Chemical abundances in the outskirts of nearby galaxy groups measured with joint Suzaku and Chandra observations

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ABSTRACT

We report results from deep Suzaku and mostly snapshot Chandra observations of four nearby galaxy groups: MKW4, Antlia, RXJ1159+5531, and ESO3060170. Their peak temperatures vary over 2–3 keV, making them the smallest systems with gas properties constrained to their virial radii. The average Fe abundance in the outskirts (R > 0.25R200) of their intragroup medium (IGrM) is ZFe = 0.309 ± 0.018 Z⊙ with χ² = 14 for 12 degrees of freedom, which is remarkably uniform and strikingly similar to that of massive galaxy clusters, and is fully consistent with the numerical predictions from the IllustrisTNG cosmological simulation. Our results support an early-enrichment scenario among galactic systems over an order of magnitude in mass, even before their formation. When integrated out to R200, we start to see a tension between the measured Fe content in ICM and what is expected from supernovae yields. We further constrain their O, Mg, Si, S, and Ni abundances. The abundance ratios of those elements relative to Fe are consistent with the predictions (if available) from IllustrisTNG. Their Type Ia supernovae fraction varies between 14%–21%. A pure core collapsed supernovae enrichment at group outskirts can be ruled out. Their cumulative iron-mass-to-light ratios within R200 are half that of the Perseus cluster, which may imply that galaxy groups do not retain all of their enriched gas due to their shallower gravitational potential wells, or that groups and clusters may have different star formation histories.

Key words: X-rays: galaxies: clusters – galaxies: clusters: intracluster medium

1 INTRODUCTION

Big Bang nucleosynthesis primarily produced all the hydrogen and helium in the Universe, and trace amounts of a few lighter elements like Li and Be. Heavier elements are later forged in stars. Clusters of galaxies, with their deep gravitational potential wells, retain substantial X-ray emitting hot gas (T ∼ 10⁷–10⁸ K), the so-called intracluster medium (ICM) (Ettori & Fabian 1999). A dominant fraction of metals in the local Universe can be found in the ICM, making them a unique astrophysical laboratory to probe nucleosynthesis and the chemical enrichment history of the Universe (Biffi et al. 2018a; Mernier et al. 2018a).

The enrichment processes in the ICM remain an open question. In the late enrichment scenarios (after the cluster is assembled), the ICM metal distributions are expected to be non-uniform, with a significant amount of azimuthal scatters (Domainko et al. 2006). For instance, galactic materials can be stripped off the galaxies and deposited in the ICM as the infalling galaxies interact with the dense gas (e.g., Gunn & Gott 1972; Fabjan et al. 2010), which enriches the ICM along the directions of infalling galaxies. Also, the metals dispersed into the ICM at later times should broadly follow the spatial distributions of galaxies, leading to flat metal mass-to-light ratios (Matsushita et al. 2013). Neither of these is consistent with the observations. Nearby massive clusters, such as Perseus, show a remarkably homogeneous Fe abundance of ∼ 0.3 Z⊙ at R > 0.25R200 (Urban et al. 2017; Werner et al. 2013). Previous studies, using Chandra, Suzaku, and XMM-Newton observations, have reported steep iron mass-to-light ratios (IMLRs) for several galaxy clusters out to 0.2–0.5R200 (e.g., Matsushita et al. 2007; Sato et al. 2009; Simionescu et al. 2011), which indicates that metal mass is more extended than the distribution of cluster galaxies. Although the ICM can achieve a uniform distribution of metals in the late enrichment process via large-scale

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The observed uniform Fe abundances and steep IMLR profiles suggest an early enrichment scenario, in which most of the enrichment occurred in the proto-cluster environment (e.g., Fabjan et al. 2010; Biffi et al. 2017). This process is primarily driven by the galactic winds and active galactic nuclei (AGN) feedback at the epoch of the peak star formation (around \( z \sim 2-3 \); Madau & Dickinson 2014). The strong galactic winds and AGN activity may have expelled much of the metals from the interstellar medium (ISM) and uniformly mixed the intergalactic gas even before the cluster was assembled.

With a better understanding of stellar nucleosynthesis over the past decades, it is now evident that most of the lighter elements, like O, Mg, and Ne, are synthesized by massive stars and expelled into the ICM by core-collapsed supernovae (SNeIa) (e.g., Nomoto et al. 2006), while the heavier elements, like Ar, Ca, Fe, and Ni, are primarily produced by Type Ia supernovae (SNe Ia) (e.g., Iwamoto et al. 1999; Sarkar et al. 2021b). Elements such as Si and S are produced relatively comparably by SNe Ia and SNecc (e.g., de Plaa et al. 2007). Therefore, the metal abundance pattern of heavier elements strongly depends on the SNe Ia explosion mechanism, and the abundances of lighter elements depend on the stellar initial mass function (IMF) of galaxies (Mernier et al. 2015, 2016b). The measurement of the abundance profiles of those metals is crucial to constrain supernovae models, and to probe the chemical enrichment history of the ICM.

The \( \alpha \)-capture (such as O, Mg, Ne, Si, S) and Fe peak elements (such as Cr, Mn, Fe, Co, Ni) can be observed from their emission lines in X-ray. Most of these emission lines originate from the K and L – shell transitions in highly ionized plasma (Chakraborty et al. 2020a,b). Since the ICM is very close to collisional ionization equilibrium and optically thin, the equivalent widths of those emission lines can easily be converted to element abundances (Böhringer & Werner 2010; Mernier et al. 2016a; Urban et al. 2017). Using Chandra observations, Rasmussen & Ponman (2007) have found that the Si/Fe ratio increases with radius, strongly suggesting an excess of SNe Ia contribution at the cluster center, while the SNecc contribution dominates at the outskirts. Later on, however, it was observed in M87 that the Si abundance profile is even more centrally peaked than Fe (Million et al. 2011). Most recently, an extensive Suzaku investigation of the nearby Virgo cluster reveals an SNIa fraction of 12–37% throughout its ICM, which challenges pure SNcc enrichment at the cluster outskirts (Simionescu et al. 2015). The current view is that abundance profile is roughly the same for all elements.

The enrichment process in lower mass systems (groups) is even less straightforward (Gastaldello et al. 2021). With deep gravitational potential wells, galaxy clusters behave like closed-box systems, holding all of the metals ever produced by the stars inside their virial radius (e.g., de Plaa et al. 2007). In contrast, galaxy groups have shallow gravitational potential wells, which makes them more vulnerable to losing material via non-gravitational processes, such as galactic winds driven by supernovae (SNe) and AGN feedback (e.g., Rasmussen & Ponman 2007; Lovisari et al. 2015; Thiloren et al. 2016). These processes may expel much of the enriched gas out of the system (Sarkar et al. 2021a). Using ASCA data, Makishima et al. (2001) found that the IMLRs in galaxy groups within 0.5 \( R_{200} \) increase with their masses, while those of galaxy clusters are not mass-dependent, and are systematically higher than groups. The metal budgets out to the virial radius of groups are relatively unexplored, due to their low surface brightness. The emission from the outskirts of groups is typically dominated by the X-ray background, which makes the measurement of metal abundances very challenging (Rasmussen & Ponman 2009). With its stable particle background and higher spectral sensitivity below 1 keV (Koyama et al. 2007), Suzaku can measure the metal abundances more precisely at \( R_{200} \) and beyond. The inclusion of snapshot Chandra observations resolves much of the Cosmic X-ray Background (CXB), which is crucial to pin down the systematic uncertainty.

In this paper, we study the metal abundances of four galaxy groups: MKW4, Antlia, RXJ1159+5531 (hereafter RXJ1159), and ESO3060170, from their centers out to \( R_{200} \), with Suzaku and Chandra. Their peak temperatures (just outside the group core at \( \sim 0.25 R_{200} \)) are 2.2 keV, 2.3 keV, 2.5 keV, and 2.7 keV, respectively. To our knowledge, they are the lowest mass systems with their gas properties constrained at \( R_{200} \). MKW4, RXJ1159, and ESO3060170 are cool core systems, while Antlia is a non-cool-core group. The thermodynamic properties of these four galaxy groups out to their virial radii are reported in Sarkar et al. (2021a), Wong et al. (2016),

### Table 1. Observational log

| Name       | Obs Id      | Obs Date | Exp. (ks) |
|------------|-------------|----------|-----------|
| **Suzaku** |             |          |           |
| MKW4 central | 800066010  | 2013 Dec 30 | 34.6 |
| MKW4 Offset 1 | 805081010 | 2010 Nov 30 | 77.23 |
| MKW4 N2 | 800807010 | 2010 Nov 30 | 97 |
| MKW4 Offset 2 | 808082010 | 2010 Nov 30 | 80 |
| MKW4 E1 | 808065010 | 2013 Dec 29 | 100 |
| MKW4 NE | 809062010 | 2013 Dec 29 | 87.5 |
| Antlia E0 | 802035010 | 2007 Nov 19 | 55 |
| Antlia E1 | 807066010 | 2012 Jun 13 | 20 |
| Antlia E2 | 807067010 | 2012 Jun 14 | 21 |
| Antlia E3 | 807068010 | 2012 Jun 15 | 19 |
| Antlia E4 | 807069010 | 2012 Jun 16 | 17 |
| Antlia E5 | 807070010 | 2012 Jun 17 | 39 |
| Antlia EB | 807071010 | 2012 Jun 18 | 38 |
| RXJ1159 N | 804051010 | 2009 May 02 | 84 |
| RXJ1159 S | 807064010 | 2012 May 27 | 81 |
| RXJ1159 E | 809063010 | 2014 May 29 | 96 |
| RXJ1159 W | 809064010 | 2014 May 31 | 94 |
| ESO3060170 central | 805075010 | 2010 May 27 | |
| ESO3060170 offset | 805075060 | 2010 May 70 | |
| **Chandra** |             |          |           |
| MKW4 central | 3234 | 2002 Nov 24 | 30 |
| MKW4 N2 | 20593 | 2019 Feb 25 | 14 |
| MKW4 E1 | 20592 | 2018 Nov 17 | 15 |
| MKW4 NE | 20591 | 2019 Mar 08 | 14 |
| Antlia E1 | 15090 | 2013 Nov 20 | 7 |
| Antlia E2 | 15089 | 2013 Nov 22 | 7 |
| Antlia E3 | 15088 | 2013 Jul 02 | 7 |
| Antlia E4 | 15086 | 2013 Nov 04 | 7 |
| Antlia E5 | 15085 | 2013 Apr 05 | 7 |
| Antlia EB | 15087 | 2013 Nov 04 | 7 |
| RXJ1159 central | 4964 | 2004 Feb 11 | 76 |
| RXJ1159 NW | 14026 | 2012 Aug 09 | 50 |
| RXJ1159 NE | 14473 | 2012 Aug 12 | 37 |
| RXJ1159 W | 14027 | 2012 Aug 09 | 13 |
| ESO3060170 central | 3188 | 2002 March 08 | 14.06 |
| ESO3060170 offset | 17219 | 2015 Oct 09 | 9.84 |
Table 2. Properties of the groups

| Name     | peak temp (keV) | $R_{200}$ (kpc) | $z$          | scale (1°) (kpc) | CC/NCC |
|----------|-----------------|-----------------|--------------|-----------------|--------|
| MKW4     | 2.2             | 884             | 0.02         | 0.443           | CC     |
| Antlia   | 2.3             | 887             | 0.009        | 0.213           | NCC    |
| RXJ1159  | 2.5             | 871             | 0.081        | 1.583           | CC     |
| ESO3060170 | 2.7         | 1150            | 0.0358       | 0.73            | CC     |

2 OBSERVATIONS AND SPECTRAL ANALYSIS

MKW4 has been observed out to the virial radius with Suzaku and Chandra in three directions (north, east, and northeast). Antlia and ESO3060170 have each been mapped to the virial radius in one direction, east and south, respectively. RXJ1159 has been observed to the virial radius with full azimuthal coverage. The detailed observations are listed in Table 1. The exposure corrected and background subtracted mosaic Suzaku images of four groups in the 0.5–2.0 keV energy band are shown in Figures A1, A2, A3, and A4, respectively. We followed the data reduction procedure described in Sarkar et al. (2021a) for MKW4, Wong et al. (2016) for Antlia, Su et al. (2015) for RXJ1159, and Su et al. (2013) for ESO3060170. In short, we extracted spectra from several annular regions, from the center out to the virial radius of each group, as marked in green annular sectors in Figures A1, A2, A3, and A4. We generated redistribution matrix files (RMF) and instrumental background files (NXB) for all regions and detectors. For each region, one ancillary response file (ARF) was generated using a β-profile image to model the ICM component; another ARF was produced for a uniform emission in a circular region of 20° radius to model the sky X-ray background.

Spectral analysis was performed using XSPEC–12.10.1 and Cash statistics (Cash 1979). We fit the spectra extracted from XIS0, XIS1, and XIS3 simultaneously. For MKW4, the spectral fitting was restricted to the energy range of 0.4 – 7 keV for XIS1 and 0.6 – 7 keV for XIS0 and XIS3 (Sarkar et al. 2021a), while the energy range of 0.5–7 keV was used for the other three groups. We fit each spectrum with a multi-component X-ray background model and a thermal emission model. For the X-ray background model, we adopted – phabs*(pow resolved CXB + pow unresolved CXB + apec MW) + apec LHB. The pow resolved CXB component represents the point sources resolved by Chandra. A mosaic image of Chandra observations of each group in the 0.5–7.0 keV energy band is shown in Figures A1, A2, A3, and A4, with all resolved point sources marked with green elliptical regions. The second power-law component (pow unresolved CXB) describes the unresolved point sources. The two thermal apec components model the foreground emissions from Milky Way (apec MW) and Local Hot Bubble (apec LHB).

Two thermal components associated with a photoelectric absorption component - phabs*(vapec + vapec) were fitted to the spectra of each group to model the ICM emission from each annulus. The galactic hydrogen column densities in the directions of MKW4, Antlia, RXJ1159, and ESO3060170 were obtained using the HEASARC NHI tool. We link the temperature of the cooler component of each region to half that of the hotter component. The normalizations of both components are allowed to vary freely. The best-fit spectral models for the outermost regions of the four groups are shown in Figure A5.

For MKW4 and Antlia, we simultaneously fit spectra from regions in different azimuthal directions. We let the temperatures and normalizations vary freely among different regions while linking the abundances of regions at the same distance from the group center. We allow the abundances of O, Mg, Si, S, Fe, and Ni to vary freely, while the rest of the elements were varied collectively. The abundances of Ar and Ca were linked to S. We are unable to constrain the S abundance for E2 and E3 pointings of Antlia. We, therefore, fixed the Si abundance to be equal to the S abundance. For the outer three regions of MKW4 at $R_{200}$, and the outer two regions of Antlia at $R_{200}$ (E4 and E5), we did not find any good constraint on their metal abundances when fitted individually. Therefore, we performed a simultaneous fitting for all those 5 regions. Their temperatures and normalizations were allowed to vary freely, but with their metallicities linked. The virial temperatures of MKW4 and Antlia are nearly the same. Both groups display entropy profiles rising to $R_{200}$. The distance of MKW4 is twice that of Antlia, which makes the outermost regions of MKW4 (R = 706-1200 kpc) cover almost the same physical radial range as the outermost two regions in Antlia (R = 828-1302 kpc). It is, therefore, reasonable to assume that they have similar metallicities at $R_{200}$.

For RXJ1159 and ESO3060170, we set their Ni abundance to 1 $Z_{\odot}$ (the best fit for MKW4 and Antlia), as we could not find a good constraint when letting it vary freely. The remaining elements were allowed to vary as described for MKW4 and Antlia. We also find it necessary to link the abundance of region 3 to that of region 4, and the abundance of region 5 to that of region 6, for ESO3060170 (the temperature and normalization of each region are free to vary). We did not perform any deprojection during spectral fitting since it may introduce systematic noise (Nulsen & Böhringer 1995; McLaughlin 1999). The best-fit Fe, O, Mg, Si, S, and Ni profiles of each group are shown in Figures A1, A2, A3, and A4.

* The Fe abundance measurement is biased low when fitting multi-phase gas with a single temperature model (e.g., Buote & Fabian 1998; Buote 2000; Gastaldello et al. 2021). Given Suzaku’s modest angular resolution, each radial bin covers a sizable physical region, likely associated with temperature variation even at cluster outskirts. When fitting a single temperature spectrum generated with Xspec fakeit to our 2T model, no bias to the metal abundance measurement is found. Therefore, our model should not introduce any bias if even the gas is single phase.

http://ned.ipac.caltech.edu

http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl
3 RESULTS

3.1 Fe abundance profiles

We obtain abundance profiles of Fe for four groups out to $R_{200}$, as shown in Figure 1 and Figures A1, A2, A3, and A4. Within $0.25 R_{200}$, their Fe abundances increase towards their centers, with MKW4 showing the strongest gradient, reaching $1.3 Z_\odot$ in the center. This may be partially due to the smaller radial bin width that has been resolved for MKW4. The Fe abundance profile of Antlia is much flatter at $R > 0.05 R_{200}$, with the smallest central Fe abundance of $0.6 Z_\odot$ at $R < 0.05 R_{200}$. Unlike the other three groups, Antlia is a non-cool-core system. The mechanism that has disrupted its core, such as a major merger, may have redistributed its central metal content at $R > 0.05 R_{200}$ (e.g., Murray et al. 2018; Lovisari & Reiprich 2019).

Even though these systems show a variety of Fe abundances at their centers, the Fe abundance profiles start to converge outside their cores. In the outskirts, the Fe abundances are mostly consistent within uncertainties. We measure an average Fe abundance of $0.309 \pm 0.018 Z_\odot$ ($\chi^2 = 14$ for 12 degrees of freedom) over the radii of 0.25–1.0 $R_{200}$. This is strikingly similar to what was found for 10 nearby massive clusters, with a $Z_F$ of $0.316 \pm 0.012 Z_\odot$ ($\chi^2 = 28.85$ for 25 degrees of freedom) over 0.25–1.0 $R_{200}$ (Urban et al. 2017), using the same Solar abundance table of Asplund et al. (2009).

We compare the measured Fe abundance at $R > 0.25 R_{200}$ of our four groups with that of simulated groups, as shown in Figure 1. We use IllustrisTNG100, a simulation run in the IllustrisTNG project (e.g., Naiman et al. 2018; Springel et al. 2018; Nelson et al. 2018; Marinacci et al. 2018; Pillepich et al. 2018), to predict the Fe abundance in the outskirts of groups. The simulated volume is $(110.7 \text{ Mpc})^3$, providing 41 simulated groups, defined as Friend-of-Friend halos within the mass range $M_{200} \sim 5 \times 10^{13} - 4 \times 10^{14} M_\odot$ at $z=0$. The abundance is measured within the range of $[0.25-1]R_{200}$, and is computed as an X-ray emission-weighted quantity, in which the X-ray emission of each simulated gas cell is obtained based on the gas thermodynamics, e.g., gas density, temperature, and metallicity, assuming an apec plasma model.

At $R < 0.5 R_{200}$, simulations predict lower Fe abundances by a factor of ~2 compared to the observations. Similar discrepancies have been found by Mernier et al. (2018b) and Leccardi & Molendi (2008) while comparing the Fe abundance profiles with the hydrodynamic simulations. Planelles et al. (2014) argue that this discrepancy can be explained by the outdated assumptions on the SNe yields, the assumed initial mass function, the fraction of binary systems, and/or the SNe efficiency of releasing metals into the ICM (Mernier et al. 2018b). We test with two different SNIa yield models, i.e., the W7 model by Iwamoto et al. (1999), used in TNG simulations, and the yield model by Badenes et al. (2006), which best-fitted with our observations, as discussed in Section 3.4. By assuming a SNIa fraction of 23%, we find that the SNIa yield model of Badenes et al. (2006) produces > 25% more Fe than that of the W7 model, which partially explains the discrepancy seen in Figure 1 left. In addition, our sample is dominated by cool core systems with concentrated metallicity distributions, while the simulation sample has a more extensive diversity of group cores. Simulations show a large scatter in the Fe profile at $R > 0.5 R_{200}$, as seen in Figure 1 left. This could be explained by the presence of satellites and high-density clumps at the outskirts. The average Fe abundance of simulated groups in the $0.25 R_{200} < R < R_{200}$ range agrees with the observations, as shown in Figure 1 (right).
3.2 Chemical composition

In addition to Fe, we have further constrained the abundance profiles of O, Mg, S, Si, and Ni, as shown in Figures A1, A2, A3, and A4. We derive their abundance ratios relative to Fe as a function of radius from the centers out to the virial radii, as shown in Figure 2. The uncertainties are calculated using Monte Carlo simulations with 2000 - 3000 realizations. We observe that the X/Fe ratios are consistent with the solar abundance within R < 0.25R$_{200}$, with O/Fe = 1.39 ± 0.12 ($\chi^2$/degrees of freedom = 16.7/6), Mg/Fe = 1.02 ± 0.09 ($\chi^2$/degrees of freedom = 17.6/5), Si/Fe = 1.13 ± 0.07 ($\chi^2$/degrees of freedom = 10.5/6), S/Fe = 1.21 ± 0.09 ($\chi^2$/degrees of freedom = 11.6/7), and Ni/Fe = 1.82 ± 0.29 ($\chi^2$/degrees of freedom = 16.5/4), which is similar to what have been measured for group centers such as the CHEERS project (Mernier et al. 2018b). The X/Fe ratios over 0.25R$_{200}$ < R < R$_{200}$ are somewhat super solar with O/Fe = 1.92 ± 0.51 ($\chi^2$/degrees of freedom = 5.2/12), Mg/Fe = 1.76 ± 0.54 ($\chi^2$/degrees of freedom = 10/12), Si/Fe = 1.62 ± 0.51 ($\chi^2$/degrees of freedom = 8/12), S/Fe = 1.70 ± 0.48 ($\chi^2$/degrees of freedom = 6/12), and Ni/Fe = 3.60 ± 1.50 ($\chi^2$/degrees of freedom = 3.4/6).

We compare the O/Fe, Mg/Fe, and Si/Fe ratios of our four groups with that of simulated groups, as shown in Figure 2. Since TNG simulations do not include S abundance, we could not compare the measured S/Fe ratio with the simulation. Our measured abundance ratios for O/Fe, Mg/Fe, and Si/Fe are consistent with the simulated groups within their 1$\sigma$ error bars.

3.3 Iron mass-to-light ratios

We investigate the IMLR from the centers out to the virial radii of these groups to compare the Fe distribution in the IGrM with their
stellar mass profiles. We use the metal abundance profiles obtained in this work, and the deprojected density profiles of MKW4, Antlia, RXJ1159, and ESO3060170 derived in Sarkar et al. (2021a), Wong et al. (2016), Su et al. (2015), and Su et al. (2013), respectively, to calculate the accumulated iron mass within a specific radius for each group. We estimate the Ks-band luminosity of each group using the Two Micron All-Sky Survey (2MASS\(^\dagger\)). We obtain a 2° × 2° mosaic image centered at each group from the 2MASS data catalog. We adopt the Galactic extinction (A\(K\)) values for both groups from NASA/IPAC Extragalactic Database\(^\dagger\). We deproject the Ks-band luminosity with

\(^\dagger\) https://irsa.ipac.caltech.edu/applications/2MASS/IM/interactive.html
\(^\dagger\) http://ned.ipac.caltech.edu

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**Figure 3.** Left: Radial profiles of IMLR with Ks-band luminosity for groups in our sample and the Perseus cluster. We obtain IMLR of Perseus from Matsushita et al. (2013). Right: The averaged fSNIa for the four groups at R < 0.25R\(_{200}\) and 0.25R\(_{200}\) < R < R\(_{200}\). Green shaded region represents the measurement scatter obtained from a large number of groups (Mernier et al. 2017). Yellow shaded region indicates the limit of fSNIa at the massive cluster core (de Plaa et al. 2007). Vertical dotted line indicates 0.25R\(_{200}\).

**Figure 4.** Left: Effective Fe yield as a function of cluster/group mass within R\(_{500}\). Circles represent Fe yield for the cluster in the sample of Ghizzardi et al. (2021), squares represent the groups in the sample of Renzini & Andreon (2014), triangles represent NGC 1550, Hydra A, and Coma in the sample of Sasaki et al. (2014). Yellow shaded region shows the expected value estimated from the SN yields derived from Maoz & Graur (2017) and Renzini & Andreon (2014). The brown shaded region shows the expected value calculated assuming higher SNIa rate from Freundlich & Maoz (2021). Right: Effective Fe yield as a function of cluster/group mass within R\(_{200}\).
radius, and the resultant luminosity profiles are used to calculate the cumulative IMLR. Figure 3 shows the IMLR of MKW4, Antlia, RXJ1159, and ESO3060170 from their centers to their virial radii. Radial profiles of the IMLR increase with the radius for all groups, suggesting that their metal distribution is more extended than the galaxy light out to R\textsubscript{200}. Their IMLRs within R\textsubscript{500} are within the scatter of what has been found for other groups (e.g., Sato et al. 2009), although that of RXJ1159 at 0.1R\textsubscript{200} is exceptionally high. The IMLR profiles of these groups converge to (4-5)×10\textsuperscript{-3} M\textsubscript{☉}/L\textsubscript{K\textsubscript{☉}} at R\textsubscript{200}, which is half that of the Perseus cluster.

We estimate the Fe yield (Y\textsubscript{Fe}), which is the ratio of total Fe mass released by stars to the total stellar mass formed for a given stellar population, as follows (Renzini & Andreon 2014; Ghizzardi et al. 2021; Gastaldello et al. 2021)

\[ Y_{\text{Fe,500}} = \frac{M_{\text{Fe,500}}^{\text{star}} + M_{\text{Fe,500}}^{\text{gas}}}{M_{\text{star,500}}(0)} \]  

where M\textsubscript{Fe,500} is the Fe mass within R\textsubscript{500}, M\textsubscript{star,500} is the Fe mass locked into the stars within R\textsubscript{500}, M\textsubscript{star,500}(0) is the mass of gas within R\textsubscript{500} that went into stars and whose present mass is reduced by a factor r\textsubscript{0}, i.e., M\textsubscript{star,500}(0) = r\textsubscript{0}M\textsubscript{star,500} (Gastaldello et al. 2021), where r\textsubscript{0} is the return factor. We adopt r\textsubscript{0} = 1/0.58 following Renzini & Andreon (2014) and Gastaldello et al. (2021). Figure 4 shows the effective Fe yield of four galaxy groups within R\textsubscript{500} and R\textsubscript{300}, respectively. We compare the Fe yield of four groups within R\textsubscript{500} with the sample of clusters studied in Ghizzardi et al. (2021), the sample of groups studied in Renzini & Andreon (2014), and the systems studied in Sasaki et al. (2014). We adopt the expected values estimated by Gastaldello et al. (2021). The Fe yields within R\textsubscript{500} for these four groups are significantly higher than that within R\textsubscript{500}, which suggests that at the group scale feedback redistributes metals, and may push (or prevent from collapse) a consistent fraction of them out to R\textsubscript{200} and beyond.

3.4 Supernovae yields

The yields of SNe Ia and SNcc are significant contributors to the metal enrichment of the ICM. We fit our measured metallicity distributions to the metallicity patterns predicted by several theoretical SNe Ia and SNcc nucleosynthesis models, following Mernier et al. (2016b). We fit the average metal abundance ratios of O/Fe, Mg/Fe, Si/Fe, and S/Fe for these groups to a combination of a single SNe Ia and a single SNcc model, and allow the relative number of SNe Ia over the total number of SNe (denoted as f\textsubscript{SNila}) free to vary (Werner et al. 2006). Mernier et al. (2016b) and Simionescu et al. (2019) pointed out that existing SNe yield models cannot successfully reproduce the observed Ni/Fe ratios, which in turn introduces significant errors in fitting parameters. We, therefore, exclude the Ni/Fe ratio from the fitting process. The α-capture elements–O and Mg are primarily produced by the SNcc, while both SNcc and SNe Ia produces Si and S. Thus, their relative abundances compared to Fe, a major SNe Ia product, are sensitive to the fitting parameters. Our measured average abundance patterns for MKW4 and Antlia fit best with the delayed detonation (DDT) SNe Ia model of Badenes et al. (2006), and with the “classical” mass-dependent SNcc model of Nomoto et al. (2006) with a progenitor metallicity of Z\textsubscript{init} = 0.02 Z\textsubscript{☉}. For RXJ1159 and ESO3060170, we obtain a best-fit by using the SNe Ia model of Badenes et al. (2006) and the SNcc model of Nomoto et al. (2013) and Sukhbold et al. (2016), respectively. Throughout this paper, we assume the SNcc yields are produced by the population of massive stars having a Salpeter IMF. (Salpeter 1955) with a common Z\textsubscript{init} (e.g., Mernier et al. 2016b). We next fit the metal abundance patterns at each radial bin of four groups to obtain their f\textsubscript{SNila} from the centers out to the virial radii. Figure 3 shows the f\textsubscript{SNila} averaged over two radial bins, from 0 - 0.25R\textsubscript{200} and 0.25 - 1.0R\textsubscript{200}. The derived f\textsubscript{SNila} decreases from 0.214 ± 0.028 at their centers to 0.138 ± 0.046 at the outskirts. Those values are broadly consistent with those of the core of massive galaxy clusters of 20%–30% (de Plaa et al. 2007; Simionescu et al. 2009) and our Milky Way of 15% (Tsujimoto et al. 1995). We note that the SNe yields constitute a crucial source of bias in the above analysis. The SNe yield models suffer from uncertainties up to a factor of 2 (e.g., Wiersma et al. 2009), and as a consequence, the derived estimation of f\textsubscript{SNila} should be interpreted with caution (e.g., de Grandi & Molendi 2009; Mernier et al. 2018b).

4 SYSTEMATIC UNCERTAINTIES

We test our results against possible systematic uncertainties introduced during spectral analysis, following Sarkar et al. (2021a). One of the most critical and uncertain components of the X-ray background is the CXB. To examine the systematic uncertainty associated with the CXB, we vary the normalization of the unresolved CXB component by 10%, with a fixed power-law slope of Γ = 1.41. We obtain that the associated impacts on all the metal abundances are within the statistical error limit. Next, we estimate the systematic uncertainties introduced by the two foreground components– MW and LHB. We vary their best-fit normalizations by 10%, which does not significantly change the measured metal abundances. Finally, we experiment with a 20% variation in Galactic column density (N\textsubscript{H}), which also has no significant impact on the measured metal abundances.

5 DISCUSSION

Using joint Suzaku and Chandra observations, we derived the abundance profiles of Fe, O, Mg, S, Si, and Ni for four nearby galaxy groups, from their centers out to their virial radii. To our knowledge, this is the first time that such measurements have been made for such low-mass systems. In the previous section, we show that our results are stable against various sources of systematic uncertainties. Below we compare the results with what we know from massive galaxy clusters, and discuss the implications of our findings.

5.1 Early enrichment scenario

Previous studies have reported a universal Fe abundance of ~ 0.3 Z\textsubscript{☉} at the outskirts of nearby massive clusters using Suzaku observations (e.g., Werner et al. 2013; Urban et al. 2017). It has also been shown that no significant redshift evolution of the global metallicity (R < R\textsubscript{500}) is found for high-redshift samples (e.g., McDonald et al. 2016; Mantz et al. 2017; Liu et al. 2020). These findings point to an early-enrichment scenario, where the ICM is enriched during the
star formation peak at $z = 2 - 3$, before the formation of galaxy clusters. The state-of-the-art hydrodynamical simulations have verified that the ICM can be substantially enriched during the peak of star formation at $2 < z < 3$ (e.g., Biffi et al. 2017, 2018a). Early AGN feedback may have played an essential role in displacing the metal-enriched gas produced within galaxies throughout the ICM (Truong et al. 2019).

We are able to constrain the metallicity profiles out to $R_{200}$ for four galaxy groups, with temperatures of $> 2.5$ keV and with masses of an order of magnitude smaller than those of massive clusters. We found a nearly flat Fe abundance profile over the radii of 0.25-1.0 $R_{200}$, as shown in Figure 1, with an average $Z_{Fe} = 0.309 \pm 0.018 Z_{\odot}$, which is remarkably similar to what is found in massive clusters. This Fe $\sim 0.3 Z_{\odot}$ uniform abundance distribution has also been found at the outskirts of two poor clusters, UGC 03957 (Thölken et al. 2016) and Virgo (Simionescu et al. 2015), whose peak temperatures are $\sim 3.5$ keV, which is between groups and clusters.

In addition to Fe, other elements (O, Mg, Si, S, and Ni) have nearly constant abundance throughout the outskirts of the groups, despite the larger uncertainties. Our findings are consistent with the same enrichment mechanism working among systems at various mass scales. Low mass systems form earlier than more massive systems in a hierarchical Universe. For metals to be deposited and well mixed before the gravitational collapse of galaxy groups, the timeline of the early-enrichment scenario, including the formation of SNIa (and their progenitor stars), needs to be pushed back further (e.g., Maoz et al. 2014; Biffi et al. 2018b).

5.2 Early enrichment population

A conundrum in the enrichment study is that the total metals observed in rich clusters cannot be explained by the visible stellar component, as shown in Figure 4 (also see E. Blackwell et al. 2021; Ghizzardi et al. 2021). This discrepancy invokes an external and universal source of metals even before the star formation episode – an Early Enrichment Population (EEP), which is not visible today (Mantz et al. 2017). The time scale of this enrichment epoch is not well constrained, but possibly at $3 < z < 10$, and such an early stellar population may be directly observable with JWST.

Our findings demonstrate that once the Fe abundance is measured out to $R_{200}$, the current stellar content of galaxy groups is insufficient to produce their total metals. Nevertheless, within $R_{500}$ and $R_{200}$, the effective Fe yields of groups are significantly smaller than those of rich clusters. In addition to Fe yields, this difference between groups and clusters is also reflected in their iron-mass-to-light ratios. As shown in Figure 3, we have derived the IMLR profiles of these groups out to $R_{200}$. Compared to the Perseus cluster, galaxy groups contain twice as much stellar light relative to their metal content. The small IMLRs of groups relative to clusters may be attributed to the relatively shallower potential wells of groups, making them unable to retain all the enriched gas against non-thermal processes such as AGN feedback. As shown in Sarkar et al. (2021a), the accumulated gas mass to total mass ratios within $R_{500}$ are consistent with the cosmic baryon fraction for galaxy clusters, which are systematically higher than those of galaxy groups. Furthermore, groups and clusters may have different star formation histories. The IGrM has a lower temperature and density than the ICM, providing a less hostile environment for the member galaxies. The higher star formation rate in galaxy groups may partially explain the small IMLR (Davé et al. 2008).

5.3 Chemical composition of galaxy groups

The additional constraints on O, Mg, Si, and S allow us to derive the chemical components and SNIa fraction of galaxy groups. The abundance ratios of O/Fe, Si/Fe, S/Fe, and Mg/Fe of the four groups in our sample are shown in Figure 2. Primarily caused by the abrupt change in the slope of the Fe abundance profile, we observe different chemical compositions between group centers and group outskirts. The X/Fe ratios within 0.25$R_{200}$ are consistent with the Solar chemical composition, for which we derive a $f_{SN}$ of 0.214 $\pm$ 0.028. This is in agreement with the average gas abundance ratios of cluster cores (de Plaa et al. 2007) and 44 nearby systems within $R < R_{500}$ (dominated by galaxy clusters) in the CHEERS sample (Mernier et al. 2017). Similar chemical composition for gas has been found at the centers of the Perseus cluster using the microcalorimeter on board Hitomi (Simionescu et al. 2019), as well as in NGC 1404, an early-type galaxy, through a joint XMM-Newton EPIC, RGS, and Chandra-ACIS study (Mernier et al. 2022). It is intriguing that ICM, IGrM, and even ISM metallicities trace the same metal abundance pattern as our Solar System rather than their dominant galaxies. This further implies a common origin of the metals among these systems. Alternatively, this also means that the stellar population we see today in clusters and groups (i.e., mainly red-and-dead population) has very little to do with the metal content of their hot halos.

Over the radii of 0.25-1.0$R_{200}$, the X/Fe ratios are generally super solar, ranging from 1.6 to 1.9, for which we derive that the SNIa fraction is $0.138 \pm 0.046$, allowing us to rule out a pure SNCe enrichment by $3\sigma$. The Fe abundance at the outskirts is unlikely to be significantly underestimated since we have employed a 2T model to mitigate the “Fe-bias”, and we have obtained a measured $Z_{Fe}$ similar to that of the rich clusters. It is worth noting that the significant uncertainties and scatter of the measurements do not allow us to claim an apparent discrepancy from the solar value for S/Fe, Si/Fe, and Mg/Fe, while the O line can not be well resolved by CCD-like detectors such as XIS. An extensive Suzaku study of the outskirts of the Virgo cluster reveals a super solar value for Mg/Fe of 1.2–1.6, while their Si/Fe and S/Fe ratios are 0.6-0.8 and 0.8-1.2, respectively. The X/Fe ratios may scatter among different systems. The results can be further complicated by the various sources of systematic effects associated with the observations of the background-dominated regimes.

6 SUMMARY

We analyzed joint Suzaku and Chandra observations of four nearby groups – MKW4, Antlia, RXJ1159+5531, and ESO3060170. Suzaku observations were used to constrain their gas properties, and Chandra data were used to refine the results by mitigating the uncertainties introduced by the CXB. We have derived abundance profiles of O, Mg, Si, S, Fe, and Ni out to the $R_{200}$ for the first time for such low-mass systems. Our results are summarized below.

- The metal abundances in the central region of Antlia are significantly lower than those of MKW4, RXJ1159+5531, and
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ESO3060170. Unlike the other three systems, Antlia is a non-cool-core group. As observed in massive system equivalents (i.e., non-cool-core clusters), more frequent merging events may have disrupted its core and erased much of the centrally peaked metallicity.

- At group outskirts (0.25-1.0R200), we measure flat metal abundance profiles for all four groups, with an average Fe abundance of ZFe = 0.309 ± 0.018 Z⊙ (χ² = 14 for 12 degrees of freedom), which is remarkably consistent with what was found in rich clusters, and predictions from IllustrisTNG for galaxy groups. The uniform metal distribution suggests that the same early enrichment process may have been at work before the gravitational collapse of groups and clusters. Early AGN feedback is likely to have played an essential role in transporting metals from galaxies to the hot gas as well as efficiently mixing the enriched gas throughout the proto cluster/group.

- We derive the accumulated iron mass-to-light ratios from the center out to the R200 of these groups. Their IMLR profiles increase with radius, indicating that the enriched gas is more extended than the stellar distribution. Near R200, the accumulated IMLR profiles of these groups are consistent with each other at 4-5x 10^-3 M⊙/L⊙K⊙. However, these values are significantly lower than the accumulated IMLR of Perseus at R300, which may imply that groups could not retain all of their enriched gas due to their shallower potential wells, and/or a halo-mass dependent star formation history.

- We compare the effective Fe yields of groups within R500 and R200, and the theoretical expectation. The iron yields measured out to R200 of these four groups show tension with respect to the expected values from empirical supernovae yields, and in contrast with what can be observed within R500. A significant amount of metals are found at the outskirts of groups. When the Fe abundance is measured out to R200, the visible stellar component in the groups is insufficient to produce the observed metals, which may pose a challenge for the chemical enrichment models in the same fashion as the one already known for clusters.

- The O/Fe, Mg/Fe, Si/Fe, and S/Fe ratios at the group centers are nearly solar and consistent with the chemical composition measured at cluster centers. The hot gas in the systems that are orders of magnitude different in mass traces the same metal abundance pattern as our Solar System rather than their dominant galaxies. The derived SNIa fraction is 14% at their outskirts, allowing us to rule out a pure core collapsed supernovae enrichment before the gravitational collapse of galaxy groups.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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Figure A1. Top left: NXB subtracted and exposure corrected mosaic *Suzaku* image of MWK4 in the 0.5-2 keV energy band. Magenta circle indicates $R_{200}$. Green annuli represent the regions used for spectra extraction. Top right: mosaic *Chandra* image of MKW4 in the 0.5-7.0 keV energy band. The resolved point sources are marked in green elliptical regions. Middle and Bottom: radial profiles of different elements from the group center to the outskirts. Vertical dotted line indicate $0.25R_{200}$. 
Figure A2. Antlia; same as Figure A1.
Figure A3. RXJ 1159; same as Figure A1.
Figure A4. ESO 3060170; same as Figure A1
Figure A5. Best-fit results of the spectral analysis for the outermost regions of four groups. We show only XIS1 spectra. Red, black, cyan, green, yellow colored lines indicate best-fit resolved CXB, unresolved CXB, ICM emission, GH, LHB components, respectively. Blue line shows the best-fit ICM emission and X-ray background together. Top panel: Black data points are for MKW4. Orange data points are for Antlia. Solid line represents MKW4 and dashed line represents Antlia. Bottom panel: spectra for RXJ1159 and ESO3060170.