of the other clusters in this region (Simionescu et al. 2009; Matsushita 2011). Simionescu et al. (2009) measured the distribution of O, Si, S, Ar, Ca, Fe, and Ni in the ICM of the Hydra A cluster within $\sim$0.1$r_{180(kT)}$. They found that O abundance decreases with radius and amount of metals are much higher than the expected values by stellar winds. They discussed the initial enrichment by SNecc in the early phase in cluster evolution and mixing of these metals. The O/Fe and Mg/Fe ratios within the cool core of the Perseus cluster are about unity in solar units (Matsushita & Tamura 2011) and agrees with the O/Fe ratio in the cool core of the Hydra A cluster (Simionescu et al. 2009). The metals already synthesized in the protocluster phase can dominate those in the central regions of these two clusters.

4.5. Gas-mass-to-light Ratio

The integrated gas-mass-to-light ratio of the Perseus cluster increases with radius out to 1800 kpc, or $\sim r_{200(HE)}$. At 1800 kpc, $M_{\text{gas}}(<r)/L_K(<r) = 16 M_{\odot}/L_{\odot}$. This value is not so different from 21 $\pm$ 4 $M_{\odot}/L_{\odot}$ for the Hydra A cluster ($(kT) = 3$ keV) at $r_{200(HE)}$. The stellar- and gas-mass fractions within $r_{500}$ depend on the total system mass (Lin et al. 2003, 2004; Sun et al. 2009; Giodini et al. 2009; Zhang et al. 2011). The gas density profiles in the central regions of groups and poor clusters were observed to be shallower than those obtained by the self-similar model, and the relative entropy level was correspondingly higher than that in rich clusters (Ponman et al. 1999, 2003; Sun et al. 2009). Then, the difference in the ratio of gas mass to stellar mass might reflect differences in distributions of gas and stars, which reflects the history of energy injection from galaxies into the ICM. To study the fractions of stars and gas in clusters of galaxies, and their dependence on the system mass, measurements beyond $r_{500}$ of other clusters are required.

Based on the Suzaku observations of the NW and E directions of the Perseus cluster, Simionescu et al. (2011) proposed that the gas-clumping effect is significant beyond $r_{500}$, and that the electron density is overestimated. Then, $M_{\text{gas}}$ within $r_{200(HE)}$ is overestimated by a factor of 1.3–1.5. Adopting this value for the gas mass, the gas-mass-to-light ratio at $r_{200(HE)}$ becomes 11–12 $M_{\odot}/L_{\odot}$, which is close to the value at 1000 kpc, or 0.6 $r_{200(HE)}$. In other words, if there is a significant clumping effect, the gas-mass-to-light ratio becomes flat beyond this radius out to $r_{200(HE)}$.

5. SUMMARY AND CONCLUSION

We analyzed XMM-Newton data of the Perseus cluster out to 0.5$r_{180(kT)}$ and derived the Si/Fe and S/Fe ratios in the ICM from the flux ratios of the Ly$\alpha$ lines of H-like Si and S to the K$\alpha$ line of He-like Fe. The small temperature dependence of the line ratio limits the systematic uncertainty in the derived abundance ratio. The derived Si/Fe and S/Fe ratios in the ICM show no radial gradient. The emission-weighted averages of the Si/Fe and S/Fe ratios beyond the cool core of the Perseus cluster are 0.91 $\pm$ 0.08 and 0.93 $\pm$ 0.10, respectively, in solar units. These abundance ratios indicate that most of Fe in the ICM within 0.5$r_{180(kT)}$ was synthesized by SNe Ia.

We collected K-band luminosities in galaxies detected with 2MASS and derived the cumulative radial profile of the K-band luminosity of stars in the Perseus cluster. We calculated the cumulative IMLR and SMLR profiles out to $r_{180(kT)}$. Furthermore, by using the electron density profiles and Fe abundance profiles in the two directions observed with Suzaku, we calculated the cumulative IMLR profile out to the virial radius. We also constrained the SMLR value out to this radius. The SMLR of the Perseus cluster out to the virial radius is significantly smaller than expected from the top-heavy IMF, which has a slope of 1.35, and is more consistent of a slope of the Salpeter IMF. With the present SN Ia rate, the IMLR within the virial radius is an order of magnitude higher than the SN Ia yield accumulated over the Hubble time. Since the IMLR increases with radius, the most of Fe from SNe Ia were synthesized in an early phase of cluster formation.

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