A uniform metallicity in the outskirts of massive, nearby galaxy clusters

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\begin{abstract}
\textit{Suzaku} measurements of a homogeneous metal distribution of $Z \sim 0.3$ Solar in the outskirts of the nearby Perseus cluster suggest that chemical elements were deposited and mixed into the intergalactic medium before clusters formed, likely over 10 billion years ago. A key prediction of this early enrichment scenario is that the intracluster medium in all massive clusters should be uniformly enriched to a similar level. Here, we confirm this prediction by determining the iron abundances in the outskirts ($r > 0.25r_{200}$) of a sample of ten other nearby galaxy clusters observed with \textit{Suzaku} for which robust measurements based on the Fe-K lines can be made. Across our sample the iron abundances are consistent with a constant value, $Z_{\text{Fe}} = 0.316 \pm 0.012$ Solar ($\chi^2 = 28.85$ for 25 degrees of freedom). This is remarkably similar to the measurements for the Perseus cluster of $Z_{\text{Fe}} = 0.314 \pm 0.012$ Solar, using the Solar abundance scale of Asplund et al.\textsuperscript{(2009)}.

\textbf{Key words:} clusters: intracluster medium – galaxies: X-rays: galaxies: clusters

\end{abstract}

1 INTRODUCTION

Clusters of galaxies, the most massive objects in the Universe, are continuously growing, both by the steady accretion of matter from their surrounding environment, and by occasional mergers with smaller sub-clusters. The diffuse intergalactic gas accreted by clusters is rapidly shock heated, giving rise to the hot ($10^7$–$10^8$ K) X-ray emitting intra-cluster medium (ICM) that pervades clusters. The ICM is in approximate virial equilibrium, with the outer boundary of the virialized region - the virial radius - being approximately equal to 1.3$r_{200}$, where within $r_{200}$ the mean enclosed mass density of the cluster is 200 times the critical density of the Universe at the cluster redshift (Lacey & Cole\textsuperscript{(1993)}). Galaxy clusters are also unique astrophysical laboratories that allow us to study nucleosynthesis and the chemical enrichment history of the Universe (see Werner et al.\textsuperscript{(2008)}). The deep gravitational potential wells of galaxy clusters hold all of the metals ever produced by stars in member galaxies, making them archaeological treasure troves to study the integrated history of star formation (de Plaa et al.\textsuperscript{(2007)}, Werner et al.\textsuperscript{(2016)}). The dominant fraction of the metals in clusters currently resides within the hot ICM, which constitutes $\geq 70\%$ of the baryonic mass content for systems above $1.4 \times 10^{14} M_\odot$ (Giodini et al.\textsuperscript{(2009)}). However, when and how these metals were injected into the intergalactic medium is not well understood.

Most of the line emission from metals in the ICM arises from K- and L-shell transitions of highly ionized elements (see Böhringer & Werner\textsuperscript{(2010)}). Because the ICM is in collisional ionization equilibrium and is optically thin, the equivalent widths of the emission lines can be converted directly into elemental abundances. The strongest line emission in the X-ray band is produced by the K-shell transitions of helium-like iron, making it an excellent tracer of chemical enrichment.

It has been known for about 40 years that a significant portion of the hot plasma in the central regions of galaxy clusters (the inner $\sim 0.3r_{200}$) has been enriched by iron produced in stars to about one-third to one-half of the Solar value (Mushotzky et al.\textsuperscript{(1978)}, 1981). In the central regions of clusters with strongly peaked ICM density distributions the abundance of iron is also peaked (e.g. De Grandi et al.\textsuperscript{(2004)}), but decreases with radius to about one-third Solar (assuming the Solar abundances of Asplund et al.\textsuperscript{(2009)}) beyond about 0.2$r_{200}$ (Leccardi & Molendi\textsuperscript{(2008)}). Due to the low X-ray surface brightness in the outskirts of clusters, metal abundance measurements beyond one-half of the virial radius of clusters remain sparse.

The best measurements of the Fe abundance distribution at large radii were performed using the \textit{Suzaku} Key Project data (1 Ms observation along 8 azimuthal directions) of the Perseus...
cluster, which provided 78 data points outside of the cluster core \((r > 0.25r_{200})\). These data revealed a remarkably uniform iron abundance, as a function of radius and azimuth, that is statistically consistent with a constant value of \(Z_{\text{Fe}} = 0.314 \pm 0.012\) Solar (using the Solar abundance scale of [Asplund et al. 2009] out to \(r_{200}\) ([Werner et al. 2013]). Subsequent Suzaku observations of the Virgo cluster extended these measurements to elements other than iron indicating an uniform chemical composition throughout the cluster volume ([Simionescu et al. 2015]). The observed homogeneous distribution suggests that most of the metal enrichment of the ICM occurred before the cluster formed and its entropy distribution became stratified, preventing further efficient mixing. A key prediction of this early enrichment scenario is that the ICM in all massive clusters should be uniformly enriched to a similar level ([Werner et al. 2013] [Fabjan et al. 2010] [Biffi et al. 2017].)

In order to test these predictions, we have analysed all archival observations of nearby galaxy clusters observed with Suzaku for which data extend to \(r > r_{200}\) and robust measurements based on the Fe-K lines can be performed at \(r > 0.25r_{200}\). ([Because the Fe-K complex is by far the strongest line complex in the X-ray spectrum, the word metallicity will in this paper refer to and will be used interchangeably with the Fe abundance.]) Our sample spans a redshift range \(z = 0.017-0.183\) and a temperature range of about 2.5–9 keV (the corresponding range of virial masses is about 1.4–14 \(\times 10^{14}\) \(M_{\odot}\) [Arnould et al. 2005].) The selected temperature range permits metallicity measurement using the Fe-K lines, allowing us to largely avoid multi-temperature biases arising from the measurements of the Fe-L complex ([Buote 2000].)

Sect. 2 describes the data analysis, spectral modeling, and the treatment of the X-ray background. In Sect. 3, we present the results. Finally, in Sect. 4 and 5, we briefly discuss the implications of these results and draw our conclusions.

## 2 OBSERVATIONS AND DATA ANALYSIS

The details of the Suzaku observations for each of the 9 clusters analyzed in this study are shown in Tab. 1. For each cluster we analyzed the data from all available X-Ray Imaging Spectrometers (XIS 0, 1, 2, 3).

### 2.1 Data Reduction

We obtained the initial cleaned event lists using the standard criteria provided by the XIS team. There is a gradual increase in the number of flickering pixels in the XIS detectors with time, which may affect the measurements, if unaccounted for. We used maps provided by the XIS team to remove the flickering pixels from the cluster observations, as well as from the night Earth observations, which were later used to create the non-X-ray background (NXB) data products.

We checked for likely solar wind charge-exchange (SWCX) emission contamination using the WIND Solar Wind Experiment

### Table 1. Details of Suzaku observations used in the analysis. The columns show, respectively, the target name, the Suzaku observation ID, the date of the observation and the clean exposure time.

| Name | Obs. ID | Obs. date | Exposure (ks) |
|------|---------|-----------|---------------|
| A1795 | 808089010 | 2013-06-27 | 17.5 |
| A1689 | 808090010 | 2013-12-31 | 53.2 |
| A1689 | 808089004 | 2014-01-13 | 7.1 |
| HYDRA A 1 | 805007010 | 2011-08-08 | 6.9 |
| HYDRA A 2 | 805008010 | 2011-09-08 | 6.9 |
| HYDRA A SE | 807088010 | 2012-06-07 | 5.5 |
| HYDRA A A Far SE | 807088010 | 2012-06-05 | 5.6 |
| HYDRA A A Far N | 807089010 | 2012-06-05 | 5.6 |
| HYDRA A A SW | 807090010 | 2012-11-10 | 39.8 |
| HYDRA A AOUT | 807091010 | 2012-06-07 | 0.3 |
| ABELL 2255 | 802060010 | 2008-01-08 | 27.6 |
| A2029 | 804024010 | 2010-01-28 | 3.5 |
| A2029 | 804024020 | 2010-01-28 | 2.6 |
| A2029 | 804024030 | 2010-01-28 | 6.3 |
| A2029 | 804024040 | 2010-01-29 | 1.9 |
| A2029 | 804024050 | 2010-01-30 | 3.5 |
| A2142 | 801055010 | 2007-01-04 | 12.0 |
| A2142 | 802090010 | 2007-08-04 | 7.1 |
| A2142 | 802091010 | 2007-09-15 | 57.7 |
| A2142 | 802092010 | 2007-08-29 | 7.0 |
| FILAMENT OF GALAXIES | 805029010 | 2010-07-29 | 19.9 |
| ABELL 2294 | 801091010 | 2008-09-17 | 14.3 |
| A2204 FIELD 1 | 805056010 | 2010-09-01 | 5.9 |
| A2204 FIELD 2 | 805057010 | 2010-08-27 | 6.9 |
| A2204 FIELD 3 | 805058010 | 2010-08-28 | 6.8 |
| A133e | 805088010 | 2010-06-07 | 50.0 |
| A133 N | 805089010 | 2010-06-05 | 50.2 |
| A133 E | 805090010 | 2010-06-09 | 51.6 |
| A133 S | 805091010 | 2010-06-08 | 51.1 |
| A133 FIELD 1 | 805092010 | 2013-12-19 | 53.6 |
| A133 FIELD 2 | 805093010 | 2013-12-20 | 50.6 |
| A133 FIELD 3 | 805094010 | 2013-12-05 | 51.9 |
| A133 FIELD 4 | 805095010 | 2013-12-06 | 52.5 |
| SWIFT J0507+1412 | 790990010 | 2014-08-03 | 82.2 |
| AWM7 | 801035010 | 2008-08-07 | 19.0 |
| AWM7 EAST OFFSET | 801036010 | 2008-08-05 | 38.5 |
| AWM7 WEST OFFSET | 801037010 | 2008-08-06 | 39.8 |
| AWM7 EAST OFFSET | 802044010 | 2008-01-27 | 85.6 |
| AWM7 SOUTH OFFSET | 802045010 | 2008-01-29 | 31.3 |
| AWM7 SOUTH OFFSET | 802045020 | 2008-02-23 | 91.2 |
| AWM7 45' EAST | 806080010 | 2011-08-07 | 36.9 |
| AWM7 27' SOUTH | 806090010 | 2012-02-18 | 35.0 |
| AWM7 45' SOUTH | 806091010 | 2012-02-17 | 34.4 |
| AWM7 NW1 | 806092010 | 2014-02-17 | 14.9 |
| AWM7 NW2 | 806093010 | 2014-02-17 | 35.3 |
| AWM7 SE1 | 806094010 | 2014-02-18 | 16.8 |
| AWM7 SE2 | 806095010 | 2014-02-19 | 35.3 |

† Observations influenced by SWCX

1 XIS2 was lost to a likely micrometeoroid hit on 2006 November 9, and therefore its data are available only for the observations from before this date.

2 Arida, M., XIS Data Analysis, [http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/abc/node9.html](http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/abc/node9.html)

3 The current maps, as well as the recipe for the removal process, are available at [http://www.astro.isas.ac.jp/suzaku/analysis/xis/nxb_new](http://www.astro.isas.ac.jp/suzaku/analysis/xis/nxb_new)
The initial identification of the point sources was carried out using the wavdetect tool. We used a single wavelet radius of 1 arcmin, which is approximately matched to the half-power radius of the X-ray telescope on Suzaku. For each cluster we created a candidate set of point sources assuming a source with a radius of 1 arcmin at each of the positions identified by wavdetect. We then calculated X-ray surface brightness profiles centered on the coordinates in Tab. 2 excluding the candidate set of point sources, and fitted an isotropic β-model to the surface brightness profile of each cluster:

\[ S_X = S_0 \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right]^{-(\beta+0.5)} + S_{\text{bkg}}, \]  

where \( r \) is the distance from the cluster center and the free parameters are the normalization \( S_0 \), the core radius \( r_c \) and \( \beta \). \( S_{\text{bkg}} \) is the surface brightness of the X-ray background, which is assumed to be constant across the whole area of the cluster. The best-fit parameters for the individual clusters are shown in Tab. 3.

We divided the mosaic images of the individual clusters by the best-fit surface brightness models and used the resulting residual images to identify by eye sources with radii larger than 1 arcmin. In these cases, we manually increased the sizes of the sources in question by the appropriate amount. The resulting updated sets of point sources (including substructures and artifacts that can appear at chip edges), which were excluded from the subsequent spectral analysis, are shown with magenta circles in Figs. A1–A9.

### 2.2 Image analysis

We extracted images from all XIS detectors in the 0.7 – 7.0 keV energy band, removing ~ 30 arcsec regions around the edges. We extracted instrumental background images in the same energy band from flickering-pixel-subtracted night Earth observations using the tool xissubr.

For each cluster, we extracted spectra from a series of concentric annuli (with each annulus containing at least 3500 cluster counts, allowing us, in principle, to measure the Fe abundance with a relative uncertainty of at most 20%). The resulting annuli are shown with magenta circles in Figs. A1–A9.

### 2.3 Point Source Detection

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### 2.4 Spectral Analysis

For each cluster, we extracted spectra from a series of concentric annular regions centered on the respective cluster’s center (see Tab. 2). The width of the annuli was set to be at least 3 arcmin, with each annulus containing at least 3500 cluster counts, allowing us, in principle, to measure the Fe abundance with a relative uncertainty of at most 20%. The resulting annuli are shown in yellow in Figs. A1–A9. Instrumental background spectra were created using Night Earth observations.

We rebinned each spectrum to a minimum of one count per 25 arcs (5 keV), where no SWCX emission lines are expected.

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spectra. For each cluster we modeled all spectra simultaneously, using the 0.7 – 7.0 keV band for the front illuminated XIS 0, XIS 2 and XIS 3 detectors, and the 0.6 – 7.0 keV band for the back illuminated XIS 1, except for observations with possible SWCX contamination (see Tab. 1), where we used the 1.5 – 7.0 keV energy band. We modeled the ICM emission in each annulus as a single temperature plasma in collisional ionisation equilibrium using the absorbed apec (ATOMDB 3.0.3) model (Smith et al. 2001).

For a given annulus, we used a single temperature and metallicity. Normalizations were allowed to vary among individual observations, but were tied among the detectors in a single observation; in other words, all spectra from a given observation were members of a single fitting group in xspec. We used the abundance table of Asplund et al. (2009) in the analysis. Galactic absorption was set to the average column along the line of sight inferred from the Leiden/Argentine/Bonn Survey (Kalberla et al. 2005). The uncertainties in all derived parameters were determined using Markov Chain Monte Carlo (MCMC) simulations. After removing the burn in period and thinning each chain, we used the mean and the standard deviation as the value and the uncertainty of each derived parameter, respectively.

2.5 Modeling the X-ray Foreground and Background

At large clustercentric radii, the cosmic X-ray foreground/background (CXFB) makes up a dominant fraction of the total X-ray emission, requiring careful modeling. Our spectral model for the CXFB included four components – an absorbed power law (PL) due to the unresolved point sources (De Luca & Molendi 2004), an absorbed thermal component modeling the Galactic halo emission (GH, Kuntz & Snowden 2000), a potential 0.6 keV foreground component that we will from now on refer to as the hot foreground (HF; Masui et al. 2009; Yoshino et al. 2009), and an unabsorbed thermal component modeling the emission from the local hot bubble (LHB, Sudher et al. 1996).

In order to better constrain the low-temperature CXFB components, we used the X-Ray Background Tool (xrbg) which calculates the average X-ray background spectra from the ROSAT All-Sky Survey diffuse background maps. For each cluster we obtained spectra from six independent circular regions with radii $r = 1.3r_{200}$ evenly surrounding the cluster so that each touches the outer edge of a circle with radius $r = 1.3r_{200}$ centered on the cluster core, as well as two neighbouring background regions. The distance from the cluster core ensures that the spectra are not significantly contaminated by emission from the ICM. This setup, as opposed to using a single annular region, allowed us to assign separate absorptions to each of the six regions, which can potentially significantly influence the modeling at ROSAT energies, 0.7 – 2.0 keV.

As stated before, for each cluster we modeled all spectra simultaneously, including the CXFB model. To limit the systematic effects that might potentially influence the fit, we first separately determined the PL parameters, that were kept fixed during the subsequent modeling. To do this, we used the spectra from the outermost annulus in a given cluster in the high energy band, 2.0 – 7.0 keV, where the PL component is dominant at large clustercentric radii. For six of the clusters in our sample, A 133, A 1689, A 1795, A 2029, A 2142, and A 2204, the outermost annulus covers only regions outside $r_{200}$. In these cases, we assumed no significant cluster emission to contribute to the spectrum and therefore the high energy fit included only the PL model. For the remaining clusters, A 262, AWM 7 and Hydra A, we accounted for potential cluster emission by including an apec component in the high energy fit, fixing its temperature to $kT = 2$ keV and keeping the normalizations in the individual observations free. The best-fit PL parameters are shown in the first two columns of Tab. 4.

In the subsequent spectral modeling, the remaining CXFB parameters were kept free and tied among all spectra from a given cluster, with the exception of the metallicity and the redshift of the three thermal components, which were fixed at unity and zero, respectively.

For each cluster, we tied together the ICM temperatures and Fe abundances in the neighboring annuli where required in order to obtain a statistically significant constraint. The final CXFB model parameters for the individual clusters are listed in Tab. 4.

2.6 Criteria For Robust Metallicity Measurements

In each cluster we formally obtained profiles of temperature and metallicity out to the outermost radii reached by the observations. However, due to the low surface brightness of the ICM, the measurements at large radii may be significantly influenced by systematic uncertainties, such as potential variations of the CXFB model throughout the cluster. To address our main scientific questions, it is therefore crucial to only use the metallicity measurements which we are confident about. We used the following criteria to identify these measurements:

- We only used the measurements at radii $r > 0.25r_{200}$ to avoid the central metallicity peak observed in most cool-core galaxy clusters. We used a similar radial range in the Perseus cluster (Werner et al. 2013), where metallicity measurements inside 20′ ($r_{200} = 82′$) were discarded.
- We only used annuli with ICM-signal-to-background (ISB) ratios around the Fe-K lines higher than 10%. This is defined as the ratio of the total number of modeled counts received from the ICM to the sum of modeled counts from the CXFB and the instrumental background, in a 1 keV wide energy band centered on the appropriately redshifted Fe-K line (rest energy $E = 6.7$ keV). The top right panels in Figs. A1-A9 show the profiles of the ISB ratios for the individual annuli (in blue), as well as the ratios for the individual observations (in red). The 10% threshold is broadly consistent with the measurements in the outermost regions of the Perseus cluster (Werner et al. 2013; Urban et al. 2014).
- Finally, we only used the annuli where the contamination from the neighbouring regions due to the wings of the broad point spread function (PSF) of the telescopes is small. The half-power diameter (HPD) of the X-ray Telescopes (XRT) on board of Suzaku is $\sim 2′$, which causes a fraction of the emission from an object to be registered elsewhere on the detector. Addressing this issue is especially important in the cool core clusters at relatively large distances ($z \geq 0.1$), since the emission from the metal-rich X-ray surface brightness peak may bias spectral measurements out to larger radii. To test for this, we used Chandra surface brightness profiles with high spatial resolution relative to Suzaku (binned to $\sim 4″$), which we convolved with a simple Gaussian model for the Suzaku point-spread function with a HPD of 2 arcmin. Using this model, for each of our annuli we calculated the fraction of emission that we expected to come from the other annuli, and removed those where it exceeded 10%. Only the two most distant clusters in our sample, A 2204 and A 1689, were affected. For both systems, we re-
Iron abundance measurements in our cluster sample plotted as a function of radius scaled to $r_{200}$. On average, the iron abundances peak in the cores of the clusters and decrease as a function of radius, flattening at radii $r > 0.25r_{200}$. The average metallicity is shown as blue solid line. The dashed line shows the best fit metallicity reported by Werner et al. (2013) for the Perseus cluster.

Table 4. The CXFB model parameters for the individual clusters. The four CXFB model components we used are the power-law component (PL), the Galactic halo (GH), the hot foreground component (HF) and the Local Hot Bubble (LHB). Subscript $n$ stands for normalization, $kT$ for temperature and $ind$ for index. Normalizations are in units of $10^{14} cm^{-5}$ arcmin$^{-2}$.

|       | PL$_{ind}$   | PL$_{n} \times 10^4$ | GH$_{T}$   | GH$_{n} \times 10^3$ | HF$_{T}$   | HF$_{n} \times 10^4$ | LHB$_{T}$ | LHB$_{n} \times 10^4$ |
|-------|-------------|-----------------------|------------|-----------------------|------------|-----------------------|-----------|-----------------------|
| A 262 | 1.43$^{+0.05}_{-0.07}$ | 9.38$^{+0.66}_{-0.64}$ | 0.15$^{+0.01}_{-0.01}$ | 2.82$^{+0.19}_{-0.19}$ | 0.94$^{+0.05}_{-0.05}$ | 2.59$^{+0.12}_{-0.22}$ | 0.103$^{+0.002}_{-0.002}$ | 1.01$^{+0.18}_{-0.30}$ |
| A 1795| 1.38$^{+0.05}_{-0.08}$  | 10.07$^{+0.84}_{-0.79}$ | 0.22$^{+0.01}_{-0.01}$ | 0.91$^{+0.18}_{-0.08}$ | N/A        | N/A                   | 0.10$^{+0.01}_{-0.01}$ | 49.10$^{+0.26}_{-0.36}$  |
| A 1689| 1.34$^{+0.04}_{-0.03}$  | 9.16$^{+0.47}_{-0.41}$ | 0.13$^{+0.01}_{-0.02}$ | 2.43$^{+0.50}_{-0.40}$ | 0.59$^{+0.05}_{-0.03}$ | 2.11$^{+0.64}_{-0.32}$ | 0.10$^{+0.01}_{-0.01}$ | 13.65$^{+0.23}_{-0.20}$ |
| Hydra A | 1.39$^{+0.07}_{-0.09}$ | 8.61$^{+1.15}_{-0.90}$ | 0.16$^{+0.01}_{-0.01}$ | 4.45$^{+1.40}_{-1.30}$ | 0.79$^{+0.11}_{-0.16}$ | 1.91$^{+0.36}_{-0.16}$ | 0.10$^{+0.01}_{-0.01}$ | 9.53$^{+1.20}_{-1.20}$  |
| A 2204| 1.25$^{+0.07}_{-0.08}$  | 7.01$^{+0.69}_{-0.63}$ | 0.18$^{+0.01}_{-0.02}$ | 6.18$^{+1.15}_{-1.05}$ | 0.58$^{+0.02}_{-0.01}$ | 13.95$^{+0.90}_{-1.39}$ | 0.10$^{+0.01}_{-0.01}$ | 13.4$^{+0.19}_{-0.37}$   |
| A 2142| 1.49$^{+1.10}_{-0.10}$ | 12.53$^{+1.62}_{-1.47}$ | 0.227$^{+0.008}_{-0.005}$ | 10.63$^{+0.45}_{-0.25}$ | 0.61$^{+0.02}_{-0.02}$ | 10.25$^{+0.22}_{-0.12}$ | 0.13$^{+0.06}_{-0.01}$ | 17.5$^{+1.08}_{-2.00}$   |
| A 133 | 1.37$^{+0.06}_{-0.05}$  | 9.19$^{+0.64}_{-0.61}$ | 0.14$^{+0.004}_{-0.004}$ | 4.88$^{+0.55}_{-0.55}$ | 0.64$^{+0.06}_{-0.02}$ | 2.51$^{+0.14}_{-0.22}$ | 0.09$^{+0.01}_{-0.01}$ | 7.3$^{+0.60}_{-0.30}$    |
| AWM 7 | 1.54$^{+0.10}_{-0.07}$  | 10.37$^{+1.27}_{-0.95}$ | 0.14$^{+0.012}_{-0.006}$ | 1.93$^{+0.58}_{-0.20}$ | 0.61$^{+0.06}_{-0.16}$ | 1.18$^{+0.35}_{-0.20}$ | 0.08$^{+0.01}_{-0.01}$ | 7.3$^{+0.65}_{-0.90}$    |

3 RESULTS

The best fit normalizations, temperatures and metallicities for the individual clusters are shown in the bottom panels of Figures A1-A9. Most of the systems in our sample are so-called cooling core clusters with bright, relatively cool, metal-rich cores. To the iron abundance measurements in this work, we also added the iron abundances measured for the non-cool core Coma cluster by Simionescu et al. (2013).

Figure 1 shows all metallicity measurements in our cluster sample plotted as a function of radius scaled to $r_{200}$. The average metallicity (shown with the solid blue line) peaks in the central region and decreases as a function of radius, flattening at radii $r > 0.25r_{200}$. We tested our results for biases associated with possible multi-temperature structure by fitting the data both in the full spectral band and above 2 keV. At radii $r > 0.25r_{200}$ the two fits...
Figure 2. Robust measurements (see text for details) of the iron abundances at $r > 0.25 r_{200}$ in the individual clusters. The clusters have been ordered by mass from the least to the most massive. The blue stripe marks the 68% confidence interval around the constant fit to these data, $Z_{Fe} = 0.316 \pm 0.012$ Solar. The red stripe shows the confidence interval around the best fit iron abundance reported by Werner et al. (2013) for the Perseus cluster, $Z_{Fe} = 0.314 \pm 0.012$ Solar.

4 DISCUSSION

We find that across our sample of 10 clusters of galaxies the Fe abundances measured outside the central regions ($r > 0.25 r_{200}$) are consistent with a constant value, $Z = 0.316 \pm 0.012$ Solar (Fig. 1). The metallicity measurements also show no significant trend with temperature (Fig. 2).

Based on the uniform iron abundance distribution in the Perseus cluster, both as a function of radius and azimuth, statistically consistent with a constant value of $Z_{Fe} = 0.314 \pm 0.012$ Solar out to $r_{200}$, Werner et al. (2013) proposed that most of the metal enrichment of the intergalactic medium occurred before clusters formed, probably more than ten billion years ago ($z > 2$), during the period of maximal star formation and black hole activity. A key prediction of the early enrichment scenario is that the ICM in all massive clusters should be uniformly enriched to a similar level. Previous indications for a uniform ICM enrichment include the small cluster to cluster scatter in the Fe abundance observed within $r_{500}$ (Matsushita 2011; Leccardi & Molendi 2008) and the observed pre-enrichment of the ICM between the clusters Abell 399/401 (Fujita et al. 2008). Our observation of a constant iron abundance at large radii across a sample of 26 independent measurements for ten massive clusters further confirms this early enrichment scenario. This early enrichment could have been driven by galactic winds (De Young 1978) which would be strongest around the peak of star formation and AGN activity (redshifts $z \sim 2 - 3$ Madau et al. 1996; Brandt & Hasinger 2005).

Recent numerical simulations by Fabjan et al. (2010) and Biffi et al. (2017) indicate that while star-formation and supernova feedback are unable to enrich the intergalactic medium uniformly, simulations which also include feedback from AGN produce remarkably homogeneous metallicity distribution in the ICM out to large radii. They show that the uniform metallicity is the result of a widespread displacement of metal-rich gas by powerful AGN outbursts that occur before the epoch of maximal star-formation and AGN activity. Biffi et al. (2017) conclude that early AGN feedback acting on high-
The early enrichment scenario, there should be no substantial increase of redshift. Contrary to initial findings (Balestra et al. 2007; Balestra et al. 2008; Balestra et al. 2009; Balestrini et al. 2012), under the early enrichment scenario, there should be no substantial redshift evolution in the ICM metallicity outside the central regions of clusters, out to z ~ 2. Recent results (Andreon 2012; Ettori et al. 2015; McDonald et al. 2016; Mantz et al. 2017) indicate that most metals in the ICM were already in place at z = 1, consistent with the picture of an early enrichment.

At various overdensities, the chemical enrichment might proceed on different time scales or with different initial mass functions, resulting in a trend with cluster mass. Within the mass range probed by our sample (factor of ~ 10), there is no evidence for dependence of ICM metallicity on total cluster mass. A more thorough analysis of the mass dependence will require reliable measurements of absolute abundances in low mass clusters and groups of galaxies, which are often made difficult for current CCD instruments by multi-temperature structure in the ICM (Simionescu et al. 2015). A lack of trend with cluster mass would either indicate a rate of metal enrichment in the early Universe that is independent of the density contrast between different regions, or a very high efficiency of mixing on large scales.

If the ICM at large radii is clumpy and multiphase (Simionescu et al. 2011; Urban et al. 2011; Simionescu et al. 2017), then its best fit metallicity, derived using a single temperature model, might be biased (Avestruz et al. 2014). The best fit Fe abundance is the most significantly biased at temperatures around 1 keV, where its value is determined based on the Fe-L lines, which are very sensitive to the underlying temperature structure (see Buote 2000). The metallicities of the clusters in our sample are determined using the Fe-K lines and depending on the temperature structure could be biased by at most 30 per cent (both toward higher and lower values; Rasia et al. 2008; Simionescu et al. 2009; Gastaldello et al. 2010). The fact that the spectral fits in the full band and above 2 keV give consistent results (see Section 3) indicates that if substantially cooler, denser clumps are present in the ICM, they do not contribute significantly to the observed emission measure and the metal budget.

In the near future, the metallicities of groups and cooler clusters could be further studied with the Astrosat satellite (Singh et al. 2014). The low earth orbit and the small inclination of the orbital plane of Astrosat provide a low and stable background environment that is required for cluster outskirts studies. The large field of view provides a sufficient grasp, enabling mapping the faint X-ray emission in the outskirts of nearby clusters that span large angular scales in the sky. Such observations will further test the possible mass-dependence of metallicity. Deep observations with XMM-Newton and Chandra will allow us to precisely determine the metallicity outside the cores of high redshift clusters, providing further constraints on the redshift evolution of metallicity. Observations with high spectral resolution obtained with the X-ray Astronomy Recovery Mission (XARM) will allow more accurately measured relative abundance ratios for clusters at low redshifts, testing our models of nucleosynthesis. In the further future, missions like Athena (Nandra et al. 2013) or Lynx 7 will allow detailed studies of metal abundances in high redshift clusters, providing comprehensive understanding of the metal cycle in the Universe.

5 CONCLUSIONS

Here, we report 26 independent metallicity measurements in the outskirts (r > 0.25r200) of ten nearby galaxy clusters. These measurements are consistent with a constant value Zec = 0.316 ± 0.012 Solar. No significant trend of metallicity versus temperature or mass is observed.

Our results corroborate the conclusions drawn from previous metallicity measurements at large radii in the Perseus cluster (Werner et al. 2013). In particular, they confirm the predictions of

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**Table 5.** Measurement radii and the best fit metallicities measured in our cluster sample.

| Cluster | r/r200  | Z/Z⊙ |
|---------|---------|-------|
| AWM7    | 0.28 ± 0.015 | 0.386 ± 0.035 |
|         | 0.32 ± 0.02  | 0.261 ± 0.043 |
|         | 0.37 ± 0.03  | 0.404 ± 0.071 |
| Hydra A | 0.30 ± 0.06  | 0.268 ± 0.035 |
|         | 0.42 ± 0.06  | 0.243 ± 0.072 |
|         | 0.54 ± 0.06  | 0.361 ± 0.115 |
| A262    | 0.28 ± 0.02  | 0.370 ± 0.053 |
|         | 0.31 ± 0.06  | 0.454 ± 0.071 |
|         | 0.43 ± 0.03  | 0.260 ± 0.083 |
|         | 0.56 ± 0.07  | 0.321 ± 0.120 |
| A2004   | 0.66 ± 0.13  | 0.413 ± 0.076 |
|         | 0.93 ± 0.13  | 0.268 ± 0.147 |
| A1795   | 0.29 ± 0.06  | 0.306 ± 0.029 |
|         | 0.40 ± 0.05  | 0.341 ± 0.056 |
|         | 0.52 ± 0.06  | 0.145 ± 0.064 |
| A2029   | 0.34 ± 0.07  | 0.355 ± 0.087 |
|         | 0.55 ± 0.14  | 0.276 ± 0.094 |
| A2142   | 0.31 ± 0.06  | 0.358 ± 0.042 |
|         | 0.43 ± 0.03  | 0.354 ± 0.064 |
| A1689   | 0.62 ± 0.12  | 0.353 ± 0.131 |
| Coma†   | 0.25 ± 0.02  | 0.285 ± 0.035 |
|         | 0.29 ± 0.02  | 0.281 ± 0.059 |
|         | 0.34 ± 0.03  | 0.240 ± 0.072 |
|         | 0.40 ± 0.03  | 0.327 ± 0.068 |
|         | 0.50 ± 0.08  | 0.260 ± 0.056 |
|         | 0.71 ± 0.13  | 0.41 ± 0.18  |

Simionescu et al. (2013)

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7 https://wwwastro.msfc.nasa.gov/lynx/
an early enrichment scenario, where the majority of metal enrichment occurs before the cluster formation, at $z > 2$.

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APPENDIX A: INDIVIDUAL CLUSTERS

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Figure A1. **Top left:** The exposure- and vignetting corrected mosaic of the Suzaku observations of A 262 in the $0.7 - 7.0$ keV energy range. The image has been smoothed with a Gaussian with width of 25 arcsec. The dashed white circle has a radius of $r_{200}$. Small magenta circles show the point sources removed from the spectral analysis. The annular regions, within which we measured the ICM metallicity, are shown in yellow. The colour bar shows the surface brightness in units of counts s$^{-1}$ arcmin$^{-2}$. **Top right:** Ratio of the number of the ICM counts to the sum of CXFB and the instrumental background counts in a 1 keV-wide energy band around the Fe-K line, in the individual observations (red) and for the complete annulus (blue). The dotted line marks the 10% threshold employed for all subsequent analysis. For observations where the ratio is close to zero, the data point does not appear in the plot. **Bottom left:** Projected temperature and normalisation profiles of A 262 (the units of the normalisation are defined in Tab. 4). The horizontal axes shows the distance from the cluster center in the units of $r_{200}$ shown in Tab. 2. The vertical dotted line marks 0.25$r_{200}$, which we conservatively assume to be the outside border of the central metallicity peak. **Bottom right:** Radial profile of the best fit projected iron abundance. Only the black data points were included in our subsequent analysis.

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Figure A2. Same as Fig. A1 but for A 1795.
Figure A3. Same as Fig. A1 but for A 1689.
Figure A4. Same as Fig. A1 but for Hydra A.
Figure A5. Same as Fig. [A1] but for A 2029.
Figure A6. Same as Fig. A1 but for A 2204.
Figure A7. Same as Fig. [A1] but for A 2142.
Figure A8. Same as Fig. A1 but for A 133.
Figure A9. Same as Fig. A1 but for AWM7.