Mem. S.A.It. Suppl. Vol. 17, 60

Memorie della
Supplementi

Metal content in Galaxy Clusters cool-cores: an XMM-Newton study, and future prospects

S. De Grandi[1], S. Molendi[2] and F. Gastaldello[2]

[1] Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Brera, Via E. Bianchi 46, e-mail: `sabrina.degrandi@brera.inaf.it` I-23807 Merate (LC), Italy
[2] Istituto Nazionale di Astrofisica – Istituto di Astrofisica Spaziale e Fisica Cosmica, Via Bassini 15, I-20133 Milano, Italy

Abstract.
We carried out a detailed study of the Si, Fe and Ni abundances in the cool cores of a representative sample of local galaxy clusters using *XMM-Newton* data. We first evaluated the systematic errors on the abundance measurements that are related to the instruments, the plasma codes and the spectral modeling. We then used the Si/Fe and Ni/Fe abundance ratios to revisit the relative contribution of type Ia and core-collapsed supernovae to the enrichment process taking into account the uncertainties on both the measured abundances and the current theoretical supernovae yields. *WFXT* will push forward sensibly abundance studies of the kind described in this paper: first by increasing dramatically the number of objects with adequate photon statistics and secondly, by means of an improved spatial resolution will allows us to study galaxy cluster cores at redshifts up to 1.

Key words. galaxies: cluster: general – galaxies: fundamental parameters – intergalactic medium – X-ray: galaxies: abundances – cosmology: observations – dark matter

1. Introduction

The detection of metal lines from X-ray observations of the intra-cluster medium (ICM) indicates that it does not have a primordial chemical composition but was enriched with material processed in stars. The measurement of heavy element abundances present in the ICM can provide important clues on the chemical evolution inside galaxy clusters.

The measurement of the abundance of an element from the X-ray spectrum is a conceptually simple process since the number of ions of the elements with respect to the number of protons is directly proportional to the equivalent width of the emission line produced by the element itself. This one-to-one correspondence is possible because the X-ray emitting plasma is optically thin and in collisional equilibrium. In practice, various sources of uncertainties are involved in the conversion process, such as the accuracy of the atomic physics, the moderate spectral resolution of the current imaging instruments which often results in line blending from both different ions of the same element or from different elements, and the presence of temperature gradients in the ICM, especially in cluster cores, that needs specific spectral modeling.

Send offprint requests to: S. De Grandi

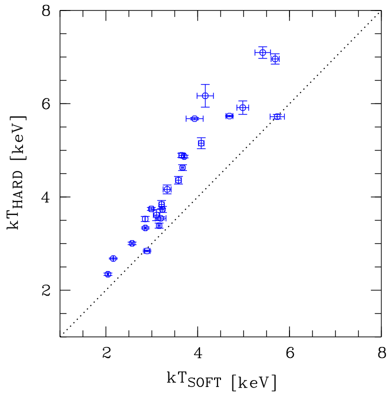

Fig. 1. ICM temperatures in the cool-core regions of the clusters in our sample measured with single-temperature models from the soft (0.7-3 keV) and the hard (2-10 keV) bands. As expected in case of multi-temperature ICM the two temperatures differ with the one derived from the hard band being higher with respect to the temperature derived from the soft band.

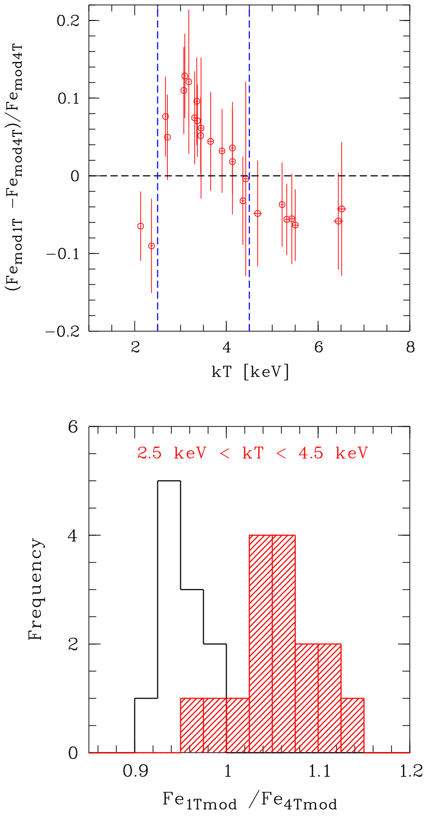

Fig. 2. **Upper panel**: relative differences between Iron measured in the cluster cool cores with a single temperature model and a multi-temperature model as a function of the temperature. The temperature in the x-axis is the one from the single temperature model measured in the broad band. The dashed lines highlighted the region between $\sim 2.5-4.5$ keV where the inverse Fe-bias is present, details on the iron biases are given in the text. **Lower panel**: histogram of the ratio between iron derived from single and multi-temperature models for the same clusters. The dashed region refers to clusters with temperatures in the 2.5 – 4.5 keV range.

With *Chandra* and *XMM-Newton* statistical errors on the derived abundances have greatly decreased, however only little attention was devoted to the characterization of systematic errors which, under some circumstances, are likely to play an important role.

The goal of this study was firstly to provide robust estimates of chemical elements, namely Si, Fe and Ni, in the cores of nearby and bright cool core clusters. In this context robust means the we included in the error budget also a careful evaluation of systematic uncertainties. Secondly, we used the derived metal abundances to study the abundance and abundance ratios (i.e Si/Fe and Ni/Fe) distributions for a well defined sample of clusters, and, finally, we provided a critical assessment of the relative role of SN types including uncertainties associated to current theoretical SN yields.

We decided to focus on the measurement of global abundances from the very central regions of cool core clusters since these regions provide us with the maximum photon statistic available due to their very intense surface brightness peaks. This allowed us to explore systematic uncertainties affecting the derived elements in great details (De Grandi & Molendi 2009).

We considered a subsample of 26 cool-core galaxy clusters from the B55 sample (Edge et al. 1990), and extracted spectra from the central regions within $0.5r_{cool}$ radius, where r_{cool} is the cooling radius taken for each cluster from the work of Peres et al. (1998). For our purposes half the cooling radius is a good sampling of the core region and has the advantage to be always within the EPIC field of view in all the clusters of our sample.

2. The systematic errors analysis

Details on the analysis can be found in (De Grandi & Molendi 2009). Here we report our main findings.

1. The cross-correlation between metal abundances acquired independently with the 3 EPIC detectors shows that to reconcile Si and Fe measurements we require a 3% systematic error.
2. Almost all core spectra show evidence of multi-temperature structure. For example applying a single temperature model on the two independent hard, 2-10 keV, and soft, 0.7-3 keV, energy bands gives significantly different temperatures for the ICM (with the temperature measured from the hard band larger than that measured from the soft one as expected in case of multi-temperature structure, see Fig. 1). We have therefore applied different multi-temperature models to the core spectra and investigated the systematic uncertainties due to the different modellization. We found that systematic uncertainties associated to the different spectral modeling, namely a 2 versus a 4 temperatures models, are below $2-3\%$.
3. In the *xspec* package there are two spectral codes, MEKAL and APEC. We have found that the two codes return somewhat different abundance values. We find that: Fe is almost unchanged, $\mathrm{Fe}_{apec}/\mathrm{Fe}_{mekal} = 1.05 \pm 0.01$; Si is somewhat higher, $\mathrm{Si}_{apec}/\mathrm{Si}_{mekal} = 1.11 \pm 0.02$ and Ni is lower, $\mathrm{Ni}_{apec}/\mathrm{Ni}_{mekal} = 0.82 \pm 0.04$. The Si/Fe ratio, as measured with *apec*, is slightly higher than that estimated with *mekal*, $(\mathrm{Si/Fe})_{apec}/(\mathrm{Si/Fe})_{mekal} = 1.06 \pm 0.02$, while Ni/Fe is substantially lower, $(\mathrm{Ni/Fe})_{apec}/(\mathrm{Ni/Fe})_{mekal} = 0.77 \pm 0.04$.
   In summary, we found that the systematic uncertainties related to the two emission codes are comparable to those associated to cross-calibration between EPIC detectors in the case of Fe (5%) and Si/Fe (6%), whereas they are the dominant source of uncertainties in the case of Si (10%), Ni (15%) and Ni/Fe (20%).
4. A single temperature analysis of a multi-temperature region, such as the one found in cool cores, leads to a biased Fe abundance (see Fig. 2). Below $\sim$ 2 keV and above $\sim$ 4 keV the measured Fe is *too low* with respect to a correct multi-temperature spectral analysis. This bias was already identified by Buote (2000a,b) for poor clusters and groups with ICM temperatures below $1-2$ keV. On the contrary, in the range between $\sim 2-4$ keV the measured Fe from a single temperature model is too high. This "inverse" Fe-bias was recently found both in a cluster simulation (Rasia et al. 2008), in the central regions of the Hydra A cluster (Simionescu et al. 2009) and A2028 (Gastaldello et al. 2009, 2010) clusters. In our sample we find that, although iron biases are present at any temperature above 2 keV, the total effect is always smaller than $10\%-15\%$, at any temperature (see Fig. 2).

2.1. Results on Abundance Measurements

The Si, Fe, Ni, Si/Fe and Ni/Fe distributions of the sample show moderate spreads (20%-30%) around their mean values (see Fig. 3) suggesting a similar ICM enrichment process at work in all cluster cores. Moreover, the mean Si, Fe and Si/Fe of our sample and their relative scatters are very similar to the values found for a sample of galaxy groups (Rasmussen & Ponman 2007) and a sample of X-ray luminous early type galaxies (Humphrey & Buote 2006). This suggests that, whatever the real proportion between different SNe types may be, the enrichment process of the hot gas associated to elliptical galaxies is likely the same in iso-

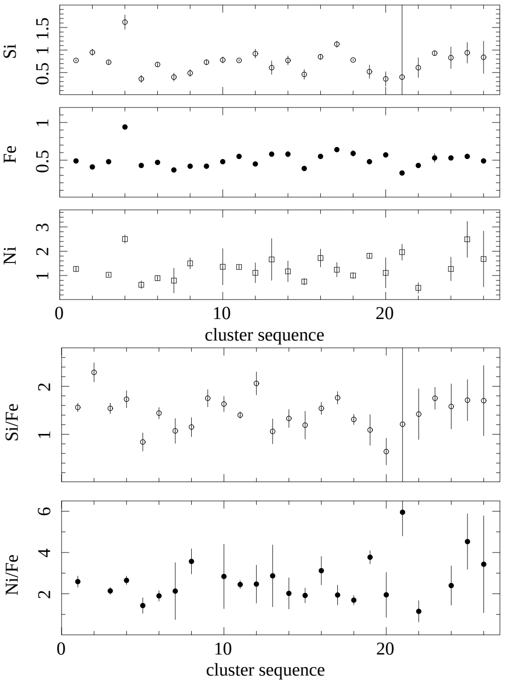

Fig. 3. **Upper panel**: Si, Fe, Ni abundance distributions within $r < r_{cool}/2$ for the sample. **Lower panel**: Si/Fe and Ni/Fe abundance ratio distributions within the same radius as above (abundances are all relative to Anders & Grevesse (1989) solar units).

lated ellipticals, dominant galaxies in groups and BCGs in clusters.

2.2. SN type Ia versus SN core-collapsed

We constrain the relative contribution of SNe using our observed Si/Fe, Ni/Fe and SN yields from theoretical works. We note that while errors on the observed abundance ratios are of the order of ~ 5%, various sets of yields are reported in the literature, for both SN type Ia and SN core-collapsed (Woosley & Weaver 1995; Iwamoto et al. 1999; Chieffi & Limongi 2004; Nomoto et al. 2006) whose associated uncertainties are of the order of tens of % (Gibson et al. 1997; Young & Fryer 2007). We therefore estimate the relative contribution of SNe, including both uncertainties on the observed abundance ratios *and* on the theoretical yields.

Assuming a 20% error on the yields we find that the SNIa Fe-mass-fraction overall permitted range is 0.48-0.79 and that the dominant source of uncertainty in the estimate of the SNIa Fe-mass-fraction are the errors on the yields.

From the SNIa Fe-mass-fraction we derived a SNIa number fraction, defined as the number of SNIa over the total number of SNe, which is between 0.10 and 0.38. This number fraction cannot be reconciled with 0 or 1, as we would need errors of 50% in the yields to reproduce 0 and errors up to 70% to have 1, which are both quite improbable.

Our conclusion is that the large uncertainties on the currently available yields prevent any precise estimate of the relative contribution of SNIa and SNcc, and that we can only say that they *both* concur to the enrichment process in cluster cool-cores.

We have shown how difficult is to determine the relative contribution of SNe to the ICM enrichment from global cool-core abundance measurements. An alternative approach is to consider radial profiles of metal abundance ratios, in this case variation of the Si/Fe ratio with the radius can be interpreted as evidence for variation of the relative contribution of the two SN types.

Unfortunately, recent works disagree in their conclusions. Finoguenov et al. (2000) using *ASCA* data for a sample of clusters and Rasmussen & Ponman (2007) using *Chandra* observations of a sample of groups found increasing Si/Fe with radius, that implies a radially increasing predominance of SNcc enrichment in the clusters outskirts. On the contrary, Tamura et al. (2004) with a sample of clusters observed with *XMM-Newton* and more recently *Suzaku* observations of various clusters and groups (collected in Fabjan et al. 2010 see their Fig. 13 and references therein) found flat Si/Fe profiles. Therefore this subject needs further investigation. This specific subject leaves space for great improvement with *WFXT* given its predicted high performances in observing the outermost cluster regions (see contribution of Ettori & Molendi in this Proceedings). *WFXT* will also allow to

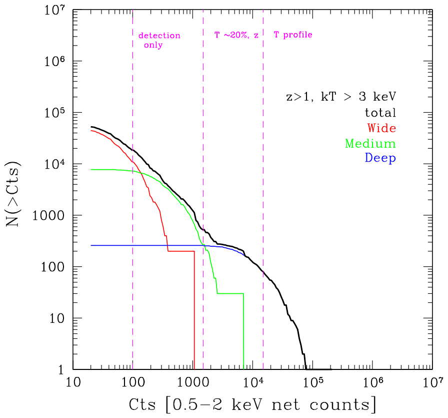

Fig. 4. Number of galaxy clusters (kT > 3 keV) that are at redshift larger than 1 in the three, wide (red line), medium (green line) and deep (blue line), surveys and their sum (black line) as a function of the total counts in the soft 0.5-2.0 keV band (P. Tozzi private comm.).

extend the study of abundance ratios to distant clusters.

2.3. A few quantitative estimates

In order to be more quantitative, we roughly estimate the number of clusters for which we can measure the temperature and abundances in one or two bins with the help of Fig. 4 (P. Tozzi private comm.). This Figure shows the expected number of clusters of galaxies (kT > 3 keV) and at $z > 1$ observed in the three surveys of *WFXT* as a function of the total source counts in the soft 0.5-2. keV band. We assume that a number of source counts between 2000 and 6000 are sufficient to achieve our scientific purpose. From Fig. 4 we estimate that 2000 counts can be collected for about 100 clusters in the medium survey and for about 300 clusters in the deep one, whereas 6000 counts can be acquired for 30 and 250 clusters in the medium and deep survey, respectively. We convert these counts (2000 and 6000 cts) in the corresponding fluxes by using the conversion factor for extended sources in the soft band computed by P. Tozzi in these same Proceedings, which is 2.22×10^{-13} (see Table 1 in P. Tozzi & the WFXT team: "*WFXT* simulations"). In the medium survey 2000 cts correspond to fluxes of $\sim 3.4 \times 10^{-14}$ erg s^{-1} cm^{-2} and 6000 cts to a flux of $\sim 1.0 \times 10^{-13}$ erg s^{-1} cm^{-2}, whereas in the deep survey 2000 cts correspond to a flux of $\sim 1.1 \times 10^{-15}$ erg s^{-1} cm^{-2} and 6000 cts to a flux of $\sim 3.3 \times 10^{-15}$ erg s^{-1} cm^{-2}. All these fluxes are well above the flux limit for extended sources of the medium (i.e., $\sim 1.44 \times 10^{-15}$ erg s^{-1} cm^{-2}) and deep ($\sim 0.2 \times 10^{-15}$ erg s^{-1} cm^{-2}) surveys (see Table 3 always in P. Tozzi & the WFXT team: "*WFXT* simulations"). Moreover, in the deep survey we will obtain a considerable sample of clusters, i.e. about hundred or more, with 10^4 net counts (see Fig. 4), corresponding to a soft band flux of 5.6×10^{-14} erg s^{-1} cm^{-2}, for which it will be possible to study temperature and abundances profiles in more than 2 bins. For comparison to the local sample of cluster cool-cores analyzed in our *XMM-Newton* work, we consider the average cool-core X-ray luminosity (1.5×10^{44} erg s^{-1} in the 2.-10. keV band), temperature (4 keV) and iron abundance (0.5 solar units) and then, by assuming a *mekal* spectral code, we estimate the expected flux for such a typical core shifted at $z = 1$ and in the soft 0.5-2. keV band. The expected flux is 2.6×10^{-14} erg s^{-1} cm^{-2} which roughly corresponds to 2000 cts in the medium survey and 6000 cts in the deep one.

From these estimates we conclude that the medium and deep *WFXT* surveys will allow us to measure the abundances of Fe and Si (Ni will always be outside the *WFXT* energy band at this high redshifts) for a large number of galaxy clusters at redshift around 1 and possibly beyond, this will allow us to extend to higher redshift the scientific topics addressed in the *XMM-Newton* work presented in this contribution.

References

Anders, E. & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Buote, D. A. 2000a, ApJ, 539, 172
Buote, D. A. 2000b, MNRAS, 311, 176

Chieffi, A. & Limongi, M. 2004, ApJ, 608, 405
De Grandi, S. & Molendi, S. 2009, A&A, 508, 565
Edge, A. C., Stewart, G. C., Fabian, A. C., & Arnaud, K. A. 1990, MNRAS, 245, 559
Fabjan, D., Borgani, S., Tornatore, L., et al. 2010, MNRAS, 401, 1670
Finoguenov, A., David, L. P., & Ponman, T. J. 2000, ApJ, 544, 188
Gastaldello, F., Ettori, S., Balestra, I., et al. 2009, ArXiv e-prints
Gastaldello, F., Ettori, S., Balestra, I., et al. 2010, ArXiv e-prints
Gibson, B. K., Loewenstein, M., & Mushotzky, R. F. 1997, MNRAS, 290, 623
Humphrey, P. J. & Buote, D. A. 2006, ApJ, 639, 136
Iwamoto, K., Brachwitz, F., Nomoto, K., et al. 1999, ApJS, 125, 439
Nomoto, K., Tominaga, N., Umeda, H., Kobayashi, C., & Maeda, K. 2006, Nuclear Physics A, 777, 424
Peres, C. B., Fabian, A. C., Edge, A. C., et al. 1998, MNRAS, 298, 416
Rasia, E., Mazzotta, P., Bourdin, H., et al. 2008, ApJ, 674, 728
Rasmussen, J. & Ponman, T. J. 2007, MNRAS, 380, 1554
Simionescu, A., Werner, N., Böhringer, H., et al. 2009, A&A, 493, 409
Tamura, T., Kaastra, J. S., den Herder, J. W. A., Bleeker, J. A. M., & Peterson, J. R. 2004, A&A, 420, 135
Woosley, S. E. & Weaver, T. A. 1995, ApJS, 101, 181
Young, P. A. & Fryer, C. L. 2007, ApJ, 664, 1033