Suzaku Observation of the Metallicity Distribution in the Intracluster Medium of the Fornax Cluster

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Abstract

The metallicity distribution in the Fornax cluster was studied with the XIS instrument on board the Suzaku satellite. The K-shell lines of O and Mg were resolved clearly, and the abundances of O, Mg, Si, S, and Fe were measured with great accuracy. The region within a 4′ radius of NGC 1399 shows approximately solar abundances of Fe, Si, and S, while the O/Fe and Mg/Fe abundance ratios are about 0.4–0.5 and 0.7 in solar units, respectively. In the outer region of the radius range 6′ < r < 23′, the Fe and Si abundances drop to 0.4–0.5 solar and show no significant gradient within this region. The abundance ratios, O/Fe and Mg/Fe, are consistent with those in the central region. We also measured the Fe abundance around NGC 1404 to be approximately solar, and the O, Ne, and Mg abundances to be 0.5–0.7 times the Fe level. A significant relative enhancement of Fe within 130 kpc of NGC 1399 and in NGC 1404 indicates an origin in SN Ia, in contrast to the species O, Ne, and Mg, which reflect the stellar metallicity. The mass-to-light ratios for O and Fe within 130 kpc of NGC 1399 are over an order of magnitude lower than those in rich clusters, reflecting the metal enrichment history of this poor cluster.

Key words: galaxies: abundances — galaxies: clusters: individual (the Fornax cluster) — galaxies: clusters: intracluster medium — galaxies: individual (NGC 1399, NGC 1404) — galaxies: ISM

1. Introduction

The metal abundances in the intracluster medium (ICM) and the hot X-ray emitting interstellar medium (ISM) of early-type galaxies provide important clues in understanding the metal enrichment history and evolution of galaxies. The ICM contains a large amount of metals, which are mainly synthesized by supernova (SN) in early-type galaxies (e.g., Arnaud et al. 1992; Renzini et al. 1993).

The ASCA satellite (Tanaka et al. 1994) first enabled us to measure the distribution of Fe in the ICM (e.g., Fukazawa et al. 2000; Finoguenov et al. 2000, 2001). The derived iron-to-light ratio (IMLR) is nearly constant in rich clusters and decreases toward poorer systems (Makishima et al. 2001). In individual clusters, the IMLR is lower around the center (Makishima et al. 2001). The Si abundance of the ICM was also measured by ASCA (Fukazawa et al. 1998, 2000; Finoguenov et al. 2000, 2001); however, since Fe and Si are both synthesized in SN Ia and SN II, the abundance results for these species cannot clearly constrain the nucleosynthesis contribution from different SN types. In contrast, O and Mg are predominantly synthesized in SNe II. Abundance measurements covering the range of species from O to Fe are therefore needed to obtain unambiguous information on the formation history of massive stars.

XMM-Newton provided the means to measure O and Mg abundances in some systems, but reliable results have been obtained only for the central regions of very bright clusters or groups of galaxies dominated by cD galaxies (e.g., Xu et al. 2002; Finoguenov et al. 2002; Tamura et al. 2003; Matsushita et al. 2003, 2006; Buote et al. 2003). In general, the measured abundances of Si and Fe are similar, while the O abundance is only about half of the Fe abundance. This indicates that cD galaxies are an important source of Si and Fe, which are mainly synthesized in SN Ia. However, our knowledge about the distributions of O and Mg in the ICM is still poor, in contrast to the detailed measurement of the Fe and Si abundances with XMM-Newton (e.g., Tamura et al. 2004).

Regarding early-type galaxies, the metal abundances in the ISM give us important information about the present metal supply into the ICM through SN Ia and stellar mass loss. In addition, O and Mg abundances should reflect the stellar
metallicity and enable us to directly look into the formation history of these galaxies.

In this paper, based on Suzaku (Mitsuda et al. 2007) observations, the abundances of O, Mg, Si, S, and Fe of the ICM in the Fornax cluster and those of O, Ne, Mg, and Fe of the ISM in NGC 1404 are discussed. The XIS (Koyama et al. 2007) instrument onboard Suzaku has good energy resolution at the O line energy with low background, providing better sensitivity than the EMOS onboard XMM-Newton. The EMOS also has a problem in measuring the Mg abundance in somewhat fainter systems, due to a strong instrumental Al line. The Mg lines are particularly useful in cluster outskirts, since the strong Galactic O line causes difficulty in measuring O emission from nearby clusters.

The Fornax cluster is a nearby poor cluster with an ICM temperature of 1.3–1.5 keV (e.g., Scharf et al. 2005). The X-ray emission shows an asymmetric spatial distribution, and the cD galaxy, NGC 1399, is offset from the center (Paolillo et al. 2002; Sharf et al. 2005), which may be related to a large-scale dynamical evolution, such as infall motions of galaxies into the cluster (Dunn, Jerjen 2006). Chandra observations suggest that there may be relative motion between NGC 1399 and the ICM, and the 2nd brightest elliptical galaxy, NGC 1404, is moving supersonically in the ICM (Scharf et al. 2005; Machacek et al. 2005). For the ICM abundances, the Fe and Si abundances within ∼ 50 kpc of NGC 1399 were measured with XMM-Newton (Buote 2002). However, due to the high background of XMM-Newton, the O and Mg abundances of the ICM were not determined.

ASCA detected excess hard X-ray emission from several groups of galaxies, including the Fornax cluster (Fukazawa et al. 2001; Nakazawa 2001). Dynamical motions in the cluster, driven by merger events, that generate a population of relativistic particles may be the origin of this emission component. Suzaku results on hard emission from Fornax will be presented in a separate article after a detailed study of the detector background.

We adopt solar abundances in Feldman (1992), where the solar O and Fe abundances relative to H are $8.51 \times 10^{-4}$ and $3.24 \times 10^{-5}$ by number. Recently, the solar photospheric abundances of C, N, O, and Ne decreased by 0.2 dex, considering three-dimensional hydrodynamical model atmospheres and nonlocal thermodynamic equilibrium (Asplund 2005 and references therein). The new solar O and Fe abundances relative to H are $4.90 \times 10^{-4}$ and $2.95 \times 10^{-5}$, respectively (Lodders 2003). The effect of the new solar abundances is discussed in section 4.

We adopt 19 Mpc (for $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$) for the distance to the Fornax cluster. The observation of Cepheids with Hubble Space Telescope yielded a distance of $18.6 \pm 0.6$ Mpc (Madore et al. 1999). Unless otherwise specified, errors are quoted at 90% confidence.

2. Observations

The Fornax cluster was observed twice as a part of the initial performance verification of Suzaku. The first observation (hereafter, the central field) was carried out on 2005 September with pointing direction 2' south and 1' east of NGC 1399.

The second one (hereafter, the north field) was centered 13' north and 4' east of NGC 1399, and was carried out on 2006 January. Figure 1 shows a 0.3–5.0 keV image for the two fields. The two peaks in the central field correspond to a cD galaxy, NGC 1399, and an elliptical galaxy, NGC 1404.

Both the X-ray Imaging Spectrometers (XIS; Koyama et al. 2007) and the Hard X-ray Detector (HXD) were operated in their nominal modes. We discarded data taken with a cut-off rigidity of less than 6 GeV, or an elevation angle less than 10° from the earth rim. This yielded exposure times of 68 ks and 85 ks for the central and the north fields, respectively. We used the response matrix files ae_xi0[0,2,3]_segc_rmf_20060213.fit for the front side illuminated (FI) detectors, XIS 0, XIS 2, and XIS 3, and ae_xi1_20060213c.rmf for the back side illuminated (BI) detector, XIS 1. The energy range analyzed here covers 0.3 to 5.0 keV for the BI detector and 0.4 to 5.0 keV for the FI detectors. The on-axis auxiliary response files ae_xi0[1,2,3]_xisnom4_20060415s.arf are used for the respective detectors, since below 5 keV, the energy dependence of the auxiliary response file is smaller than the statistical errors. We also ignored the energy range between 1.82 and 1.84 keV in the spectral fit, since the response matrix around the Si edge has some problems.

3. Analysis and Results

3.1. Spectra of NGC 1399 and ICM

The data from each XIS detector were accumulated within concentric rings, centered on NGC 1399. The spectrum of the bright galaxy NGC 1404 was separately analyzed, and a region with a radius of 4' centered on this galaxy was masked out for this portion of the analysis. As for the background, we had to consider the non X-ray background (NXB), the cosmic X-ray background (CXB), and the Galactic emission, which arise from the local hot bubble (LHB) and the Milky Way halo (MWH). Figure 2 shows the spectra for the outermost ($r > 16'$) region of the Fornax cluster, compared with the blank-sky (Lockman Hole observed on 2005 November) and the night-earth spectra accumulated over the same region of the detector. In the low-energy band the Lockman-Hole data is not appropriate for the background, since the temperature and intensity of the Galactic emission differ significantly with sky region and the low-energy efficiency of the XIS instrument has been declining since launch due to contamination on the XIS filters (Koyama et al. 2007). Therefore, we subtracted the night-earth data as the non X-ray background, and the CXB and the Galactic emission are included as models in the spectral fit.

We fitted the background-subtracted spectra with a model consisting of 4 components: a single-temperature vAPEC model (Smith et al. 2001) for the ICM, a power-law model for discrete sources and the possible hard component, a power-law model for the CXB, and an APEC model for the LHB. (We exclude MWH component since, as summarized in table 1, fits exclude MWH component since, as summarized in table 1, fits for the LHB were subject to a common interstellar absorption, $N_H$, fixed at the Galactic value, $1.3 \times 10^{20}$ cm$^{-2}$. The ICM abundances of C
and N were fixed to solar, while those of the other species were allowed to vary. For the XIS 1 (BI) spectra of the north field, the temperature and normalization of the Galactic emission were left free with abundance fixed to solar. For the other FI and BI spectra, the parameters of the Galactic emission were fixed to the best-fit values obtained with the BI detector for the \( r > 16' \) region in the north field, which are summarized in Table 1. Within a radius of 4', we also applied a two-temperature model for the ICM, where the metal abundances of the two components were assumed to have the same value.

As mentioned above, contamination has been building up on the XIS camera filters, and thus reducing the low-energy efficiency. A spectral model describing this effect has been developed. We assume the chemical composition of the contamination to have a O/C number ratio of 1/6, and in the fits we allow the thickness of the molecular layer to vary independently for each XIS detector. Later we assess systematic uncertainties arising from our models of the Galactic emission and contamination.

Table 2 summarizes the results of the spectral fits. The BI and FI detectors (in Table 2 labeled XIS 1 and XIS 023, respectively) have given generally consistent best-fit values for the temperature and the abundance. Within \( r = 4' \), the two-temperature model significantly improved the fit. For \( r < 2' \), the fit around the H-like O line of the XIS 1 is not satisfactory; the \( \chi^2 \) value for the limited energy range 0.57–0.73 keV is 20 for 12 bins. Adding another temperature component does not improve the fit in the inner region. For the FI detectors, as described in subsection 3.2 below, the O abundance may also have a systematic uncertainty at \( r < 2' \), since the derived value of the column density of the contaminant is significantly higher than that in the empirical model.

The temperature of the ICM is almost constant at 1.3 keV from a radius of 4' to 16' and outside 16', and it drops to 1 keV (Figure 4). Within 4', we need two-temperature components, 0.8 keV and 1.4 keV, to fit the spectra.

Table 2. Parameters of background obtained with the BI detector for \( r > 16' \) in the north field.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHB ( kT ) (keV)</td>
<td>0.08</td>
</tr>
<tr>
<td>MWH ( kT ) (keV)</td>
<td>0.20</td>
</tr>
<tr>
<td>Ratio of normalization of MWH/LHB</td>
<td>0.0 (&lt; 0.06)</td>
</tr>
<tr>
<td>CXB photon index</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Chandra data (Humphrey, Buote 2006). On the other hand, the Mg abundance is 20–30% lower and O is a factor of 2–3 lower compared with the level of Si, S, and Fe. Adding temperature components did not change the abundance ratios, although the error bars of the absolute abundances became larger. Figure 6 summarizes the abundance ratios of O, Mg, Si, and S divided by the Fe value in units of the solar ratio. The O abundance within a radius of 2′ may have a large systematic uncertainty, since the spectral fit around the O line had a problem. The abundance ratios are consistent with having no radial gradients. On the average, the O/Fe, Mg/Fe, Si/Fe, and S/Fe values are 0.47 ± 0.05 (excluding r < 2′′), 0.72 ± 0.05, 0.93 ± 0.05, and 0.96 ± 0.05 in solar units, respectively, clearly indicating that the ratio grows as a function of the atomic number.

3.2. Uncertainties in the Spectral Fits

In this section, we consider the uncertainties in the abundance determination due to those in the spectral models and in the calibration of the detectors.

In order to look into the systematic effect by the plasma code on the abundance determination, we fitted the spectra with the vMEKAL model (Mewe et al. 1985, 1986; Kaastra 1992; Liedahl et al. 1995) and compared the results with those from the APEC model. The reduced $\chi^2$ from the vMEKAL model are systematically larger than the vAPEC case, since the latter model gives improved fits for the Fe-L lines. As a result, the Mg abundance from the vMEKAL model is 20–40% lower than the vAPEC fit, although the temperature and abundances of O, Si, S, and Fe agree within 10%. Figure 7 shows the representative spectrum around the Mg K-shell lines. The best-fit vAPEC model and the observed spectrum agree well in this energy range, while the vMEKAL model tends to overpredict the He-like Mg line. The $\chi^2$ values for the limited energy range 1.25–1.45 keV are 7.3 and 18.7 for 14 bins for the vAPEC model and vMEKAL model, respectively. Therefore, the Mg abundance derived from the vAPEC model is more reliable than the vMEKAL fit, and the systematic uncertainty in the Mg abundance concerning the atomic data is thought to be much less than 40%.

The true value of the metal abundance at the center may be higher, because of projection effects and the point spread function of the X-ray telescope, both of which tend to dilute the central sharp feature. The XMM-Newton data, fitted with a two-temperature model, show the Fe abundance within 20 kpc to be 1.5–2 solar (Buote 2002). We fitted the central r < 2′ spectrum with 2 APEC models with the temperature and abundance of one component fixed at the best-fit values for 4′ < r < 6′. The resultant abundance ratios remained the same, but higher abundances by dozens of percent were allowed.

Since the Milky Way emits in O, modeling uncertainties could cause systematic uncertainty in determining the O abundance of the ICM. The MWH component has a higher

<table>
<thead>
<tr>
<th>$r^*$ (kpc)</th>
<th>Model</th>
<th>XIS</th>
<th>$kT$ (keV)</th>
<th>EM ratio</th>
<th>O (solar)</th>
<th>Mg (solar)</th>
<th>Si (solar)</th>
<th>S (solar)</th>
<th>Fe (solar)</th>
<th>$\chi^2$/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>1T†</td>
<td>1</td>
<td>0.99</td>
<td>0.18</td>
<td>0.31</td>
<td>0.49</td>
<td>0.64</td>
<td>0.51</td>
<td></td>
<td>461/147</td>
</tr>
<tr>
<td>0-2</td>
<td>2T‡</td>
<td>1</td>
<td>1.48 ± 0.10</td>
<td>0.60 ± 0.07</td>
<td>0.34 ± 0.05</td>
<td>0.97 ± 0.13</td>
<td>1.14 ± 0.13</td>
<td>1.09 ± 0.19</td>
<td>1.18 ± 0.16</td>
<td>145/145</td>
</tr>
<tr>
<td>0-2</td>
<td>1T</td>
<td>023</td>
<td>1.00</td>
<td>0.24</td>
<td>0.35</td>
<td>0.54</td>
<td>0.63</td>
<td>0.60</td>
<td></td>
<td>848/256</td>
</tr>
<tr>
<td>0-2</td>
<td>2T</td>
<td>023</td>
<td>1.35 ± 0.02</td>
<td>0.70 ± 0.12</td>
<td>0.47 ± 0.10</td>
<td>0.64 ± 0.07</td>
<td>0.94 ± 0.07</td>
<td>0.92 ± 0.11</td>
<td>0.98 ± 0.04</td>
<td>270/253</td>
</tr>
<tr>
<td>2-4</td>
<td>1T</td>
<td>1</td>
<td>1.24 ± 0.02</td>
<td>0.28 ± 0.06</td>
<td>0.38 ± 0.11</td>
<td>0.68 ± 0.09</td>
<td>0.57 ± 0.12</td>
<td>0.62 ± 0.03</td>
<td></td>
<td>253/154</td>
</tr>
<tr>
<td>2-4</td>
<td>2T</td>
<td>1</td>
<td>1.41 ± 0.05</td>
<td>0.20 ± 0.02</td>
<td>0.44 ± 0.09</td>
<td>0.88 ± 0.17</td>
<td>1.07 ± 0.14</td>
<td>0.83 ± 0.18</td>
<td>0.97 ± 0.10</td>
<td>164/152</td>
</tr>
<tr>
<td>2-4</td>
<td>1T</td>
<td>023</td>
<td>1.27 ± 0.01</td>
<td>0.30 ± 0.08</td>
<td>0.40 ± 0.07</td>
<td>0.67 ± 0.06</td>
<td>0.76 ± 0.08</td>
<td>0.65 ± 0.03</td>
<td></td>
<td>356/258</td>
</tr>
<tr>
<td>2-4</td>
<td>2T</td>
<td>023</td>
<td>1.47 ± 0.11</td>
<td>0.23 ± 0.08</td>
<td>0.45 ± 0.11</td>
<td>0.65 ± 0.08</td>
<td>0.90 ± 0.09</td>
<td>0.95 ± 0.08</td>
<td>0.90 ± 0.10</td>
<td>285/256</td>
</tr>
<tr>
<td>4-6</td>
<td>1T</td>
<td>1</td>
<td>1.33 ± 0.02</td>
<td>0.17 ± 0.06</td>
<td>0.35 ± 0.14</td>
<td>0.54 ± 0.09</td>
<td>0.59 ± 0.14</td>
<td>0.55 ± 0.05</td>
<td></td>
<td>157/123</td>
</tr>
<tr>
<td>4-6</td>
<td>1T</td>
<td>023</td>
<td>1.34 ± 0.01</td>
<td>0.24 ± 0.09</td>
<td>0.49 ± 0.08</td>
<td>0.67 ± 0.07</td>
<td>0.63 ± 0.10</td>
<td>0.56 ± 0.03</td>
<td></td>
<td>223/218</td>
</tr>
<tr>
<td>6-11</td>
<td>1T</td>
<td>1</td>
<td>1.23 ± 0.02</td>
<td>0.31 ± 0.08</td>
<td>0.40 ± 0.10</td>
<td>0.32 ± 0.09</td>
<td>0.30 ± 0.17</td>
<td>0.42 ± 0.04</td>
<td></td>
<td>156/129</td>
</tr>
<tr>
<td>6-11</td>
<td>1T</td>
<td>023</td>
<td>1.31 ± 0.02</td>
<td>0.20 ± 0.08</td>
<td>0.35 ± 0.08</td>
<td>0.37 ± 0.08</td>
<td>0.49 ± 0.10</td>
<td>0.40 ± 0.03</td>
<td></td>
<td>274/230</td>
</tr>
<tr>
<td>8-16</td>
<td>1T</td>
<td>1</td>
<td>1.24 ± 0.02</td>
<td>0.23 ± 0.06</td>
<td>0.36 ± 0.10</td>
<td>0.40 ± 0.07</td>
<td>0.37 ± 0.11</td>
<td>0.49 ± 0.05</td>
<td></td>
<td>200/174</td>
</tr>
<tr>
<td>8-16</td>
<td>1T</td>
<td>023</td>
<td>1.25 ± 0.01</td>
<td>0.31 ± 0.07</td>
<td>0.36 ± 0.04</td>
<td>0.42 ± 0.04</td>
<td>0.49 ± 0.06</td>
<td>0.54 ± 0.03</td>
<td></td>
<td>789/651</td>
</tr>
<tr>
<td>16-23</td>
<td>1T</td>
<td>1</td>
<td>1.06 ± 0.01</td>
<td>0.23 ± 0.08</td>
<td>0.33 ± 0.14</td>
<td>0.44 ± 0.10</td>
<td>0.43 ± 0.21</td>
<td>0.43 ± 0.04</td>
<td></td>
<td>110/83</td>
</tr>
<tr>
<td>16-23</td>
<td>1T</td>
<td>023</td>
<td>1.06 ± 0.01</td>
<td>0.24 ± 0.08</td>
<td>0.33 ± 0.06</td>
<td>0.29 ± 0.05</td>
<td>0.45 ± 0.11</td>
<td>0.43 ± 0.04</td>
<td></td>
<td>375/288</td>
</tr>
</tbody>
</table>

* The radius from the center of NGC 1399.
† The ratio of emission measure of the lower to higher temperature components.
‡ The single-temperature vAPEC model for the ICM.
§ The two-temperature vAPEC model for the ICM.
Fig. 3. (Upper panel) The XIS 0 (red) and XIS 1 (black) spectra from $r < 2'$, with the night-earth data subtracted as the background, fitted with a 4-component model: two vAPEC models for the ICM, a power law for the CXB, and an APEC model for the Galactic emission. (Lower panel) The spectra at $8' < r < 16'$ in the north field, fitted with the same model but with a single-temperature vAPEC model for the ICM. Residuals are shown at the bottom of each panel.

Fig. 4. Temperature profile of the ICM using the single-temperature vAPEC model (open circles) and the two-temperature vAPEC model (open triangles) derived from XIS 1 (solid lines) and XIS 0, 2, 3 (dotted lines) detectors.

Fig. 5. Abundance profiles of O, Mg, Si, S, and Fe based on the single-temperature vAPEC model (open circles) and the two-temperature vAPEC model (open triangles) derived from the XIS 1 (solid lines) and XIS 0, 2, 3 (dotted lines) detectors. In the Mg abundance panel, the diamonds are the best-fit values derived from the vMEKAL model (see text).

Fig. 6. O abundance versus the assumed temperature of the MWH. For the data in the outermost region ($r > 16'$) at the average temperature, $0.20\text{keV}$, of the MWH (Lumb et al. 2002), the O abundance has not changed very much from the temperature than the LHB and, therefore, may contribute to the H-like O line. To investigate this effect, we added an APEC model for the MWH and repeated the spectral fit. Figure 8 shows the O abundance versus the assumed temperature of the MWH.
Fig. 6. Abundance ratios of various elemental species compared to Fe for 3 radial regions: \( r < 4' \) (red), \( 4' < r < 11' \) for the central field (blue), \( r > 8' \) in the north field (black), and NGC 1404 (green). Only the \( r < 4' \) data are fitted with a two-temperature model. For the O/Fe ratio, the closed circle and closed diamond correspond to \( r < 2' \) and \( r > 2' \), respectively. The open symbols are the abundance ratios using the new solar abundance in Lodders (2003). The error bars do not include systematic errors, which are estimated to be \( \sim 20\% \) for the O/Fe and Mg/Fe ratios.

results in subsection 3.1. However, when the temperature of the MWH is higher, lower O abundances are allowed, while the upper limit of the O abundance does not change. For the data in the \( 8' < r < 16' \), even when the temperature of the MWH is 0.20 keV, lower O abundances are required.

The chemical composition, column density, and uniformity of the contaminant on the XIS filter are still poorly known and, therefore, we have to carefully check its effect on the abundance determination. Outside a radius of 2', the column densities of C derived from our spectral fit mostly agree with those determined from the hardware calibration within a systematic error of several times \( 10^{17} \) cm\(^{-2} \) (Koyama et al. 2007). However, within 2', the spectral fit gives significantly higher column densities for the FI detectors by \( 1-2 \times 10^{18} \) cm\(^{-2} \). This discrepancy may be related to the astrophysical spectral model, since all of the FI detectors give a similarly high value of the column density. When we fit the spectra by fixing the column density to the value given by the contamination model from the hardware calibration, with the hydrogen column density allowed to vary, the O abundance increases by \( 10\% \).

The contaminant is not spatially uniform on the filter. In the north field, the regions where we accumulated the spectra have different column densities. To check the effect, we divided the region of \( r > 8' \) in the north field into two regions: namely, outside and inside of the radius of 6' from the detector center. We derived similar O and Fe abundances for the two regions, verifying that the spatial nonuniformity of the contaminant is not a significant problem.

Since the O/C ratio of the contaminant can be smaller than our current best estimate of 1/6, we also fitted the spectra using ratios of 1/10 and 1/20. This gave a systematically lower O abundance than the nominal case by 10% and 20% for the O/C ratios of 1/10 and 1/20, respectively. The temperature and abundances of the other elements did not change significantly.

In summary, uncertainty in Fe-L modeling may cause 20–30% systematic errors in the Mg abundance. If the temperature of the MWH is higher than \( \sim 0.2 \) keV, the O abundance becomes lower in the outer regions. The uncertainty
concerning the thickness and chemical composition of the XIS contaminant results in an ~ 20% systematic error in the O abundance. However, the observed constancy with the radius of the derived ratio of Mg to O, which are both mostly synthesized in SN II, indicates that our O and Mg abundance may not be strongly affected by these uncertainties.

3.3. NGC 1404

We accumulated an on-source spectrum of NGC 1404 within a radius of 3′ centered on the galaxy. The background spectrum was taken from the Lockman-Hole observation over the same detector region. Since the surface brightness of NGC 1404 is high, the uncertainty in the Galactic emission is negligible. In order to subtract the local ICM component, we took a spectrum just outside of the on-source region within a radius 3′–4.2′, from which we subtracted the Lockman-Hole spectrum integrated over the same detector coordinate. The spectrum for this ring region was fitted with a model consisting of 2 vAPEC components: one for the ISM and the other for the ISM of NGC 1404 with a fixed temperature of 0.6 keV, which was derived from the spectral fit of the on-source region. The temperature of the ICM component was derived to be 1.44 ± 0.10 keV. Using this temperature, we returned to the on-source (r < 3′) spectrum and fitted it with a 3-component model: 2 vAPEC models and a thermal bremsstrahlung. Two thermal components are for ISM and ICM, with the ICM temperature and abundance fixed at the values of the previous ring-region fit. The thermal bremsstrahlung with a fixed temperature of 10 keV represents a discrete source contribution. As for the column density of the contaminant, we assumed the expected value from the calibration (Koyama et al. 2007) and the hydrogen column density was allowed to vary freely. The spectra for the XIS 0, XIS 2, and XIS 3 detectors were fitted simultaneously.

The results are summarized in table 3. The temperature of the ISM was determined to be 0.6 keV. Except for the Si abundance, the results from the BI and FI detectors are mostly consistent. The abundances of O, Ne, Mg, and Fe become higher in order, ranging from 0.5 to 0.9 solar. Figure 9 shows the confidence contours of the O abundance against the Fe abundance. The elliptical shape of the contour indicates that the abundance ratio is better determined than the abundances themselves. The abundance ratios among O, Mg, and Fe, are close to those obtained for NGC 1399 and the ICM (figure 6). The Si abundance has a large systematic uncertainty, since the dominant He-like Si line at kT = 0.6 keV falls in the energy where the response matrix has a problem.

The spectra of XIS 0 and XIS 1 are shown in figure 10. The reduced χ2 values are 1.3–1.4, and there are residual structures around 0.7–0.8 keV, which are likely to be related to poorly modeled Fe-L lines. The residual structures are seen in the fits for all detectors, but are not easily recognized in the spectra of NGC 1399 and ICM where the temperature is higher. These discrepancies in the Fe-L energy range are also seen in the RGS spectrum of the X-ray luminous elliptical galaxy, NGC 4636, whose ISM temperature is also ~ 0.6 keV (Xu et al. 2002). A two-temperature vAPEC model for the ISM did not improve the reduced χ2 for the NGC 1404 fit very much. Therefore, there might still be some problem in the Fe-L atomic data.

The reduced χ2 value for a single-temperature MEKAL model for the ISM is higher than the vAPEC fit and the derived Fe abundance is lower. However, the abundance ratios of O, Ne, Mg, and Fe agree within 10–20% between the two models. Therefore, systematic uncertainties in the O, Ne, and Mg abundances due to the uncertainty in the Fe-L atomic data may not be large.

We also tried the fit with a different background, which consisted of data for dark Earth, a ring-like region with r = 3′–4.2′ just outside the on-source region, and a region near the edge of the detector. Then, the best-fit values of the abundances changed by dozens of percent, while the abundance ratios remained the same.

At a temperature of 0.6 keV, the abundances were mainly determined by the ratio of line strengths to the continuum level below 0.6 keV. We allowed the contaminant column density to vary, and fitted the spectrum of each detector with the same model. The Fe abundance decreased as we increased the column density (figure 11). As shown earlier, adopting the standard thickness of the contaminant from Koyama et al. (2007), the Fe abundance is about solar for all detectors.

<table>
<thead>
<tr>
<th>Model</th>
<th>XIS</th>
<th>kT (keV)</th>
<th>N_H (10^{20} cm^{-2})</th>
<th>O (solar)</th>
<th>Ne (solar)</th>
<th>Mg (solar)</th>
<th>Si (solar)</th>
<th>Fe (solar)</th>
<th>χ^2/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>vAPEC 1T</td>
<td>023</td>
<td>0.60 ± 0.01</td>
<td>0.6 ± 0.6</td>
<td>0.44 ± 0.08</td>
<td>0.71 ± 0.14</td>
<td>0.78 ± 0.13</td>
<td>0.71 ± 0.18</td>
<td>1.07 ± 0.20</td>
<td>619/467</td>
</tr>
<tr>
<td>vAPEC 1T†</td>
<td>023</td>
<td>0.59 ± 0.01</td>
<td>2.4 ± 0.6</td>
<td>0.42 ± 0.05</td>
<td>0.46 ± 0.11</td>
<td>0.58 ± 0.11</td>
<td>0.96 ± 0.14</td>
<td>0.79 ± 0.04</td>
<td>215/154</td>
</tr>
<tr>
<td>vAPEC 2T‡</td>
<td>023</td>
<td>0.60 ± 0.01</td>
<td>2.1 ± 2.1</td>
<td>0.39 ± 0.06</td>
<td>0.61 ± 0.09</td>
<td>0.66 ± 0.11</td>
<td>0.58 ± 0.11</td>
<td>0.96 ± 0.15</td>
<td>618/465</td>
</tr>
<tr>
<td>vAPEC 2T§</td>
<td>023</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vMEKAL 1T</td>
<td>023</td>
<td>0.59 ± 0.01</td>
<td>3.1 ± 1.1</td>
<td>0.37 ± 0.08</td>
<td>0.76 ± 0.16</td>
<td>0.89 ± 0.15</td>
<td>1.26 ± 0.24</td>
<td>1.18 ± 0.09</td>
<td>204/151</td>
</tr>
<tr>
<td>vMEKAL 1T†</td>
<td>023</td>
<td>0.27 ± 0.02</td>
<td>3.9 ± 1.0</td>
<td>0.31 ± 0.04</td>
<td>0.35 ± 0.06</td>
<td>0.41 ± 0.05</td>
<td>0.35 ± 0.06</td>
<td>0.52 ± 0.02</td>
<td>732/461</td>
</tr>
<tr>
<td>vMEKAL 1T‡</td>
<td>023</td>
<td>0.58 ± 0.01</td>
<td>2.6 ± 0.5</td>
<td>0.39 ± 0.05</td>
<td>0.39 ± 0.11</td>
<td>0.66 ± 0.10</td>
<td>0.87 ± 0.15</td>
<td>0.71 ± 0.06</td>
<td>229/154</td>
</tr>
</tbody>
</table>

* The single temperature model for the ISM.
† The simultaneous fit of the spectra of XIS 0, XIS 2, and XIS 3.
‡ The two-temperature model for the ISM.
§ Not constrained.
Fig. 9. The 90% confidence contours of O abundance against Fe abundance for NGC 1404. The thin curves are for XIS 0, 2, 3, and the thick ones for XIS 1. Solid black curves show the single-temperature vAPEC fit, and solid red curves are for the vMEKAL case. The solid blue contours were derived while allowing the contaminant thickness to vary. The solid line shows an O/Fe ratio of 0.5 and the dashed lines denote ratio values of 0.4 and 0.6.

Fig. 10. XIS 1 (black) and the XIS 0 (red) spectra of NGC 1404 fitted with a 3-component model: 2 vAPEC models for the ISM and ICM, and a bremsstrahlung for discrete sources. The contribution of each component is shown with a dashed line.

The metal abundance of the hot ISM of NGC 1404 was first derived with ASCA (Loewenstein et al. 1994), and an extremely low value of \( \sim 0.2 \) solar was obtained. With ASCA, we were unable to determine the continuum level below 0.6 keV. Also, there was a problem in the atomic data of Fe-L lines, and an incorrect assumption about the abundance ratio resulted in the very low abundance value (Arimoto et al. 1997; Matsushita et al. 2000). With Suzaku, we can detect both the continuum below 0.6 keV and the peak of the O line, and, therefore, the systematic uncertainty has been much reduced.

In summary, the Fe abundance of the X-ray emitting gas of NGC 1404 is shown to be about solar, and the O/Fe, Ne/Fe, and Mg/Fe ratios are 0.50 ± 0.06, 0.61 ± 0.11, and 0.73 ± 0.11, respectively, in solar units. The uncertainty in the thickness of the contaminant and the background give systematic error in the Fe abundance by dozens of percent, while they do not affect the abundance ratios.

4. Discussion

4.1. Summary of the Abundance Determination

Suzaku observations of the Fornax cluster have revealed abundance profiles of O, Mg, Si, S, and Fe in the ICM for a wide region extending 130 kpc north and 60 kpc south of the cD galaxy, NGC 1399. Also, in NGC 1404, abundances of O, Ne, Mg, and Fe in the ISM were derived. Hereafter, we call the region within a radius of 4′ from NGC 1399 as the NGC 1399 region, and outside of this circle as the ICM region. The Fe abundances in the NGC 1399 region and in NGC 1404 are about solar, and the abundance decreases to 0.5 solar in the ICM region. The abundance ratios among O, Mg, Si, S, and Fe show common values for all 3 regions (figure 6). On average, the O/Fe, Mg/Fe, Si/Fe, and S/Fe ratios of the NGC 1399 region and the ICM region are 0.47 ± 0.05 (excluding \( r < 2′ \) where the spectral fittings have problems around O lines), 0.72 ± 0.05, 0.93 ± 0.05, and 0.96 ± 0.05 in solar units, respectively. The O/Fe, Mg/Fe, and Ne/Fe ratios for the ISM of NGC 1404 are 0.50 ± 0.06, 0.61 ± 0.11, and 0.73 ± 0.11, respectively. Adopting new solar abundances in Lodders (2003), the O/Fe ratios of the NGC 1399 region and the ICM region increase to 0.81 ± 0.09 in solar units.
The O/Fe and Ne/Fe ratios in NGC 1404 also increase to 0.9 ± 0.1 and 1.0 ± 0.2 in solar units, respectively (figure 6). These abundance ratios are similar to those observed around cD galaxies and in elliptical galaxies (e.g., Xu et al. 2002; Tamura et al. 2003; Matsushita et al. 2003, 2006). However, the observed constant O/Fe and Mg/Fe ratios differ from other systems in which a radial increase in the O/Fe ratio has possibly been seen. For example, the O/Fe ratio of the ICM increases by dozens of percent within 80 kpc for M 87 (Matsushita et al. 2003). The other systems have poorer statistics, but the O abundance spatial variation seems flatter than Fe (e.g., Tamura et al. 2004).

In the remainder of this section, we discuss the abundance pattern of O/Ne/Mg and O/Si/Fe and consider nucleosynthesis by SN II and SN Ia (subsections 4.2 and 4.3). In subsection 4.4, the O and Mg abundances of the NGC 1399 region and NGC 1404 are compared to the stellar metallicity of these galaxies. Subsection 4.5 considers the Fe abundance of these galaxies in light of their currently estimated SN Ia rates. Finally, the O and Fe mass-to-light ratios in the ICM region are derived in subsection 4.6, where we also discuss the origin of the metals in the ICM.

### 4.2. Abundance Pattern of O/Ne/Mg and Nucleosynthesis of SN II

Since SN Ia are not significant sources of O, Ne, and Mg, the abundance pattern of these elements can be used to infer the contribution from SN II. The observed Mg/O ratio is consistent among NGC 1404, the NGC 1399 region, and the ICM region, and the average value is 1.5 in solar units. Considering the systematic uncertainty of 20–30%, this value is close to the level in other systems, M 87 (Matsushita et al. 2003; Werner et al. 2006), the Centaurus cluster (Matsushita et al. 2006), NGC 4636 (Xu et al. 2002), and NGC 5044 (Tamura et al. 2003), as summarized in figure 12, although the Mg/O ratio for NGC 5044 is larger than 2. We selected these groups and clusters observed with XMM-Newton for comparison, since they are all giant elliptical galaxies and the Mg/O ratio of the gas surrounding them reflects the composition of their stars. In addition, they are among the brightest objects with well-observed spectra clearly showing O emission lines from the EMOS (M 87 and the Centaurus cluster) and RGS (M 87, NGC 4636, and NGC 5044). These Mg/O ratios for the cD and elliptical galaxies reflect the metallicity of the stars. Also, the result suggests that possible old SN II ejecta from early-type galaxies may be the main component of these elements in the ICM region.

In order to compare nucleosynthesis in elliptical galaxies and spiral galaxies, it is worth comparing the abundance pattern in the ICM and ISM of elliptical galaxies with that of stars and ISM in our Galaxy. It is important to bear in mind that the methods of abundance determination for these various classes are very different, which can introduce some systematic uncertainties in the comparison. Adopting the new solar abundance model in Lodders (2003). Those of disk stars by Edvardsson et al. (1993; red closed circles) and Clementini et al. (1999; red dotted box) in the Galaxy are also plotted. The red solid and dashed boxes correspond to the mean values of thick and thin disk stars in the bin of [Fe/H] = −0.45 to −0.55 by Reddy et al. (2006).

![Fig. 12.](image1)

![Fig. 13.](image2)
absorption, and the obtained values are 1–2 (Yao, Wang 2006) and 1.3–2.3 (Ueda et al. 2005), respectively. Therefore, at least concerning the ratios of O/Ne/Mg, there is no obvious difference in the nucleosynthesis products of SN II between elliptical galaxies and the Galaxy.

4.3. Abundance Pattern of O/Si/Fe

The abundance ratios for O/Si/Fe in the NGC 1399 region and the ICM region and for O/Fe in NGC 1404 are close to the previous measurements around the brightest eS galaxies and in the central galaxies of groups of galaxies, including M 87 (Matsushita et al. 2003), the Centaurus cluster (Matsushita et al. 2006), NGC 4636 (Xu et al. 2002), and NGC 5044 (Tamura et al. 2003), as summarized in figure 13. The Si abundance of the Fornax cluster is 0.1 dex higher than the sum of SN II nucleosynthesis model described in Iwamoto et al. (1999) and classical deflagration SN Ia model, W7 (Nomoto et al. 1984), which predicts an Fe/Si abundance ratio of 2.6. The Si abundances of other clusters are also 0.1–0.2 dex higher than the sum.

In order to account for the high Si abundance, Finoguenov et al. (2002) and Matsushita, Finoguenov, and Böhringer (2003) suggested that ejecta of SN Ia should have an Fe/Si ratio of about 1 solar. Matsushita et al. (2006), Buote et al. (2003), Humphrey and Buote (2006) also discussed higher Si abundance production by SN Ia, although some Chandra data in Humphrey and Buote (2006) are consistent with the W7 model. This Fe/Si ratio may be explained by explosion models. A higher fraction of Si is indicated in the delayed detonation model, WDDs (Iwamoto et al. 1999), which give a range of Fe/Si ratios from 1 to 3, which might be related to the age of the system (Umeda et al. 1999). A sum of the SN II nucleosynthesis model plus the WDD1 model is consistent with the data showing the highest Si/Fe ratios, while nearly all of the data points lie between this model and the low Si producing SN Ia nucleosynthesis model (e.g., W7 or WDD3).

Another reference of the total nucleosynthesis from SN II in the Galaxy is the abundance pattern of metal-poor Galactic stars. Since the SN II nucleosynthesis model might have some systematic uncertainty, it is important to compare the abundance pattern of the ICM and the sum of the metal poor Galactic stars and SN Ia model, although abundances of stars might have 0.1–0.2 dex uncertainty, as described in Asplund (2005). Adopting the new solar abundance model in Lodders (2003), the [O/Fe] of ICM increases by 0.2 dex (figure 13). Then, the O/Si/Fe pattern of the ICM becomes more consistent with the sum of the Galactic metal poor stars and W7.

4.4. Stellar Metallicity in Elliptical Galaxies

In elliptical galaxies, the O and Mg abundances in the hot gas should be equal to those in mass losing stars, since these elements are not synthesized to any great extent by SN Ia. Therefore, X-ray observations can probe the stellar metallicity over the entire galaxy, which is virtually impossible with optical observations. The stellar metallicity of elliptical galaxies is usually studied by optical spectroscopy using the Mg absorption line index (e.g., Kobayashi, Arimoto 1999), which depends not only on the Mg abundance, but also on the total metallicity where the O contribution matters most. The problem is that the index also depends on the age distribution of the stars and optical spectroscopy tends to be limited to within the central region of galaxies. In addition, these values are based on abundance studies in the Galactic stars, which might change when considering the uncertainties in calculation of stellar atmosphere (Asplund 2005).

Adopting the new solar abundance in Lodders (2003), the O and Mg abundances of the ISM of NGC 1404 are about 0.7 solar. Those of NGC 4636 are 0.8 and 0.65 solar (Xu et al. 2002), and therefore the two galaxies should have a similar stellar metallicity; in addition, we would expect the O and Mg abundances of the stars in the two galaxies to be 0.6–0.8 solar. The Mg$_2$ index of NGC 1404 has only been measured at the galaxy’s center; Faber et al. (1989) quote a value of 0.317. This is close to the central value of 0.311 seen in NGC 4636 whose Mg$_2$ index has been observed out to $\sim 1 r_e$. Considering the gradient of the index, the extrapolated stellar metallicity of NGC 4636 is about 0.7 solar (Kobayashi, Arimoto 1999). Thus, in NGC 4636 the ISM metallicity and stellar metallicity derived from the Mg$_2$ index are consistent. Assuming that the stars in NGC 1404 have a similar metallicity gradient to NGC 4636, we can also conclude that the ISM metallicity and stellar metallicity should be consistent as well.

The central Mg$_2$ index of NGC 1399 is 0.344, which is higher than those of NGC 4636 and NGC 1404. The O and Mg abundance of the NGC 1399 region are consistent or higher than those of NGC 4636 and NGC 1404, since the absolute value of the abundance of the NGC 1399 may be higher by dozens of percent when one considers projection.

4.5. SN Ia Nucleosynthesis in Elliptical Galaxies

The observed Fe abundance in the ISM of NGC 1399 and NGC 1404 can constrain the present metal supply from galaxies to the ICM. Assuming the SN II abundance pattern by Iwamoto et al. (1999), $\sim 80\%$ of Fe and $\sim 40\%$ of Si are synthesized by SN Ia. The Fe abundance enriched by SN Ia in an elliptical galaxy 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, $\alpha_*$ is the SN Ia rate, and $\alpha_*$ is the stellar mass loss rate. Fe in the hot ISM of these galaxies is mainly produced by SN Ia, since SN II synthesize much more O and Mg than Fe. We used the mass-loss rate from Ciotti et al. (1991) assuming the age to be 13 Gyr, which is approximated by $1.5 \times 10^{-11} L_B t_{15}^{-1.3} M_{\odot} \text{yr}^{-1}$, where $t_{15}$ is the age in unit of 15 Gyr and $L_B$ is the B-band luminosity. $M_{\text{Fe}}$ produced by one SN Ia explosion is likely to be $\sim 0.6 M_{\odot}$ (Iwamoto et al. 1999). Combining with the SN Ia rate optically observed by Cappellaro et al. (1997) which is $0.13 \pm 0.05 h_{75}^2$ SN Ia/100yr/10$^{10} L_B$, the resultant Fe abundance only considering the SN Ia contribution is 2–4 solar. This value is higher than the presently observed Fe abundance, indicating a lower SN Ia rate.

4.6. Mass to Light Ratio for O and Fe in the ICM and Origin of the Metals

Since metals in the ICM are all synthesized in galaxies, the metal-mass-to-light ratios are important to study the chemical evolution of the ICM. Within a radius of 130 kpc, or 0.13 $r_{180}$, most of the optical light comes from NGC 1399
and several other bright galaxies, including NGC 1404. The total luminosity of NGC 1399 has an uncertainty since the surface brightness of the cD halo is very low. Recent CCD photometry by Karick, Drinkwater, and Gregg (2003) showed the B-band luminosity of NGC 1399 to be $2.8 \times 10^{10} \, L_\odot$, and the total B-band stellar luminosity of galaxies within 130 kpc to be $8 \times 10^{10} \, L_\odot$. Using old photographic data by Schombert (1986), Saglia et al. (2000) derived the stellar luminosity profile of NGC 1399 out to nearly 1° from the galaxy center. At 130 kpc, the B-band luminosity of NGC 1399 reaches $\sim 10^{11} \, L_\odot$. Including the halo component, the total B-band luminosity of all the galaxies within 130 kpc becomes $1.5 \times 10^{11} \, L_\odot$.

The gas mass profile was derived by Paolillo et al. (2002) based on the ROSAT data, and, within 130 kpc, the gas mass is estimated to be $10^{11} \, M_\odot$. As a result, the O mass-to-light ratio (OMLR) and Fe mass-to-light ratio (IMLR) within 130 kpc are $2 \times 10^{-3} \, M_\odot / L_\odot$ and $4 \times 10^{-4} \, M_\odot / L_\odot$, respectively. These values are over an order of magnitude larger than those for richer clusters. With ASCA, the IMLR for rich clusters was measured to be $\sim 0.01 \, M_\odot / L_\odot$, while groups of galaxies gave smaller values (Makishima et al. 2001), although the angular resolution of ASCA was often not sufficient to obtain the metallicity distribution, and the obtained IMLR might be overestimated. With XMM, Tamura et al. (2004) derived IMLR for several clusters within $\sim 250 \, h^{-1}$ kpc to be $\sim 0.01 \, M_\odot / L_\odot$. Measurements of the OMLR for rich clusters are not reliable (Tamura et al. 2004; Kawaharada 2006). Our results can be compared with the Centaurus cluster, whose temperature is 4 keV. Within a radius of $0.11 \, r_{180}$, the OMLR and IMLR for the Centaurus cluster are $3 \times 10^{-2} \, M_\odot / L_\odot$ and $4 \times 10^{-3} \, M_\odot / L_\odot$, respectively, and about an order of magnitude larger than those in the Fornax cluster (Matsushita et al. 2006).

The total amount of Fe and O, when normalized by the stellar luminosity and accumulated over the Hubble time, should be similar among the clusters, unless many of these elements are lost from the system. The constancy of the metal mass would be like the case in the Fornax cluster, as well as in rich clusters, since most of the stellar light in the Fornax cluster comes from bright old galaxies, just as in rich clusters (Kuntschner 2000). One difference between the poor and rich clusters is that the gas in poor clusters and groups of galaxies is more extended than in rich clusters, compared with the stellar distribution (e.g., Ponman et al. 1999). Since the Fe abundance in the ICM does not depend on the ICM temperature (Fukazawa et al. 1998), the difference in the OMLR and IMLR should almost purely reflect the difference in the gas fraction. Since the hot gas in poor clusters and groups commonly show higher entropy than the case of pure gravitational heating (e.g., Ponman et al. 1999), the gas in poor clusters, such as Fornax, may have expanded significantly. The metal distribution in the ICM may be used as a tracer of the history of such gas heating, since both metal enrichment and heating time scales determine the metal distribution in the ICM.

The O/Fe ratios in the Fornax cluster indicate that the Fe has been mostly produced by SN Ia. If the gas and stellar distribution remain the same within 130 kpc of NGC 1399, the accumulation time scale by SN Ia may be much shorter than the Hubble time. Therefore, significant amounts of O and Mg have to come from stellar mass loss, although the time dependence of the mass loss rate and SN Ia rate is not clear. Therefore, within a radius of $0.13 \, r_{180}$ in the Fornax cluster, the OMLR directly ejected from old SN II may be even lower. For example, to accumulate half of the observed OMLR with stellar mass loss requires 7 Gyr. Here, we assumed that the O abundance of stars is 0.45 solar and the age of the galaxies is 13 Gyr, and used the mass loss rate from Ciotti et al. (1991). Therefore, most of the O from old SN II may lie beyond $0.13 \, r_{180}$.

5. Summary and Conclusion

With Suzaku observations of the Fornax cluster, the abundances of O, Mg, Si, and Fe of the ICM up to 130 kpc north and up to 60 kpc south of NGC 1399, and O, Ne, Mg, and Fe abundances of NGC 1404 were derived accurately. The Fe abundances around NGC 1399 and NGC 1404 are about solar, and drop to 0.5 solar in the ICM. The elemental abundance ratios show common values around NGC 1399, NGC 1404, and the ICM: Si and S have similar abundances to Fe; also the O/Fe, Ne/Fe, and Mg/Fe ratios are 0.5–0.7 solar in units of the solar ratio. The O, Ne, and Mg abundances of NGC 1404 and the NGC 1399 region are consistent with the stellar metallicity of these galaxies. Most of the Fe around NGC 1399, NGC 1404, and the ICM should have been synthesized by SN Ia. The abundance ratios of O/Fe and Si/Fe in the gas are consistent with a mixture of SN Ia ejecta of the W7 model and metal-poor Galactic stars. The values for the IMLR and OMLR are much smaller than in rich clusters, which indicates that most of the metals may be outside of the region that we observed. The metal distribution of the ICM may be used as a tracer of the cluster history.

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References
