Suzaku Observation of HCG 62: Temperature, Abundance, and Extended Hard X-Ray Emission Profiles

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(Received 2007 August 30; accepted 2007 October 27)

Abstract

The compact group of galaxies HCG 62 (z = 0.0145) was observed for 120 ks with Suzaku XIS and HXD-PIN. The XIS spectra for four annular regions were fitted with a two-temperature vapc model with variable abundance. The Galactic component was described by a two-temperature vapc model, and constrained to have a common surface brightness among the four annuli. We confirmed the multi-temperature nature of the intra-group medium, as reported previously, with a doughnut-like high temperature ring at radii 3.3–6.5. Abundances of Mg, Si, S, and Fe were well-constrained. We examined the possible “high-abundance arc” at ~ 2 southwest from the center; however, Suzaku data did not confirm it. We suspect that it is a misidentification of an excess hot component in this region as the Fe line. Neither XIS (5–12 keV) nor HXD-PIN (12–40 keV) gave positive detection of the extended hard X-rays previously reported with ASCA, although our upper limit did not exclude the ASCA result. The 5–12 keV intensity in the r < 3.3 region turned out to be 70 ± 19% higher than the nominal CXB level, and Chandra and Suzaku data suggest a concentration of hard X-ray sources with an average photon index of Γ = 1.38 ± 0.06. The cumulative mass of O, Fe, and Mg in the intra-group medium and the metal mass-to-light ratio were compared with those in other groups. The possible role of AGN or galaxy mergers in this group is also discussed.

Key words: galaxies: abundances — galaxies: clusters: individual (HCG 62) — galaxies: interactions — galaxies: intergalactic medium — X-rays: diffuse background — X-rays: galaxies: clusters

1. Introduction

Groups of galaxies have played a key role in the formation of the universe. Most importantly, they act as building blocks in the framework of a hierarchical formation of structures (e.g., Navarro et al. 1995). In this sense, the properties of groups should be critically compared with those in clusters of galaxies, to test the general hypothesis that groups of galaxies indeed represent the condition in clusters when they have not been evolved. For example, the baryon-to-dark-matter ratio and the metal abundance in groups of galaxies can be a measure to be tested whether rich clusters are indeed a simple superposition of many groups, or that some other mechanism may be involved.

The groups are characterized by a short dynamical time scale, and we expect galaxy encounters to take place frequently in such a high-density environment. An X-ray search for evidence of dynamical processes in the form of hard non-thermal emission would be an important subject of observational studies. The relatively low gas temperature compared with rich clusters greatly helps us to find such emission, even with standard CCD instruments. Also, it is well known that group gas tends to contain significantly high entropy if one extrapolates the scaling relation holding for clusters (Ponman et al. 1999). A simulation study indicated that simple galactic winds were unable to significantly raise the entropy in cluster-size hot gas (Borgani et al. 2005). This indicates that a certain heat input or preheating occurred over a widespread region, and groups of galaxies offer us an opportunity to closely look into such an effect.

Another aspect concerning groups of galaxies is their role in the chemical enrichment of cluster hot gas. It has been shown that rich clusters maintain all of the metals produced by the cluster galaxies (Fukazawa et al. 1998); however, early-type galaxies are thought to have released most of the metals formed through past supernova explosions (Makishima et al. ...)
2001). We should note that these galaxies almost always reside in groups and clusters of galaxies, and that their X-ray haloes may not be clearly separable from the surrounding gas. Groups of galaxies lie in the region where metal confinement can be marginally possible. This means that by looking into the distribution of various metals in groups, we can measure the efficiency of metal confinement, and further estimate how each metal has been injected into intergalactic space. The low temperature (< 2 keV) of the group gas also greatly helps us to study emission lines from various metals, ranging from oxygen to iron.

HCG 62 is one of the brightest and well-studied groups of galaxies among the Hickson compact groups of galaxies (Hickson et al. 1989) located at \( z = 0.0145 \) (Mulchaey et al. 2003). Zabludoff and Mulchaey (2000) extensively surveyed a 1.5 \( \times \) 1.5 deg\(^2\) region around the group and measured the redshifts of 154 galaxies. They identified 63 of them as being members of the group within a radius of 50′ (900 kpc), and the measured velocity dispersion, \( \sigma = 390^{+37}_{-34} \) km s\(^{-1}\), is a typical value for galaxy groups. The central region within \( r < 1.1 \)′ is dominated by three galaxies [HCG 62a (NGC 4778), HCG 62b (NGC 4776), and HCG 62c (NGC 4761)], which are all classified as S0 galaxies. The kinematics of these galaxies suggests possible interactions among them (Spavone et al. 2006; Rampazzo et al. 1998). Such a high galaxy density and low velocity dispersion are considered to result in a galaxy merger; Ponman and Bertram (1993) suggested that they should culminate in a final merger within a few billion years, consisting of a large elliptical galaxy embedded in an extended X-ray halo.

HCG 62 is also known as the first compact galaxy group to be detected in X-ray to have an extended hot gas (intra-cluster or group medium: ICM), and the ICM properties have been extensively studied using ROSAT and ASCA (e.g., Ponman & Bertram 1993; Pildis et al. 1995; Finnougenov & Ponman 1999; Mulchaey et al. 2003). Furthermore, a spatially extended hard X-ray excess over the ICM emission was detected with ASCA (Fukazawa et al. 2001; Nakazawa et al. 2007), and the X-ray properties have been extensively studied using ROSAT and ASCA (e.g., Ponman & Bertram 1993; Pildis et al. 1995; Finnougenov & Ponman 1999; Mulchaey et al. 2003). The extended X-ray halo.

In this paper, we report on results from Suzuki observations of HCG 62. Owing to the low and stable background, as well as good sensitivity to emission lines below ~1 keV of the X-ray Imaging Spectrometer (XIS: Koyama et al. 2007), accurate determinations of O and Mg abundances to outer regions have become feasible. Suzuki is also effective to constrain the extended hard X-ray emission in combination with the Hard X-ray Detector (HXD: Takahashi et al. 2007). This paper is organized as follows: in sections 2 and 3, we describe the Suzuki observations and the data reduction, and show images of HCG 62 obtained with Suzuki in section 4. In sections 5–7, we describe spectral analyses and the derived temperature and abundance profiles, and examine the existence of the “high-abundance arc” in section 8. In section 9, the significance of the extended hard X-ray emission with Suzuki is carefully considered. We discuss the temperature and metallicity distributions, the metal mass-to-light ratio, and galaxy mergers in section 10, and a summary is given in section 11.

We use \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\) or \( h_{100} = 0.7, \Omega = 1 - \Omega_M = 0.73 \) throughout this paper. At a redshift of \( z = 0.0145 \), 1′ corresponds to 17.8 kpc. The virial radius is given by \( r_{180} = 1.95 h_{100}^{3/2} k(T)/10 \) keV = 1.08 Mpc (Markevitch et al. 1998; Evrard et al. 1996) for the average temperature of \( k(T) = 1.5 \) keV. We adopt a Galactic hydrogen column density of \( N_H = 3.03 \times 10^{20} \) cm\(^{-2}\) in the direction of HCG 62 (Dickey & Lockman 1990). As for the definition of the solar abundance ratio, we followed Anders and Grevesse (1989). Errors are in the 90% confidence range for a single interesting parameter.

### 2. Observations

Suzuki carried out observations of the central part of HCG 62 in 2006 January as a part of the Science Working Group (SGW) time. The observation log is shown in table 1. The XIS instrument was set to the normal clocking mode with data formats of 5×5 and 3×3 editing modes. See Koyama et al. (2007) for details of the operation mode. The XIS images are shown in figure 1. We used the version 0.7 processing data, and the analysis was performed with HEASoft 6.1.1 and XSPEC 11.3.2t. After applying the standard data-selection criteria [elevation from the sunlit Earth rim, DYE > 5°, elevation from the Earth rim, ELV > 5°, time after the South Atlantic Anomaly (SAA) passage, T SAA _HXD > 256 s], the exposure time of XIS was 119.3 ks. Events of bad CCD event grades, bad columns, and hot/flickering pixels were removed, by choosing GRADE = 0, 2, 3, 4, or 6, STATUS < 262144, and applying “sisclean” FTOOLS.

The HXD PIN and PMT were operated with nominal high-voltage supply and setups (Kokubun et al. 2007). From the background modeling limitations as of the beginning of 2006, we selected time regions with the magnetic cut-off rigidity

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**Table 1.** Suzuki observation log of HCG 62.

| Observation ID       | 800013020 |
|----------------------|-----------|
| Target coordinates   | (RA NOM, DEC NOM) = (12h53m06s, -9°12′14") |
| Date of observation  | 2006 January 20, 09:19–23, 12:00 UT |
| Exposure time        | XIS:119.3 ks HXD-PIN: --- (No COR selection) XIS: 85.4 ks HXD-PIN: 75.1 ks (COR > 8 GV) |

*Normal satellite pointing direction in J2000.0.
Fig. 1. (a) Exposure-corrected XIS image in 0.5–4.0 keV, (b) in 6–10 keV energy range, and (c) hardness ratio image of 1–2 keV to 0.5–1 keV bands. Images of (a) and (c) are smoothed with a Gaussian of $\sigma = 17^\circ$, and (b) is with $\sigma = 33^\circ$. The estimated components of the NXB and CXB were subtracted, but no vignetting correction was applied. Green circles correspond to 3.3, 6.5, and 9.8 radii, from inner to outer, centered on HCG 62. No COR selection was applied, and both BI and FI sensors were co-added, in order to maximize the photon statistics. The $^{55}\text{Fe}$ calibration source areas at corners are included in (a) and (c), but excluded in (b). White circles in (b) represent locations of point sources detected by XMM-Newton. Sources shown by smaller circles were also detected with Chandra.

Fig. 2. Observed spectra at the annular regions for (a)–(d) BI and (e)–(h) FI sensors. Estimated components of the NXB and CXB were subtracted, which are indicated by blue and red histograms. COR $> 8$ GV screening was applied. The $^{55}\text{Fe}$ calibration source areas are included for the accumulation regions of (d) and (h), but excluded for others.

(COR) being larger than 8 GV, and T_{SAA, HXD} $> 1000$ s. With these screenings, we obtained 75.1 ks of exposure for the PIN detector. We do not consider the GSO data of the HXD instrument in this paper.

3. Data Reduction

In this section, we describe our spectral analysis of the ICM with XIS. First, we extracted spectra from four annular regions of 0.0–3.3, 3.3–6.5, 6.5–9.8, and 9.8–13’, centered on the target coordinates given in table 1. As for the background, we assumed a nominal cosmic X-ray background (CXB) spectrum with a power-law photon index of $\Gamma = 1.4$, and a surface brightness of $5.97 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in 2–10 keV (Kushino et al. 2002). The non X-ray background (NXB) spectra were estimated from a database of the dark Earth observations with Suzaku for the same detector area and with the same distribution of COR (Tawa et al. 2008). In order to increase the signal-to-noise ratio by reducing the NXB count rate, especially for the group outskirts and in high-energy bands ($E \gtrsim 4$ keV), we further required COR $> 8$ GV for the spectral analysis. After this screening, the exposure time dropped to 85.4 ks; however, the fit residuals in the higher energy band were reduced, and the spectral fits became almost acceptable, as described in a later section.

In figure 2, the spectra of the back-illuminated sensor (BI = XIS 1) and the sum of three front-illuminated sensors (FIs = XIS 0, XIS 2, XIS 3) for four annular regions after background subtraction are presented. The estimated spectra of the CXB and NXB are overlaid. The uncertainty in the CXB spectrum is $\sim 10\%$ or more (Kushino et al. 2002), depending on the accumulation area of the spectrum, and the reproducibility of the NXB is $\lesssim 5\%$ for 100 ks observation spanning 2–3 d (Tawa et al. 2008). The $^{55}\text{Fe}$ calibration source regions at two CCD corners were included when we accumulated spectral data for the 9.8–13’ annulus; however, the energy range of the fit was limited to 0.4–4 keV. The calibration source regions in the 6.5–9.8 annulus were excluded, and the fitting energy range was set at 0.4–7.5 keV for 0.0–3.3, 3.3–6.5, and 6.5–9.8 annuli. In addition, the energy range around the Si K-edge
(1.825–1.840 keV) was ignored in the spectral fit. Table 2 summarizes the area, coverage, energy range, and the BI and FI counts for the observed spectra and the estimated NXB and CXB spectra. The fraction of the background, $f_{\text{BGD}} = (\text{NXB} + \text{CXB})/\text{OBS}$, was less than 50%, even at the outermost annulus, although the Galactic component is not considered here.

The responses of the XRT and XIS were calculated by “xisimarfgen” version 2006-08-26 ancillary response file (ARF) generator (Ishisaki et al. 2007) and “xisrmfgen” version 2006-10-26 response matrix file (RMF) generator. A slight degradation of the energy resolution was considered in the RMF, and a decrease of the low-energy transmission of the XIS optical blocking filter (OBF) was included in the ARF. The ARF response was calculated assuming a surface brightness profile, $S(r)$, based on the combined analysis of Chandra and XMM-Newton data in 0.5–4 keV within $r < 14'$. The profile is described by a 3$\beta$-model, which is given in table 3 of Morita et al. (2006). The fraction of the assumed intensity from the corresponding sky for each annulus using the “xisim” simulator (Ishisaki et al. 2007), as shown in table 3. The stray fraction was not significant, and less than 1/3 in the worst case. Although we did not conduct a deprojection analysis, we have confirmed that this analysis would not change the best-fit parameters significantly.

### Table 2. Area, coverage of whole annulus, SOURCE\_RATIO\_REG, and observed/estimated counts for each annular region.

| Region * | Area † (arcmin$^2$) | Coverage ‡ | SOURCE\_RATIO\_REG | Energy (keV) | BI counts § | FI counts § |
|----------|---------------------|------------|---------------------|--------------|-------------|-------------|
| 0'0–3'3 | 33.4                | 100.0%     | 51.3%               | 0.4–7.5      | 35067       | OBS 5.5%    |
| 3'3–6'5 | 100.1               | 100.0%     | 16.8%               | 0.4–7.5      | 20095       | NB 26.4%    |
| 6'5–9'8 | 147.1               | 88.2%      | 13.5%               | 0.4–7.5      | 16943       | CXB 38.8%   |
| 9'8–13' | 36.8                | 15.8%      | 2.1%                | 0.4–4.0      | 2726        | 629 41.1%   |
| $r < 1'$ | 3.8                 | 100.0%     | 33.2%               | 0.4–7.5      | 11191       | OBS 2.0%    |
| NE arc  | 14.8                | 100.0%     | 9.0%                | 0.4–7.5      | 10420       | NB 8.2%     |
| SW arc  | 14.8                | 100.0%     | 9.0%                | 0.4–7.5      | 13358       | CXB 6.4%    |

SOURCE\_RATIO\_REG represents the flux ratio in the assumed spatial distribution on the sky (3$\beta$-model) inside the accumulation region to the entire model, and written in the header keyword of the calculated ARF response by “xisimarfgen”.

* See figure 1a for the first four annuli, figure 7a for the latter three.

† The average values among four sensors are presented.

‡ SOURCE\_RATIO\_REG = Coverage $\times \int_0^{r_{\text{out}}} S(r) r \, dr / \int_0^{r_{\text{in}}} S(r) r \, dr$, where $S(r)$ represents the assumed radial profile of HCG 62, and we defined $S(r)$ in $26' \times 26'$ region on the sky.

§ OBS denotes the observed counts including NXB and CXB in 0.4–7.5 keV or 0.4–4 keV. NXB and CXB are the estimated counts. $f_{\text{BGD}} = (\text{NXB} + \text{CXB})/\text{OBS}$.

### Table 3. Estimated fractions of the ICM photons accumulated in the annular detector regions.

| Detector | Sky region | 0'0–3'3 | 3'3–6'5 | 6'5–9'8 | 9'8–13' | $r > 13'$ |
|----------|------------|---------|---------|---------|---------|-----------|
| XRT      | 95.6%      | 4.4%    | 0.0%    | 0.0%    | 0.0%    |
| XIS      | 17.2%      | 68.6%   | 14.1%   | 0.0%    | 0.0%    |
| XIS      | 0.2%       | 8.2%    | 81.3%   | 10.2%   | 0.0%    |
| XIS      | 0.0%       | 0.2%    | 8.8%    | 90.0%   | 1.0%    |

Estimated fractions of the ICM photons accumulated in the annular detector regions coming from the corresponding sky by “xisim” simulator for BI (XIS 1) at 1 keV. These numbers are not much different ($\leq 1\%$) for other sensors and the examined energy bands.

4. X-Ray Image

The XIS images in 0.5–4 keV and 6–10 keV are shown in figures 1a and 1b. The estimated contributions of NXB and CXB were subtracted, and the exposure was corrected, but no vignetting correction was applied. A magnified image of the central region in 0.5–4 keV without Gaussian smoothing is also shown in figure 7a, which is discussed in section 8. There is a slight positional shift of the X-ray peak by less than 0'3 from the region center, due to the source position error of 19'', corresponding to the 90% error circle radius of the Suzaku telescopes after an astrometry correction for the thermal distortion of the spacecraft (Uchiyama et al. 2008). Though this astrometry correction was not incorporated in our analysis, the shift of the average pointing direction due to the thermal distortion is estimated to be 6', which gives a minor effect.

Although the 0.5–4 keV image is dominated by the ICM...
emission, the intensity gradient becomes weaker at the outer two annuli, where the Galactic emission has comparable intensity. In 6–10 keV, the thermal ICM emission can hardly be seen as shown in figure 1b, which is a linear-scale plot of the intensity. However, some extended emission can be seen within $r < 3'$. It is notable that this emission seems to be elongated along the direction of the two cavities (32” north–east and 20” south–west), which were observed with Chandra (Vrtilek et al. 2002; Morita et al. 2006). There are other extended hard emissions that do not match point sources (white circles) as detected with XMM-Newton. The statistical significance of the hard X-ray emission is discussed in section 9.

Figure 1c shows a hardness ratio image based on the 1–2 keV and 0.5–1 keV intensities. Although a vignetting correction was not performed, the two energy bands show very similar vignetting features. The transmission degradation due to the OB contaminant was not corrected for either, which is larger for the 0.5–1 keV band and at the central part of the CCD. Therefore, the hardness ratio shows a systematic drop from the center to the outer regions for a constant temperature distribution. In the hardness image, there is a clear doughnut-like structure with a high hardness ratio around an annulus of 3.3–6.5. This is probably due to a relative dominance of the high-temperature component in the ICM, which is mostly occupied by the cool component at the group core, as already reported by Morita et al. (2006). They also found a sharp temperature drop from $kT_{\text{Hot}} \sim 1.5$ keV at $r \sim 3'$ to $\sim 0.6$ keV at $r \sim 10'$, which may well form the doughnut-like hot structure. However, the Galactic component becomes comparable to the ICM in the outer annuli, so the overall temperature structure needs to be examined in detail.

5. Spectral Analysis

We carried out spectral fits to the observed spectra in the four annular regions. The estimated NXB and CXB were subtracted from the spectra, but we estimated the parameter error ranges by adjusting these background intensities by $\pm 10\%$. The fitting model consisted of the following components:

1. Galactic hot gas: we tried both single (Gal 1T; $kT_{\text{Gal}}$) and two-temperature (Gal 2T; $kT_{G1}$, $kT_{G2}$) models for this component. In both models, the surface brightness was constrained to be equal among the four annuli, and apec models with solar abundance at $z = 0$ were utilized. When a single temperature was assumed, the common temperature over the four annuli and its surface brightness were varied as two free parameters. In the two-temperature case, we had to fix both temperatures because of strong coupling with the ICM temperatures. Based on previous reports (e.g., Lumb et al. 2002; Kuntz & Snowden 2000; Snowden et al. 1998), we assumed $kT_{G1} = 0.138$ keV, attributed to the Local Hot Bubble and $kT_{G2} = 0.344$ keV as the Milky-Way Halo, respectively. The intensities of these two components were varied as free parameters. Though these temperatures are slightly higher than those obtained with ROSAT (Kuntz & Snowden 2000) or XMM-Newton (Lumb et al. 2002), we chose the values that gave the largest difference from the Gal 1T results within the ROSAT error range. We also note that the location of HCG 62, $(l, b) = (303^\circ, 54^\circ)$ in the Galactic coordinate, is within $\sim 15^\circ$ from the Galactic Bulge and the North Polar Spur — Loop I (Snowden et al. 1995). The influence of the assumed temperatures on the ICM abundance is examined in section 7.

2. Low-Mass X-ray Binaries (LMXBs): the discrete source contribution in member galaxies of HCG 62 was included only for 0.0–3.3 annulus, assuming thermal bremsstrahlung emission, $z\text{bremss}$, at $z = 0.0145$ with a fixed temperature of $kT = 7$ keV and a fixed intensity. The intensity, $F_X = 9.3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (0.3–8 keV), employed here is based on the Chandra results by Kim and Fabian (2004), in which the integrated LMXB luminosity, $L_X$, was related to the B band optical luminosity, $L_B$, as

$$L_X/L_B = (0.9 \pm 0.5) \times 10^{30} \text{ erg s}^{-1}/L_B\odot. \quad (1)$$

3. ICM in HCG 62: we assumed a two-temperature ($kT_{\text{Hot}}$, $kT_{\text{Cool}}$) optically-thin thermal plasma model, vphase, at $z = 0.0145$ for ICM based on the previous Chandra and XMM-Newton studies (Morita et al. 2006). As an exception, only a single temperature was considered in the Gal 2T model for the outermost annulus (9.8–13’), because we could not constrain $kT_{\text{Hot}}$. As for the metal abundance, we grouped the relevant metals into six groups, namely, Mg and Al; S, Ar and Ca; Fe and Ni were combined, and O, Ne, and Si were varied individually.

Consequently, Gal 1T: constant $\times [\text{phabs} \times (\text{vphase} + \text{vphase} + z\text{bremss}) + \text{apec}]$, or Gal 2T: constant $\times [\text{phabs} \times (\text{vphase} + \text{vphase} + z\text{bremss}) + \text{apec} + \text{apec}]$ model was adopted for the spectral fit. The phabs factor denotes the Galactic absorption due to neutral atoms, and the hydrogen column density was fixed to $N_H = 3.03 \times 10^{20}\text{ cm}^{-2}$ (Dickey & Lockman 1990). Note that this absorption model is also affected by the assumed solar abundance table, as discussed in Appendix 2 of Sato et al. (2007a). In order to constrain the surface brightness of the Galactic component, a total of 8 spectra, with BI and FI sensors for the four annuli, were simultaneously fitted. A constant factor was introduced to compensate for any possible flux discrepancy between the BI and FI sensors; however, it turned out to be unity within $\pm 5\%$.

The fitted spectra are presented in figure 3, and the best-fit parameters are summarized in table 4. The flux and the normalization in the table are for the FI spectra. The reduced $\chi^2$ values are $\simeq 1.2$ for the two models, and slightly better for the Gal 2T model with $\Delta \chi^2 = 15$. Both models are statistically rejected if we consider only the statistical errors; however, they become acceptable when a systematic error of 5% is added in each bin. The reduced $\chi^2$ is particularly large in the innermost region ($r < 3.3$), where temperature gradient was observed with Chandra (Morita et al. 2006). The residuals of the fit show a large scatter around 1–1.5 keV in figures 3a and 3e. This is presumably because the Fe-L line complex of the multi-temperature ICM was not well-fitted by the simple two-temperature vphase model. We will further describe the results on temperature and metal abundance separately.

6. Temperature Profile

Radial temperature profile and the ratio of the vphase normalizations between hot and cool ICM components are shown
in figures 4a and 4b. The different models of the Galactic emission (1T or 2T) gave a difference in ICM temperature of about 0.5 keV for the hot and cool ICM components, except for the innermost region. Though the previous Chandra and XMM-Newton results seem to be consistent with the Gal 1T case, the Galactic component had been neglected in that analysis. Very crudely, $kT_{\text{Hot}} \sim 1.5$ keV, and $kT_{\text{Cool}} \sim 0.8$ keV. The cool component is strongest in the innermost region, and even though it seems to decline in the outer regions, possible coupling with the Galactic emission makes a precise estimation difficult. The radius of $10' \sim 180$ kpc corresponds to $\sim 0.16 \, r_{\text{180}}$, and the temperature decline, observed in several other clusters, is not clearly recognized in this system due partly to the multi-phase nature of ICM. However, hardening of the spectra at the 3.3–6.5 annulus and softening in the outer two annuli suggested by the hardness ratio image in figure 1c are evident in figures 4a and 4b for both models of the Galactic emission.

Figure 4c shows the surface brightness profile with Suzaku for the Gal 2T model, compared with the $3\beta$-model obtained with Chandra and XMM-Newton (Morita et al. 2006). The observed profiles look almost consistent with this model, while the Suzaku intensity for the Gal 1T model is slightly higher at the outermost annulus. We note that, although the surface brightness of the hot ICM component decreases steeply, the cool component stays almost constant at $r > 3.3$. The intensity is comparable to the Galactic component, $S_{\text{G1+G2}}$, and it is very difficult to separate these two components clearly. Further offset observations with Suzaku and/or high resolution spectroscopy with, e.g., microcalorimeters, are anticipated.

We have estimated the systematic errors caused by background subtraction and by an estimation of the XIS filter contamination. We varied the sum of the NXB and CXB by ±10%, and the contamination thickness by ±20%, respec-
The hot-component intensity is comparable to the Galactic emission. On average, the two cases give largely different abundance values up to 0.3 solar in the regions of $r > 3'$, although they overlap within 90% statistical errors. Figures 6a–6i show confidence contours between the O abundance for the inner three annuli and the Galactic temperatures. In the Gal 2T model, either of the two temperatures was fixed to the assumed value when we calculated the contours. Only for the group center region, did we obtain a tight and consistent value of 0.35 ± 0.08 solar (Gal 2T case). The assumed temperatures were slightly lower or higher than the temperatures at the $\chi^2$-minimum for the $kT_{G1}$ or $kT_{G2}$ case, respectively, and gave a higher O abundance, though it was only at the 1σ level. The Gal 2T model gave a higher O abundance than the Gal 1T case in the outer three annuli; however, the O abundance was less than 0.32 solar at the 90% confidence, excluding the outer-most annulus, which had large statistical errors. Thus, the spatial profile of the O abundance is likely to be almost flat, or declining with the radius.

We note that the Ne abundance had a problem in the spectral fit due to coupling with the Fe-L feature. Therefore, regarding the spatial structure, we dealt with the remaining four elemental groups: Mg, Si, S, and Fe. The four abundance results look quite similar to each other, including the central value and the radial gradient. The central abundances

| Table 4. Summary of the best-fit parameters for single (Gal 1T) or two (Gal 2T) temperature Galactic component models. |
|---|---|---|---|---|---|---|---|---|---|---|
| Gal 1T | $kT_{Hot}$ (keV) | $kT_{Cool}$ (keV) | O (solar) | Ne (solar) | Mg, Al (solar) | Si (solar) | S, Ar, Ca (solar) | Fe, Ni (solar) | $\chi^2$/dof |
| 0'0–3'3 | 1.65±0.03 | 0.766±0.007 | 0.39±0.08 | 1.66±0.24 | 1.24±0.14 | 0.97±0.07 | 1.12±0.13 | 0.82±0.06 | 654/473 |
| 3'3–6'5 | 1.48±0.06 | 0.753±0.027 | 0.10±0.07 | 0.07±0.07 | 0.55±0.18 | 0.36±0.11 | 0.12±0.07 | 0.58±0.10 | 512/421 |
| 6'5–9'8 | 1.23±0.06 | 0.588±0.048 | 0.00±0.10 | 0.04±0.16 | 0.22±0.10 | 0.20±0.07 | 0.41±0.14 | 0.17±0.02 | 467/405 |
| 9'8–13' | 1.43±0.20 | 0.301±0.043 | 0.07±0.08 | 0.72±0.34 | 0.41±0.56 | 0.39±0.51 | 0.00±0.54 | 0.25±0.19 | 301/285 |
| All | | | | | | | | | 1934/1584 |

| Gal 2T | $kT_{Hot}$ (keV) | $kT_{Cool}$ (keV) | O (solar) | Ne (solar) | Mg, Al (solar) | Si (solar) | S, Ar, Ca (solar) | Fe, Ni (solar) | $\chi^2$/dof |
| 0'0–3'3 | 1.66±0.03 | 0.773±0.007 | 0.39±0.08 | 1.71±0.25 | 1.26±0.14 | 0.91±0.10 | 1.16±0.13 | 0.84±0.06 | 657/473 |
| 3'3–6'5 | 1.63±0.17 | 0.990±0.060 | 0.25±0.14 | 0.36±0.24 | 0.39±0.13 | 0.35±0.08 | 0.38±0.10 | 0.29±0.04 | 500/421 |
| 6'5–9'8 | 1.81±0.28 | 1.047±0.074 | 0.15±0.13 | 0.00±0.15 | 0.25±0.15 | 0.20±0.06 | 0.36±0.16 | 0.20±0.05 | 451/405 |
| 9'8–13' | 1.02±0.06 | 0.38±0.33 | 0.00±0.26 | 0.00±0.20 | 0.11±0.22 | 0.00±0.45 | 0.11±0.03 | 311/287 |
| All | | | | | | | | | 1919/1586 |

Note: Normalization of the $vapec$ component scaled with a factor of $SOURCE_{RAATIO REG}/AREA$ in table 2. $K = SOURCE_{RAATIO REG}/AREA \times \frac{f n_{e} n_{H} dV}{4 \pi (1+z)^{2} D_{A}^{2}} \times 10^{-20}$ cm$^{-2}$ arcmin$^{-2}$, where $D_{A}$ is the angular diameter distance to the source.

1. Normalization of the $apec$ component divided by the solid angle, $f^2 = \pi \times (20')^2$, assumed in the uniform-sky ARF calculation (20' radius from the optical axis of each XIS sensor), $K = \frac{f n_{e} n_{H} dV}{4 \pi (1+z) D_{A}^{2} D_{N}^{2}} \times 10^{-20}$ cm$^{-2}$ arcmin$^{-2}$.

2. Surface brightness in 0.4–4 keV in units of photons cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$, calculated in the same way as the normalization, and corrected for the Galactic absorption of $N_{H} = 3.0 \times 10^{20}$ cm$^{-2}$.

The metal abundances were determined for the six element groups individually, as shown in figures 5a–5f. The O abundance is strongly affected by how we model the Galactic emission. The two cases give largely different abundance values up to 0.3 solar in the regions of $r > 3'$, although they overlap within 90% statistical errors. Figures 6a–6i show confidence contours between the O abundance for the inner three annuli and the Galactic temperatures. In the Gal 2T model, either of the two temperatures was fixed to the assumed value when we calculated the contours. Only for the group center region, did we obtain a tight and consistent value of 0.35 ± 0.08 solar (Gal 2T case). The assumed temperatures were slightly lower or higher than the temperatures at the $\chi^2$-minimum for the $kT_{G1}$ or $kT_{G2}$ case, respectively, and gave a higher O abundance, although it was only at the 1σ level. The Gal 2T model gave a higher O abundance than the Gal 1T case in the outer three annuli; however, the O abundance was less than 0.32 solar at the 90% confidence, excluding the outer-most annulus, which had large statistical errors. Thus, the spatial profile of the O abundance is likely to be almost flat, or declining with the radius.

We note that the Ne abundance had a problem in the spectral fit due to coupling with the Fe-L feature. Therefore, regarding the spatial structure, we dealt with the remaining four elemental groups: Mg, Si, S, and Fe. The four abundance results look quite similar to each other, including the central value and the radial gradient. The central abundances
Elemental abundances plotted against radii from the group center. Diamonds in thin lines represent the Suzaku best-fit results with the Gal 1 $T$ model and diamonds in thick lines represent the results with the Gal 2 $T$ model. Dashed lines denote the movable range of the best-fit abundance when the NXB + CXB components are changed by $\pm$10%, and dotted lines denote the range when the absorption column of the XIS contaminant is changed by $\pm$20%. Gray crosses are adopted from the previous results with Chandra and XMM-Newton by Morita et al. (2006), in which Ne was fixed to have the same value with the O abundance.

Confidence contours between O abundance of the ICM component and temperature of the Galactic component with the Gal 1 $T$ model for (a)–(c), and with the Gal 2 $T$ model for (d)–(i). The contours represent 10, 90%, and 99% confidence regions from inner to outer, corresponding $\Delta \chi^2 = +2.3$, +4.6, and +9.21 from the $\chi^2$-minimum. The cross markers represent the best-fit locations in table 4, while the filled gray circles represent the $\chi^2$-minimum, which are different from the best-fit for the Gal 2 $T$ model because the temperatures of the apec models were fixed in the fitting whereas $kT_G$ was allowed to change in these plots.

There are between 0.8–1.2 solar, and the abundances decline to about 1/5 of the central value in the 6.5–9.8 annulus. Also note that the abundance results for the four elements in $r < 9.8$ all agree within 15% between the two choices of the Galactic component, even though the resultant temperatures exhibit large discrepancy, as can be seen in figure 4a. This indicates that these abundance results are fairly robust.

Again, we looked into the effect of errors in the NXB and CXB intensities and the OBF contamination thickness. As shown by dotted lines in figures 5a–5f, the systematic effect is less than the statistical error for all regions. Our Suzaku results are also consistent with the previous results with Chandra and XMM-Newton, plotted with gray crosses. However, the errors are much smaller in the outer three annuli, owing to a much deeper exposure and good sensitivity of Suzaku XIS.

### 8. Does “High-Abundance Arc” Exist?

Gu et al. (2007) reported that there was a high-abundance arc region at about 2' from the X-ray peak spanning from south to northwest, and a part of it roughly coincides with the outer edge of the southwest X-ray cavity. The reported abundance result with Chandra ACIS-S3 is $0.84^{+0.19}_{-0.10}$ solar in the radial range 1.77–2.21 of the southwest half arc (region B + C in table 1 of Gu et al. 2007). The abundance was even higher than the level at the group center ($r < 0.44$). The projected 0.7–7 keV spectrum was fitted with a single absorbed apec model with the absorption fixed to the Galactic value. They used the solar abundance table of Grevesse and Sauval (1998), where the iron number abundance relative to hydrogen is $3.16 \times 10^{-5}$, which is less than our value of $4.68 \times 10^{-5}$ by Anders and Grevesse (1989).

In order to confirm the “high-abundance arc” with Suzaku, we split the central 0.0–3.3 region into three parts: $r < 1.1$, northeast (NE) arc, and southwest (SW) arc, respectively, as
The best-fit parameters with the Galactic component do not affect the best-fit results in this region, as shown in figures 4 and 5. Though we confirmed the abundance gradient in \( r > 3.3 \), as suggested by Morita et al. (2006), no excess abundance larger than the central \( r < 1.1 \) region was observed in the SW arc, which contains the “high-abundance arc”. Comparing the NE and SW arcs, the SW one tends to show a slightly higher value, although their 90% error ranges of the abundances overlap. One outstanding feature in the SW arc is that the intensity of the hot ICM component is much higher than the cool one among the three regions examined, as can be seen in figure 7d with blue and magenta lines.

Since the angular resolution of Suzaku (~ 2' in half-power diameter; Serlemitsos et al. 2007) is much worse than that of Chandra (\( \leq 1' \)), X-ray emission from the “high-abundance arc” may be substantially diluted by the surrounding emission. However, the spectral sensitivity and the photon statistics with Suzaku are quite high, which are important to determine the elemental abundance. One possible explanation is that the excess intensity of the hot ICM component in the SW arc could have been mis-identified as the “high-abundance arc”.

We also note that the abundances were 0.35, 0.20, and 0.28 solar for \( r < 1.1 \), NE arc, and SW arc, respectively, when the Suzaku spectra were fitted with the single absorbed apec model in the 0.7–7 keV using the Grevesse and Sauval (1998) abundance, as just performed by Gu et al. (2007). Though a somewhat high abundance in the SW arc was obtained, the abundance of the SW arc suggests that the abundance gradient in the SW arc may be substantially diluted by the surrounding emission.

### Table 5. Best-fit parameters for spectra in \( r < 1.1 \), NE arc, and SW arc with the Gal 2T model.

| Region  | \( kT_{\text{Hot}} \) (keV) | \( kT_{\text{Cool}} \) (keV) | O (solar) | Ne (solar) | Mg, Al (solar) | Si (solar) | S, Ar, Ca (solar) | Fe, Ni (solar) | \( \chi^2/\text{dof} \) |
|---------|-----------------|-----------------|-----------|------------|----------------|------------|----------------|----------------|----------------|
| \( r < 1.1 \) | 1.63^{+0.06}_{-0.06} | 0.755^{+0.009}_{-0.009} | 0.45^{+0.17}_{-0.14} | 1.99^{+0.32}_{-0.45} | 1.80^{+0.19}_{-0.29} | 1.42^{+0.05}_{-0.14} | 1.66^{+0.29}_{-0.26} | 1.22^{+0.18}_{-0.15} | 549/473 |
| NE arc | 1.74^{+0.08}_{-0.09} | 0.778^{+0.012}_{-0.015} | 0.31^{+0.15}_{-0.13} | 1.76^{+0.40}_{-0.44} | 1.23^{+0.25}_{-0.24} | 0.96^{+0.18}_{-0.17} | 0.84^{+0.22}_{-0.20} | 0.71^{+0.10}_{-0.10} | 545/473 |
| SW arc | 1.55^{+0.05}_{-0.05} | 0.785^{+0.013}_{-0.013} | 0.37^{+0.16}_{-0.14} | 1.65^{+0.45}_{-0.41} | 1.34^{+0.25}_{-0.23} | 1.00^{+0.15}_{-0.17} | 1.26^{+0.23}_{-0.21} | 0.86^{+0.11}_{-0.10} | 520/473 |

| Region  | \( kT_{G1} \) (keV) | \( kT_{G2} \) (keV) | \( K_{\text{Hot}} \) | \( K_{\text{Cool}} \) | \( S_{G1} \) | \( S_{G2} \) | \( S_{\text{CXB}} \) | \( S_{\text{LMXB}} \) | \( \text{Dof} \) |
|---------|-----------------|-----------------|----------------|----------------|------------|------------|-------------|-------------|-----------|
| \( r < 1.1 \) | 0.138 (fix) | 0.344 (fix) | 91.2^{+9.8}_{-9.5} | 138.0^{+18}_{-17} | 1.3 (fix) | 0.9 (fix) | 77.8 | 274.2 | 1.2 |
| NE arc | ↑ | ↑ | 14.3^{+1.4}_{-1.1} | 12.1^{+1.4}_{-1.4} | ↑ | ↑ | 9.4 | 15.8 | ↑ |
| SW arc | ↑ | ↑ | 17.1^{+1.5}_{-1.4} | 10.1^{+1.1}_{-1.0} | ↑ | ↑ | 13.1 | 14.9 | ↑ |

Definitions of \( K \)'s and \( S \)'s are the same as table 4.
dance value was much lower than our results given in table 5. Moreover, the model was rejected with a high statistical significance of $\chi^2/\text{dof} \approx 2$. The multi-phase nature of ICM is an important factor, as discussed in section 6, and treating the data with a single temperature model can result in quite a different abundance value.

9. Extended Hard X-Ray Emission

9.1. Observed Counts and NXB Reproducibility

The XIS spectra in figures 5a–3h suggest hard X-ray emission in excess of the group thermal and LMXB emission in the energy range above ~5 keV. As already mentioned in section 4, the 6–10 keV hard-band image shows an elongated feature along the NE and SW directions around the group center. It is partly because of a clump of point sources of $\sim 1.5$maside the group center, but the feature appears to be directed to the two cavities. The point-source contribution at the group center is discussed later in this section. On the other hand, in the region of $r > 3.3$mas there seems to be no clear correlation with point sources. Since diffuse hard emission in HCG 62 was reported based on an ASCA observation (Fukazawa et al. 2001; Nakazawa et al. 2007), we investigate the properties of the hard emission with the Suzaku data.

Table 6 summarizes the observed total counts compared with the expected contributions from the background (NXB and CXB) and the group emission (ICM and LMXB). With statistics, the excess counts are significant by more than the 3σ level in all three annuli. We compared these results with the previous ASCA flux (Fukazawa et al. 2001; Nakazawa et al. 2007). Nakazawa et al. (2007) reported that a hard excess flux within the $3'-15'$ region was $0.92_{-0.17}^{+0.10} \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (2–10 keV), which is roughly $\sim 1/3$ of the CXB intensity. We calculated the expected counts with this flux, assuming a spatially flat distribution. The results are shown in “ASCA” raw in table 6. The present Suzaku counts generally look consistent with the ASCA results. However, the systematics associated with the reproducibility of the NXB must be carefully examined.

Tawa et al. (2008) report that the intrinsic variability of NXB is 4.46, 5.60, 3.20% for XIS 0, 2, 3 in 5–12 keV after the standard screening procedure. In this study, the NXB counts over 5 ks, which correspond to 2–3 d of observation, were compared with an exposure-weighted sum of the COR sorted data for night Earth observations. Therefore, the 90% confidence range of the NXB fluctuation for the FI sensors is $1.6 \times \sqrt{4.46^2 + 5.60^2 + 3.20^2}/3 = 7.2 \pm 1.1\%$. They also claim that this level can be reduced to $6.5 \pm 1.0\%$ when an updated cut-off rigidity calculation of COR2 is used as the NXB indicator, and the following additional screening criteria are applied:

$$T_{\text{SAA}, \text{HXD}} > 436 \quad \text{AND,}$$

$$\left(\text{SAT}_{\text{LAT}} > -23 \quad \text{OR} \quad \text{SAT}_{\text{ALT}} < 576.5\right) \quad \text{AND,}$$

$$\left(\text{SAT}_{\text{LAT}} < +29 \quad \text{OR} \quad \text{SAT}_{\text{ALT}} < 577.5\right) \quad \text{AND,}$$

$$\text{TIME} \geq 181470000,$$

where $\text{SAT}_{\text{LAT}}$ (°) denotes the orbital location of the satellite in the geographic latitude, $\text{SAT}_{\text{LAT}}$ (km) is the altitude of the satellite, and TIME (s) is accumulative seconds since 2000 January 1, 00:00:00 (UTC). Though we selected COR > 8 GV, which is different from the Tawa et al. (2008) study, we also tested the COR2 sorted NXB estimation after data screening with equation (2). Because the result was almost identical to the values given in table 6, we adopt $\pm 6.5\%$ as the 90% confidence range of the NXB systematic error for the XIS-FIs in 5–12 keV.

9.2. Outer Region and Study with HXD-PIN

Taking this NXB error into account, the excess hard counts in the 3.3–6.5 and 6.5–9.8 annuli, as shown in table 6a, are no more significant. In figure 8, we plot the OBS – NXB spectra of the XIS-FIs and HXD-PIN compared with the CXB, NXB, and ICM spectra. The XIS-FIs spectrum in the 3.3–9.8 annulus exhibits an apparent excess over the nominal CXB spectrum by Kushino et al. (2002); however, it becomes quite consistent if the ICM and 6.5% NXB spectra are added (orange histogram). The observed counts above 12 keV shown in table 6b also suggests that the NXB counts are a few percent higher than our estimation. The effective area of the XRT above 12 keV is so small that almost all of the observed counts should be due to the NXB, although the reproducibility in this energy band has not been studied.

In addition, the HXD-PIN data in the 12–40 keV region is fairly consistent with the nominal CXB spectrum, given by
equation (1) of Gruber et al. (1999) in the energy range of 3–60 keV to be

\[
S(E) = 7.877 E^{-0.29} \exp \left( \frac{E}{41.13} \right) \frac{\text{keV}}{\text{keV cm}^2 \text{ s sr}}.
\]  

The residual counts after subtracting the official NXB events amount to \((1.3 \pm 0.2 \pm 1.0) \times 10^{-2} \text{ counts s}^{-1} \) (15–40 keV). The former error stands for a statistical 1\(\sigma\) error, while the latter is a systematic error of \(\sim 3.5\% \) (1\(\sigma\)), derived from a document on the Suzaku web page.\(^1\) We used the released response of the HXD-PIN for the HXD nominal position, `hxd_pinhxnom_20060814.rsp`, and scaled by the opening angle of 0.3 deg\(^2\) of “fine collimators” (Takahashi et al. 2007). The CXB contribution, corrected for a normalization difference of 13\% between XIS and PIN, was derived as 1.9 \times 10^{-2} \text{counts s}^{-1}, which agrees with the observed intensity, if one takes into account the background systematics. Therefore, HXD-PIN shows no signature of strong-excess hard X-rays in the 15–40 keV spectrum. If we take the PIN background systematics to be 5.6\% at the 90\% confidence, the upper limit on the flux is \(6.2 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \) (15–40 keV).

9.3. Excess in Central Region

On the other hand, the 0’0–3’3 region shows significant excess counts with the XIS-FIs, even considering the uncertainty in the NXB flux. This region contains the cavities and possibly an X-ray weak AGN, together with four bright member galaxies (Zabludoff & Mulchaey 2000). As shown in table 6a, the estimated LMXB flux from these galaxies can account for only 30\% of the observed excess after subtracting the NXB, CXB, and ICM components. Even though the X-ray to optical luminosity ratio scatters by about 60\%, as indicated by equation (1), this scatter is unable to explain the whole excess flux. The residual excess can be explained if there are more hard sources in excess of the nominal LMXBs in a similar order. To examine this, we looked into the high-resolution Chandra image to directly measure the point-source contribution. There are 17 sources cataloged by Harrison et al. (2003) in this region, and their locations are presented in figure 9, overlaid on the Chandra ACIS-S3 image with an exposure of 49.15 ks. The 2–10 keV fluxes of these sources distribute around \((0.7–8.2) \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \), which can be converted to a luminosity of \((3.3–39) \times 10^{33} \text{ erg cm}^{-1} \text{s} \), at the redshift of HCG 62. This luminosity range is higher than the level

\(^{1}\) [http://www.astro.isas.jaxa.jp/suzaku/doc/suzakumemo/suzakumemo-2006-42.pdf].
of typical LMXBs. We extracted the source spectra within $r < 3''$, and took the background from the $3''$–$6'$ annulus for each source. The combined spectrum, shown in figure 10, can be fitted well with a power-law model with $\Gamma = 1.38 \pm 0.06$, fairly consistent with the nominal CXB slope. However, the total flux amounts to $(2.81 \pm 0.24) \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1}$, which is higher than the expected CXB intensity, $\pi \times (3.3')^2 \times 5.97 \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1} = 1.73 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1}$, by a factor of 1.62 $\pm$ 0.14. This almost completely explains the relative excess flux of 70 $\pm$ 19% over the CXB, as shown in table 6a.

Although the point-source contribution is much higher than the expected level, it is still consistent with the CXB fluctuation. Kushino et al. (2002) reported a field-to-field intensity fluctuation of $\sigma_{\text{CXB}} = 6.5\%$, with a detector beam size of $\Omega \sim 0.4$ deg$^2$ in the 2–10 keV band with the ASCA GIS. Assuming a simple Euclidean log $N$–log $S$ relation as $N(> S) \propto S^{-2.5}$, the CXB fluctuation scales as $\sigma_{\text{CXB}} \propto \Omega^{-0.5}$. This gives relative $1\sigma$ fluctuations of 42%, 25%, and 19% for the 0.0–3.3, 3.3–6.5, and 6.5–9.3 annuli, respectively, so that the observed excess of $\sim 70\%$ at $r < 3'$ is within the 90% confidence range.

To summarize, there is a suggestion of extended hard X-ray emission reported by the ASCA GIS in the Suzaku XIS data. However, the uncertainties in the NXB and CXB may well be associated with HCG 62. Lastly, we warn that the hard excess flux increases by a large factor if we include all of the XIS data, particularly with COR $< 8$ GV, in the spectral analysis, which is certainly due to the artificial effect of the NXB reproductibility. This indicates that suppression of the background counts with better screening criteria is essential in the analysis of such extended hard X-ray emission.

10. Discussion

10.1. High-Temperature Ring

We found a doughnut-like high-temperature ring at $3':3$–$6':5$ surrounding the group center, as shown in the hardness image of figure 1c. Spectral fits, shown in figure 4b, indicated an excess in the intensity ratio of hot-to-cool ICM components in this annulus. We note that the co-existence of the hot and cool components was already observed with Chandra and XMM-Newton (Morita et al. 2006), based on a deprojection analysis. However, as shown in figure 11a of Morita et al. (2006), the hot component should occupy more than $\geq 90\%$ of the volume if the two components are under a pressure balance. In other words, the total thermal energy given by the product of the pressure and the volume, $P V$, is dominated by the hot component in this annulus.

We therefore assume that the $3':3$–$6':5$ (60–120 kpc) annulus is filled with the hot ICM with a temperature of $kT_{\text{Hot}} \simeq 1.6$ keV, and the electron density is $n_e \simeq 7 \times 10^{-4} \text{ cm}^{-3}$ for simplicity. Then, the gas pressure and the total energy are $P = 1.92 n_e kT_{\text{Hot}} = 2.2 \text{ eV cm}^{-3}$ and $E = PV = 5.8 \times 10^{59} \text{ erg s}^{-1}$, respectively. The bolometric luminosity is $L_{\text{bol}} = 1.1 \times 10^{42} \text{ erg s}^{-1}$ using the $v_{\text{spec}}$ model with the elemental abundances given in table 4 (Gal 2T) for this annulus. This gives a radiation cooling time of

$$\tau_{\text{cool}} = E / L_{\text{bol}} = 17 \text{ Gyr},$$

which is longer than the Hubble time. The thermal conduction time is calculated as

$$\tau_{\text{cond}} = r^2 / \kappa_S = 0.33 \text{ Gyr}$$

$$\times \left( \frac{r}{100 \text{ kpc}} \right)^2 \left( \frac{kT_{\text{Hot}}}{1.6 \text{ keV}} \right)^{-2} \left( \frac{n_e}{7 \times 10^{-4} \text{ cm}^{-3}} \right)^{-0.5},$$

assuming the Spitzer thermal conductivity, $\kappa_S$ (Spitzer 1962). Though this time scale is much shorter than the Hubble time, the thermal conduction may be suppressed by a large factor if there are turbulent magnetic fields, and the time scale may become comparable to, or longer than, the age of a few Gyr.

Morita et al. (2006) suggested that the hydrostatic equilibrium is broken at $r \sim 5'$, and that the outflow of the hot ICM may occur, based on the result of a steep temperature drop at $r \sim 5'$–$10'$. In this case, the hot ICM may be expanding with nearly the sound velocity, $v_s = \sqrt{kT_{\text{Hot}} / \mu m_p} = 640 \text{ km s}^{-1}$, where $\gamma = 5/3$ and $\mu = 0.62$. The expanding time scale is

$$\tau_s = r / v_s = 0.15 \left( \frac{r}{100 \text{ kpc}} \right) \left( \frac{kT_{\text{Hot}}}{1.6 \text{ keV}} \right)^{-0.5} \text{ Gyr}.$$  

Thus, the total power input required to form the high-temperature ring can be roughly estimated as

$$W = E / \tau_s = 1.2 \times 10^{44} \text{ erg s}^{-1}.$$  

This power is by about two orders of magnitude higher than that required to generate the two cavities in the central region of HCG 62. The large implied power and the absence of strong AGN activity in this group suggest that the hot ring may be caused by some large-scale dynamical process in the central region of the group.

10.2. Metallicity Distribution in ICM

The present Suzaku observation of HCG 62 showed abundance distributions of O, Ne, Mg, Si, S, and Fe out to a radius of $10' \simeq 180 \text{ kpc}$. Ne abundance has a large ambiguity due to a strong coupling with Fe-L lines, as mentioned in section 7. The distributions of Mg, Si, S, and Fe are quite similar to each other, while the O profile in the outer region has a large uncertainty. We plot the abundance ratios of O, Mg, Si, S against Fe as a function of the projected radius in figure 11. Here, the values in the outermost region ($r > 9.8$) were excluded because of large uncertainties. The ratios $\text{Mg/Fe}$, $\text{Si/Fe}$, and $\text{S/Fe}$ are consistent to be a constant value of around 1.5–2, while the $\text{O/Fe}$ ratio seems to increase with the radius. These features have been seen with Chandra and XMM-Newton by Morita et al. (2006), and the present result gives a good confirmation in the outer region.

Recent Suzaku observations have presented abundance profiles in several other systems: an elliptical galaxy NGC 720 (Tawara et al. 2008), the Fornax cluster and NGC 1404 (Matsushita et al. 2007a), and a cluster of galaxies Abell 1060 (Sato et al. 2007b). While the $\text{Si/Fe}$ ratio is almost the same among all the systems, Mg/$\text{Fe}$ ratio is slightly higher in HCG 62 and Abell 1060 than in NGC 720, the Fornax cluster,
and NGC 1404. We compared the abundances in HCG 62 with those in the Fornax cluster, as shown in figure 11. Regarding the Fornax cluster, we used \( r_{180} = 1.00 \sqrt{kT/1.3 \text{ keV Mpc}} \), and \( z = 0.00429 \) corrected to the reference frame defined by the 3 K microwave background radiation (NASA/IPAC Extragalactic Database: NED). The solar abundance by Feldman (1992) with \([\text{Fe}/\text{H}] = 3.24 \times 10^{-5}\) employed by Matsushita et al. (2007a) was scaled by a factor of 0.7 to match the Anders and Grevesse (1989) value of \([\text{Fe}/\text{H}] = 4.68 \times 10^{-5}\).

HCG 62 shows a lower Fe abundance than that of the Fornax cluster in the central region at \( r < 0.05 r_{180} \), but the abundances become similar at \( r \approx 0.1 r_{180} \). The abundance ratios of O/Fe, Mg/Fe, Si/Fe, and S/Fe are quite similar between HCG 62 and the Fornax cluster at \( r \approx 0.1 r_{180} \).

Tamura et al. (2004) reported abundance ratios for 19 clusters studied with XMM-Newton, and the mean Si/Fe ratio in cool and medium-temperature clusters with \( kT < 6 \text{ keV} \) was \(~1.4\), consistent with our HCG 62 result. Their O/Fe ratio, \(~0.6\), in the cluster core also agrees with our result. Matsushita et al. (2003, 2007b) also reported the abundance ratio for M 87 and the Centaurus cluster, respectively. M 87 showed the Mg/O ratio to be \(~1.3\) in the central region, and the Centaurus cluster indicated the O/Fe and Si/Fe ratios within \( 8' \) to be consistent with our results. The Mg/O ratio for HCG 62 with XMM-Newton (Morita et al. 2006) is \(~3.3\) within \( 1' \), which is almost the same as our result of \(~3.6\) within \( 3' \). The Mg/O ratios in other groups are \(~2.5\) for NGC 5044 (Tamura et al. 2003), and \(~1.3\) for NGC 4636 (Xu et al. 2002), both measured with XMM-Newton RGS.

Sato et al. (2007b) studied contributions of type Ia and II supernovae to the metal enrichment, based on Suzaku results of HCG 62, Abell 1060, AWM 7, NGC 570 (Sato et al. 2007a, 2008).

### 10.3. Metal Mass-to-Light Ratio

The metal mass-to-light ratios (MLRs) for oxygen, iron, and magnesium (OMLR, IMLR, and MMLR, respectively) were examined. First, we show the metal mass profiles in figure 12a, based on the 3-dimensional gas mass profile by Morita et al. (2006) and the abundance profile measured with Suzaku. The derived iron mass within a 3-dimensional radius of \( R < 200 \text{ kpc} \)
is \((1.5–3) \times 10^8 M_\odot\), which is quite consistent with the previous measurement in figure 11e of Morita et al. (2006). We obtained the magnesium mass to be \((0.7–1.1) \times 10^8 M_\odot\). Though the oxygen mass has large errors, as can be seen in figure 12a, it is unlikely that oxygen has a smaller mass than iron. Therefore, the \(27T\) model (crosses) is preferred to the \(17T\) one (solid and dotted lines). The estimated oxygen mass is \(~ 10^9 M_\odot\), within \(R < 200\) kpc.

Secondly, we adopted Zabludoff and Mulchaey (2000) results as the member galaxy catalog of HCG 62 (12 galaxies in \(r < 13' \sim 230\) kpc), and their redshifts were used to estimate the 3-dimensional distribution. Since only the \(R\)-band optical magnitudes are provided in this catalog, we converted them into \(B\)-band magnitudes using the color of \(B - R = 2.0\) mag for the HCG 62a galaxy at the center (Hickson et al. 1989), and \(A_B = 0.224\) after NASA/IPAC Extragalactic Database (NED) in the direction of HCG 62.

We thus calculated the integrated values of OMLR, IMLR, and MMLR within \(r < 230\) kpc, as shown in figure 12b; they turned out to be \(~ 4 \times 10^{-3}, \sim 4.6 \times 10^{-3}, \sim 1.5 \times 10^{-3}\) \(M_\odot/L_\odot\), respectively. The errors are only based on the statistical errors of the metal abundances in the spectral fit, and the uncertainties of the gas mass profiles and the luminosities of the member galaxies were not considered. The IMLR values are consistent with the collective results with ASCA by Makishima et al. (2001). The MMLR and IMLR show a similar steep increase with radius up to \(r \sim 100\) kpc, and seem to reach almost a plateau at \(100–200\) kpc. This feature is not apparent for the OMLR, due partly to the large uncertainty. The behavior of MLR curves would be related to different enrichment processes, as discussed in Morita et al. (2006).

We also point out that the derived OMLR and IMLR for HCG 62 are much larger than those of the Fornax cluster (Matsushita et al. 2007a) as shown in figure 12b. Particularly, the difference in IMLR is significant, although that in OMLR is marginal due to the uncertainty in the Galactic emission. These two systems have a similar potential depth with \(k(T) \sim 1.3\) keV. This feature may indicate that the Fornax cluster is a younger system with a smaller number of SN Ia for the Fe production, since the cluster formation, and/or that the metal distribution in the Fornax may be much more extended. A possible difference of the initial mass function (IMF) between the two may account for some fraction of the discrepancy in the MLRs. Ikebe et al. (1996) discovered that there are two distinct length scales of dark-matter concentration in the Fornax cluster, and the cD galaxy NGC 1399 is off-centered by \(~ 50\) kpc with respect to the cluster hot gas. There is also an X-ray luminous elliptical galaxy, NGC 1404, at 10' south–west of NGC 1399. These features suggest that the Fornax system may be dynamically young and that galaxy interactions in ICM may have caused extended metal distribution.

### 10.4. AGN Versus Mergers

HCG 62 exhibits several interesting activities in both the central and the outer regions: namely, two cavities (Vrtilek et al. 2002; Morita et al. 2006), extended hard X-ray emission (Fukazawa et al. 2001; Nakazawa et al. 2007), multi-phase ICM (Morita et al. 2006; this work), possible “high-abundance arc” (Gu et al. 2007), and a doughnut-like high-temperature ring (this work). One might relate the central features with an AGN activity; however, the central galaxy (HCG 62a = NGC 4761) currently shows little evidence of AGN activities in both optical (Coziol et al. 1998; Shimada et al. 2000; Coziol et al. 2004) and radio bands, as summarized in subsection 8.1 of Morita et al. (2006) and subsection 3.1 of Gu et al. (2007). Morita et al. (2006) also have placed an upper limit on the X-ray luminosity of the AGN to be \(L_X \leq 10^{39}\) erg s\(^{-1}\) (0.5–4 keV). Since the Suzaku HXD-PIN shows no excess over the CXB flux (figure 8), heavily absorbed AGN with an intrinsic luminosity larger than \(~ 3 \times 10^{42}\) erg s\(^{-1}\) (15–40 keV) is also ruled out. Another possibility related with the HCG 62 activity can be recent mergers, as suggested in the above-mentioned previous works. Energy inputs from magneto-hydrodynamic interactions of the member galaxies with the ICM (Makishima et al. 2001) can be another possible mechanism.

We found a concentration of hard sources in \(r < 3'3\) with average photon indices of \(\Gamma \sim 1.4\). As shown in subsection 9.3, this concentration, itself, is within the range of CXB fluctuation; however, the spatial coincidence with the group center is remarkable, as can be seen in figure 1b. Since the source luminosities are \((3.3–39) \times 10^{37}\) erg s\(^{-1}\) (2–10 keV) at HCG 62, we suggest that some of the sources may be remnants of minor mergers that were previously central black holes of the merged galaxies. The overdensity of X-ray sources with \(L_X = (4.0–250) \times 10^{39}\) erg s\(^{-1}\) (2–10 keV) in the fields of A 194 and A 1060 was also reported by Hudaverdi et al. (2006). Optical identifications of these objects will be of great interest.

### 11. Summary

- Suzaku confirmed the multi-phase nature of the ICM out to a radius of \(~ 10'\). We found a doughnut-like high-temperature ring at 3.3–6.5 in the hardness image, which is caused by a higher hot component intensity over the cool component, as shown by the spectral fit. Possible ICM heating by the mass accretion is suggested.
- We could not confirm the “high-abundance arc” in the SW arc in the 1.1–3.3 annulus reported by Gu et al. (2007), and we suggest that it is a possible misidentification of an excess hot ICM component as the Fe line.
- The Mg-to-Fe ratio showed an enhancement at the center, thus confirming the previous Chandra and XMM-Newton result. The temperature, surface brightness, and O abundance at \(r > 3'3\) were subject to modeling of the Galactic component, while the Mg, Si, S, and Fe abundances were fairly robust. The \(27T\) model was preferred in terms of the surface-brightness profile and the integrated O mass.
- The O abundance was \(~ 0.4\) solar at the center, and less than 0.5 at \(r > 3'3\). The abundance ratios \(O/Fe, Mg/Fe, Si/Fe,\) and \(S/Fe\) showed similar values with those in the Fornax cluster in \(r \sim 0.1\) kpc. A comparison of 19 clusters with HCG 62 showed consistent levels of \(O/Fe \sim 0.6\) and \(Si/Fe \sim 1.4\). On the other hand, HCG 62 showed \(Mg/O \sim 3.6\) at \(r > 3'3\), significantly higher than in other groups and giant ellipticals.
- The OMLR and IMLR values in HCG 62 are by about an
order of magnitude higher than the Fornax cluster results at \( r \sim 130 \) kpc, while our IMLR agrees with a collection of the ASCA results.

- A thermal fit and the 6–10 keV image indicated an excess above \( \sim 5 \) keV in most of the radii; however, it was not significant considering the uncertainties in the NXB and CXB fluctuations. ASCA detection of the hard excess is still consistent with our results.
- We found an excess X-ray emission of 70 ± 19% times the nominal CXB intensity (5–12 keV) within \( r < 3/3 \), and most of it could be explained by a concentration of hard X-ray sources detected with Chandra. We suggest some of the sources could be remnants of minor mergers.

Part of this work was financially supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan, Grant-in-Aid for Scientific Research No. 14079103, 15340088, 15001002, 16340077, 18740011, 19840043.

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