The evolution of the spatially resolved metal abundance in galaxy clusters up to z = 1.4* (Research Note)

S. Ettori1,2, A. Baldi3, I. Balestra4, F. Gastaldello5,6, S. Molendi5, and P. Tozzi7

1 INAF, Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy
e-mail: stefano.ettori@oabo.inaf.it
2 INFN, Sezione di Bologna, viale Berti Pichat 6/2, 40127 Bologna, Italy
3 Physics and Astronomy Dept., Michigan State University, East Lansing, MI 48824, USA
4 INAF, Osservatorio Astronomico di Trieste, via G.B. Tiepolo 11, 34131 Trieste, Italy
5 INAF–IASF, via Bassini 15, 20133 Milan, Italy
6 Department of Physics and Astronomy, University of California at Irvine, 4129 Frederick Reines Hall, Irvine, CA 92697–4575, USA
7 INAF, Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, 50125 Firenze, Italy

Received 5 December 2014 / Accepted 1 April 2015

ABSTRACT

Context. We present the combined analysis of the metal content of 83 objects in the redshift range 0.09–1.4, and spatially resolved in the three bins (0–0.15, 0.15–0.4, >0.4) R500, as obtained with similar analysis using XMM-Newton data in our previous two papers.

Aims. By combining these two large data sets, we investigate the relations between abundance, temperature, radial position and redshift in the intracluster medium.

Methods. We fit functional forms to the combination of the different physical quantities of interest, i.e., intracluster medium (ICM) metal abundance, radius, and redshift. We use the pseudo-entropy ratio to separate the cool core (CC) cluster population, where the central gas density tends to be relatively higher, cooler and more metal rich, from the non-cool core systems.

Results. The average, redshift-independent, metal abundance measured in the three radial bins decreases moving outwards, with a mean metallicity in the core that is even three (two) times higher than the value of 0.16 times the solar abundance in Anders & Grevesse (1989, Geochim. Cosmochim. Acta, 53, 197) estimated at z = 0.

Conclusions. Our study defines the limits that numerical and analytic models describing the metal enrichment in the ICM have to meet.

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

1. Introduction

The hot, thin X-ray emitting plasma in galaxy clusters (i.e. the intracluster medium, ICM) is enriched with metals ejected from supernovae (SNe) explosions through subsequent episodes of star formation and subsequent diffusion through several mechanisms, e.g., ram pressure stripping, galactic winds, outflows from active Galactic nuclei, galaxy-galaxy interactions (e.g. Renzini 1997; Schindler & Diaferio 2008).

X-ray observations provide direct measurements of the metal abundance in the ICM, as well as their radial distribution and variation as a function of time. These measures represent the “footprint” of cosmic star formation history and are crucial to tracing the effect of SN feedback on the ICM at different cosmic epochs (e.g. Ettori 2005; Calura et al. 2007; Cora et al. 2008; Fabjan et al. 2010).

Several studies have addressed the radial distributions of metals in the ICM at low redshift (e.g. Finoguenov et al. 2000; De Grandi & Molendi 2001; Irwin & Bregman 2001; Tamura et al. 2004; Baldi et al. 2007; Leccardi & Molendi 2008; Snowden et al. 2008). A few others have constrained the evolution of the metal abundance at z ≥ 0.3 (e.g. Balestra et al. 2007; Maughan et al. 2008; Anderson et al. 2009; a statistical analysis of the combination of these different data sets is presented in Andreon 2012). In Baldi et al. (2012a), we have presented...
the XMM-Newton analysis of 39 galaxy clusters at 0.4 < z < 1.4, covering a temperature range of 2 ≤ kT ≤ 12.8 keV. We were able to resolve their abundance in three radial bins.

In this work, we combine this data set with that presented in Leccardi & Molendi (2008), which includes 44 objects at z < 0.31, with gas temperatures between 2.9 keV and 11.3 keV. The analysis performed on the XMM-Newton data in the two samples is identical and can be statistically combined to probe the ICM abundance as a function of radial position and redshift.

We adopt a cosmological model with H₀ = 70 km s⁻¹ Mpc⁻¹, Ω_m = 0.3, and Ωₐ = 0.7 throughout. Solar abundance values published in Anders & Grevesse (1989) are adopted for reference. Confidence intervals are quoted at 1σ unless otherwise stated.

2. Data analysis

Details on the X-ray data reduction and analysis are presented in Leccardi & Molendi (2008) and Baldi et al. (2012a), which include a discussion on the systematic effects that could affect our estimates of the ICM metallicity. Most of these measurements, which are for high temperature (kT > 2 keV) systems at medium-high redshifts (z > 0.1), are mainly based on the strength of the iron K line (at the rest-frame energies of 6.6−7.0 keV)\(^1\). We briefly mention here that we performed a simultaneous spectral fit on spectra accumulated from the two MOS detectors over the energy range 0.7−8.0 keV, using a Cash statistics applied to the source plus background counts, with a modelled background emission. The free parameters of the thermal model apec in XSPEC (Arnaud 1996) are temperature, abundance, and normalization. Local absorption is fixed to the Galactic neutral hydrogen column density, as obtained from radio data (Kalberla et al. 2005), and the redshift to the value is measured from optical spectroscopy.

Because of the better statistics in lower redshift clusters, the X-ray spectral analysis of most objects in Leccardi & Molendi (2008) was performed using a finer radial binning with respect to Baldi et al. (2012a). Thus, we had to degrade the spatial resolution of Leccardi & Molendi (2008) abundance profiles to match its resolution with Baldi et al. (2012a) and obtain uniform abundance profiles in three radial bins: 0−0.15 R₅₀₀, 0.15−0.4 R₅₀₀, and >0.4 R₅₀₀, where R₅₀₀ is estimated through a scaling relation (e.g. Vikhlinin et al. 2006; see Baldi et al. 2012 for details) by using a global gas temperature that does not include the core emission (<0.15 R₅₀₀). We first carried out the spatial degradation by interpolating the abundance profile (and its relative error) over the radial points of the observed surface brightness profile S(r) of each cluster. Then, we used the surface brightness profile as a weighting factor for the interpolated abundance profile, together with the errors on the abundance profile itself, so that – in each resulting bin – regions with higher surface brightness and smaller uncertainties in the measure of the abundance would have a larger weight in the computation of the average abundance. This scheme reproduces an emission−weighted profile of the metal abundance. Hydrodynamical simulations have shown that an emission−weighted metallicity matches the original value in simulations at better than 5% (e.g. Rasia et al. 2008). Following this approach, the average abundance \(\langle Z \rangle\), and the relative error \(\sigma(Z)\), in the \(R_{\text{min}}\)−\(R_{\text{max}}\) bin was computed as:

\[
\langle Z \rangle = \frac{\sum_{i=1}^{n} w_i Z_i}{\sum_{i=1}^{n} w_i}, \quad \sigma(Z) = \left( \frac{\sum_{i=1}^{n} S_i}{\sum_{i=1}^{n} w_i} \right)^{0.5},
\]

where \(Z_i\) and \(\sigma_Z\) are the abundance profile and the error on the abundance profile, respectively, \(w_i = S_i/\sigma_Z^2\) is the weighting factor, and the sum is done over the \(n\) radial bins falling in the radial range \(R_{\text{min}}\)−\(R_{\text{max}}\) in the abundance profile of each cluster, as measured in Leccardi & Molendi (2008).

3. Results on the spatially resolved abundance evolution

This work presents our final effort to use archived data to constrain the evolution of the spatially resolved ICM abundance. Our analysis separates the central regions, where cool cores (if any) appear, and the rest of the cluster atmosphere. We require that the spectrum from which the metallicity is measured contains at least 300 net counts. We consider a total of 221 data points corresponding to the spatially resolved spectroscopic measurements of the metal abundance distribution in 83 galaxy clusters in the redshift range 0.092−1.393. By estimating the pseudo-entropy ratio \(\sigma = (T_0/T_1) \times (EM_0/EM_1)^{1/2}\), where \(T_0\) and \(T_1\) are the temperatures measured in the \(r < 0.15 R_{500}\) region and in the \(0.15−0.4 R_{500}\) annulus, respectively, and \(EM_0\) and \(EM_1\) are the corresponding emission measures, we define as non-cool core (NCC) clusters 54 (out of 83) objects that have \(\sigma > 0.6\) (see e.g. Leccardi et al. 2010; Baldi et al. 2012b). The data points are plotted as function as radius and redshift, separating between CC and NCC systems, in Fig. 1. All the results are presented in Table 1.

In the \(r < 0.15 R_{500}\) radial bin, we have 70 data points over the entire redshift range. The distribution of the metal abundance correlates significantly with the redshift (Spearman’s rank \(ρ_γ = -0.25\), corresponding to a significance of 2.1σ versus the null-hypothesis of no correlation; see Table 2), with the temperature \(ρ_T = -0.3, 2.5\sigma\) and with the pseudo-entropy ratio \(ρ_σ = -0.4, 3.3\sigma\). These correlations point towards a significant effect induced from the cooling activities taking place in these regions, where the ICM at high density radiates more efficiently, lowering its global temperature and increasing its metal budget (see e.g. Leccardi & Molendi 2008). Fitting the data points in this bin with a power law in the form \(Z ∝ (1+z)^{γ}\), we obtain \(γ = 1.60 ± 0.22\), which differs from zero at high significance (>6σ). When a bootstrap analysis is done, i.e. the fit is repeated \(10^5\) times after a random sampling with replacement and the median, we consider the 1st and 3rd quartiles to estimate location and dispersion of the distribution of the best-fitting parameters. We also find that the central values are recovered, but the relative errors are increased by about a factor of 2, mostly because a more proper sampling of the intrinsic scatter is performed with the bootstrap analysis. The negative evolution (\(γ > 0\)) is still detected in >99.9 per cent of the replica. When we consider CC and NCC systems separately, the normalization \(Z_0\) is different by a factor of 2.2 in favour of CC systems, where a negative evolution is still detected at very high significance. Instead, no evolution is measured (\(γ = 0.5 ± 0.4\)) in NCC objects, although the case for negative evolution is still observed in about 80% of the bootstrapped repetitions.

---

\(1\) The full data set analysed here is available at http://pico.bo.astro.it/~settori/abun/xmm.dat and at the CDS.
Eighty-three data points are located in the radial bin $0.15 < r < 0.4 R_{500}$, where a $2.8\sigma$ significant correlation between pseudo-entropy ratio and redshift is detected, suggesting an increase of $\sigma$ (i.e. larger incidence of NCC systems) with the redshift. A mild anti-correlation between $Z$ and redshift is also present in this bin (significance of $2.2\sigma$). We measure $\gamma = 0.70 \pm 0.32$ ($1\sigma$ range of $0.16\sim1.31$ after bootstrap analysis). The case for negative evolution is still observed in about 91% of the bootstrapped samples. Similar values are measured in the population of NCC clusters, which dominates the sample in this radial bin, with a normalization (and a mean metallicity value) that is lower than the corresponding value measured for CC systems by about 30 per cent.

Finally, we do not find evidence of negative redshift evolution of the metallicity in the last radial bin considered in our analysis ($r > 0.4 R_{500}$), either. In this case, we constrain a value for $\gamma$ of $0.26 \pm 0.61$ ($\gamma > 0$ with a probability $P \approx 65\%$ after bootstrap analysis) with 68 data points. Similar results are obtained in the CC and NCC populations, where an average value of $Z = 0.16 Z_{\odot}$ is estimated.

As the sample is highly heterogeneous and not in any sense representative of the cluster population, it is not expected to

---

Table 1. Results of the combined analysis on the redshift and radial distribution of the metal abundance.

| Sample    | $N$  | $\chi^2$ | $\sigma$ | $Z_{\odot}$ | $\gamma$ | $\beta$ | Constant (

|-----------|------|----------|----------|-------------|----------|---------|----------|
| $0.15 R_{500}$ | 70 | 267.1 | 0.151 | 0.020 | 0.648 | 0.031 | 1.60 | 0.22 | 1.59 | 0.49 | $0.451 \pm 0.009$ |
| Only CC   | 27 | 140.7 | 0.159 | 0.031 | 0.795 | 0.046 | 2.19 | 0.28 | 2.10 | 0.51 | $0.493 \pm 0.011$ |
| Only NCC  | 43 | 50.6  | 0.053 | 0.038 | 0.360 | 0.041 | 0.45 | 0.40 | 0.51 | 0.79 | $0.320 \pm 0.019$ |
| $0.15 - 0.4 R_{500}$ | 83 | 147.7 | 0.044 | 0.012 | 0.261 | 0.022 | 0.70 | 0.32 | 0.66 | 0.49 | $0.220 \pm 0.009$ |
| Only CC   | 29 | 27.9  | 0.012 | 0.025 | 0.287 | 0.032 | 0.30 | 0.47 | 0.33 | 0.26 | $0.269 \pm 0.013$ |
| Only NCC  | 54 | 96.8  | 0.048 | 0.017 | 0.197 | 0.027 | 0.37 | 0.46 | 0.37 | 0.61 | $0.178 \pm 0.012$ |
| $> 0.4 R_{500}$ | 68 | 74.4  | 0.029 | 0.028 | 0.168 | 0.028 | 0.26 | 0.61 | 0.33 | 0.88 | $0.158 \pm 0.014$ |
| Only CC   | 27 | 40.1  | 0.071 | 0.038 | 0.131 | 0.030 | 0.68 | 0.84 | 0.71 | 1.14 | $0.158 \pm 0.019$ |
| Only NCC  | 41 | 30.7  | 0.000 | 0.026 | 0.228 | 0.043 | 1.39 | 0.92 | 1.31 | 0.85 | $0.157 \pm 0.020$ |

All       | 221 | 506.3 | 0.092 | 0.010 | 0.702 | 0.031 | 1.33 | 0.18 | 1.31 | 0.41 | $0.56 \pm 0.03$ |

Notes: The columns show: the selected sample; the number of fitted data points; the total $\chi^2$ value; the intrinsic scatter estimated by requiring that the reduced $\chi^2$ is equal to 1; the best-fit parameters of the adopted functional form $Z(r,z) = Z_0 (1 + (r/0.15 R_{500})^2)^p (1+z)^q$. Median, 1st and 3rd quartiles from the distribution of the best-fitting parameters in the bootstrap analysis over a sample of $10^5$ repetitions are indicated in round parentheses. In the last column, labelled "constant", we list the weighted-mean, its relative error and the dispersion around it in round parentheses.
Table 2. Spearman’s rank correlation coefficients.

| Sample | $\rho_r$ | $\rho_T$ | $\rho_\sigma$ | $\rho_{\sigma z}$ |
|--------|---------|---------|-------------|--------------|
| 0–0.15 $R_{500}$ | -0.25 (2.07) | -0.31 (2.54) | -0.39 (3.27) | 0.18 (-1.51) |
| 0.15–0.4 $R_{500}$ | -0.24 (2.18) | -0.13 (1.14) | -0.13 (1.18) | 0.31 (-2.80) |
| >0.4 $R_{500}$ | -0.20 (1.63) | -0.09 (0.75) | -0.10 (0.84) | 0.23 (-1.85) |
| All | -0.20 (3.04) | -0.09 (1.27) | -0.20 (2.93) | 0.25 (-3.66) |

Notes. The Spearman’s rank correlation coefficients (and the significance of the differences) are calculated in the inner radial bin $(r < 0.15 R_{500})$, the region immediately surrounding the core $(0.15 R_{500} < r < 0.4 R_{500})$, and the outskirts of the cluster $(r > 0.4 R_{500})$. The best-fitting value is the mean metallicity in the local systems. The pseudo-entropy ratio is larger in NCC systems.

We stress that this work provides the most robust constraints reachable with archived XMM-Newton and Chandra data on the distribution of the metal abundance as a function of radius and redshift in the ICM. Larger samples of high redshift X-ray clusters, together with deeper Chandra and XMM-Newton observations even of the clusters already present in the archive, would be crucial to putting tighter constraints on the evolution of the ICM metal abundance. These samples are also needed to provide a robust modelling of the physical processes responsible for the enrichment of the cluster plasma during its assembly over cosmic time, from the accumulation of the iron mass in the CC cluster cores (e.g. De Grandi et al. 2004; Böhringer et al. 2004) to the history of the processes responsible for the metal release into the ICM through ejections from supernovae Types Ia and II (e.g. Ettori 2005), as well as through galaxy transformation in the cluster volume (e.g. Calura et al. 2007) and their modelling in joint semi-analytic/hydrodynamical numerical simulations (e.g. Cora et al. 2008; Fabjan et al. 2010).

Acknowledgements. We thank Sabrina De Grandi and Mauro Sereno for their discussion. We acknowledge financial contribution from contracts ASI-INAF I/009/10/0 and Prin-INAF 2012 on “A unique data set to address the most compelling open questions about X-Ray Galaxy Clusters”. We thank the anonymous referee for useful comments that helped to improve the presentation of the results in this paper.

References

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Anderson, M. E., Bregman, J. N., Butler, S. C., & Mullis, C. R. 2009, ApJ, 698, 317
Andreon, S. 2012, A&A, 546, A6
Arnaud, K. A. 1996, in Astronomical Data Analysis Software and Systems V, eds. G. H. Jacoby, & J. Barnes, ASP Conf. Ser., 101, 17
Baldi, A., Ettori, S., Mazzotta, P., Tozzi, P., & Borgani, S. 2007, ApJ, 666, 835
Baldi, A., Ettori, S., Molenid, S., et al. 2012a, A&A, 537, A14
Baldi, A., Ettori, S., Molenid, S., & Gastaldello, F. 2012b, A&A, 545, A41
Balestra, I., Tozzi, P., Ettori, S., et al. 2007, A&A, 462, 429
Böhringer, H., Matsushita, K., Churazov, E., Finoguenov, A., & Ikebe, Y. 2004, A&A, 416, L21
