Brief history of the metal accumulation in the intracluster medium

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ABSTRACT
We use models of the rates of Type Ia supernovae (SNe Ia) and core-collapse supernovae, built in such a way that both are consistent with recent observational constraints at $z \lesssim 1.6$ and can reproduce the measured cosmic star formation rate, to recover the history of the metals accumulation in the intra-cluster medium. We show that these SN rates, in unit of SN number per comoving volume and rest-frame year, provide on average a total amount of Iron that is marginally consistent with the value measured in galaxy clusters in the redshift range $0 - 1$, and relative evolution with redshift that is in agreement with the observational constraints up to $z \approx 1.2$. Moreover, we verify that the predicted metals to Iron ratios reproduce the measurements obtained in nearby clusters through X-ray analysis, implying that (1) about half of the Iron mass and $\gtrsim 75$ per cent of the Nickel mass observed locally are produced by SN Ia ejecta, (2) the SN Ia contribution to the metal budget decreases steeply with redshift and by $z \approx 1$ is already less than half of the local amount and (3) a transition in the abundance ratios relative to the Iron is present between redshifts $\approx 0.5$ and 1.4, with core-collapse SN products becoming dominant at higher redshifts.

Key words: galaxies: cluster: general – X-ray: galaxies – intergalactic medium – cosmology: observations.

1 INTRODUCTION

The primordial cosmic gas is composed by Hydrogen (about 75 per cent by mass), Helium ($\sim 24$ per cent), and traces of other light elements, like Deuterium, Helium-3, Lithium and Berillium. When this gas collapses into the dark matter halos typical of galaxy clusters ($\gtrsim 10^{14} M_{\odot}$), it undergoes shocks and adiabatic compression, reaching densities of about $10^{-3}$ particles cm$^{-3}$ and temperatures of the order of $10^9$ K. For these physical conditions, the plasma is optically thin and its X-ray emission is dominated by thermal bremsstrahlung processes. Its enrichment by metals (i.e. elements with atomic number larger than 5) proceeds by the releases to the medium of the products of the star formation activities that take place in the member galaxies.

An effective way to estimate the metal abundance by number relative to Hydrogen is to measure the equivalent width of lines emitted by highly ionized elements (e.g. Mushotzky et al. 1996, Fukazawa et al. 1998, Finoguenov, David & Ponman 2000) and then with the observatories of the new generation, such as Chandra (e.g. Ettori et al. 2002, Sanders et al. 2004) and XMM-Newton (e.g. Böhringer et al. 2001, Gastaldello & Molendi 2002, Finoguenov et al. 2002).

A direct application of the detection of emission lines from these highly ionized elements is the possibility to describe the way the intracluster medium (ICM) is enriched of metals, whether by products from explosions of supernovae (SN) type Ia, mainly rich in Fe and Ni, or by outputs of collapsed massive stars (Core Collapsed SN), with relative higher contributions of $\alpha$-elements like O, Si, S. However, the ability to resolve and measure elemental abundances other than Iron, which was observed in the early days of the X-ray analysis of galaxy clusters (e.g. Mitchell et al. 1976, Serlemitsos et al. 1977) has required a significant improvement in the spectral resolution and sufficiently large telescope effective areas that have been reached initially with the X-ray satellite ASCA (e.g. Mushotzky et al. 1996, Fukazawa et al. 1998, Finoguenov, David & Ponman 2000) and then with the observatories of the new generation, such as Chandra (e.g. Ettori et al. 2002, Sanders et al. 2004) and XMM-Newton (e.g. Böhringer et al. 2001, Gastaldello & Molendi 2002, Finoguenov et al. 2002).

In the present work, we reverse the problem and infer from observed and modeled SN rates the total and relative amount of metals that should be present in the ICM both locally and at high redshifts. Through our phenomenological approach, we adopt the models of SN rates as a function of redshift that reproduce well both the very recent observational determinations of SN rates at $z \gtrsim 0.3$ (Dahlen et al. 2004, Cappellaro et al. 2005) and the measurements of the star formation rate derived from UV-luminosity densities and IR data sets. We then compare the products of the enrichment process...
Table 1. Adopted values for the average atomic weight (W), solar abundance by number with respect to Hydrogen (A, from Anders & Grevesse 1989), total synthesized isotopic mass per SN event (m_{Ia} and m_{CC} from Table 1 in Nomoto et al. 1997; nucleosynthesis products of SN Ia are those from the deflagration model W7, whereas SN CC yields are integrated over the mass range 10−50M_⊙ with a Salpeter IMF) and corresponding abundance ratios by numbers with respect to the Iron, with each abundance normalized to the solar photospheric value \( A(Y_i) = m_i/m_{Fe} \times W_{Fe}/W_i \times A_{Fe}/A_i \).

| metal | W   | A   | m_{Ia} | Y_{Ia} | m_{CC} | Y_{CC} |
|-------|-----|-----|--------|--------|--------|--------|
| Fe    | 55.845 | 4.68e-5 | 0.743 | 0.091 | 1.805 | 3.818 |
| O     | 15.999 | 8.51e-4 | 0.143 | 0.037 | 2.129 | 3.526 |
| Si    | 28.086 | 3.55e-5 | 0.153 | 0.538 | 0.122 | 2.284 |
| S     | 32.065 | 1.62e-5 | 0.086 | 0.585 | 0.041 | 2.284 |
| Ni    | 58.693 | 1.78e-6 | 0.141 | 4.758 | 0.006 | 1.647 |

The iron abundance determined with X-ray spectra, like O, Si, S and Ni, were investigated initially with data from ASCA, and more recently with the larger effective area and improved spectral and spatial capabilities of XMM-Newton (e.g. Tamura et al. 2004) present statistics of abundance ratios, also resolved spatially, for a sample of 19 objects observed with Chandra and presented in Tozzi et al. (2003) and Ettori et al. (2004a), that have a detection significant at the level of 2σ of the Iron line emission and for which a single emission-weighted temperature and the radial profile of the gas density were measured, we obtain a best-fitting log(M_{Fe}/10^{10}M_⊙) = 0.66(±0.06) + 1.47(±0.18) log(kT/5keV) (scatter of 0.23) and infer a total Iron mass for a 5 keV cluster at the median \( z = 0.63 \) of M_{Fe}(< R_{500}) = (2.7 ± 0.4) \times 10^{10}M_⊙, with a scatter limited within the values of (1.6, 4.6) \times 10^{10}M_⊙. These values are plotted in Fig. 1. We assume that most (if not all) of the mass of the metals is located within R_{500}, even though this radius encloses just about 13 per cent of the virial volume (R_{500} ≈ 0.5R_{vir}). A further contribution from the outer cluster regions is however marginal: from numerical simulation (e.g. Ettori et al. 2004b) and extrapolated data (e.g. Arnaud, Pointecouteau & Pratt 2005), one can estimate that M_{500}/M_{vir} ≈ 0.6 and, by assuming that in the outskirts (1) the metallicity is < 0.1 times the solar value, A_⊙, whereas its mean value in the central regions is about 0.3A_⊙, and (2) the gas follows the dark matter distribution, one can evaluate that M_{Fe}(R_{500} < r < R_{vir})/M_{Fe}(r < R_{500}) ≲ 0.2.

Apart from Fe, the most prominent lines detectable in X-ray spectra, like O, Si, S and Ni, were investigated initially with data from ASCA (an analysis of the average abundance of all the galaxy clusters in the ASCA archive is presented in Baumgartner et al. 2005) and more recently with the larger effective area and improved spectral and spatial capabilities of XMM-Newton (e.g. Tamura et al. 2004) present statistics of abundance ratios, also resolved spatially, for a sample of 19 galaxy clusters. In Fig. 1 we summarize these results by plotting the relative number abundance ratios. The Iron abundance is about 0.3A_⊙, although the ASCA measurements have a very narrow distribution around the mean of 0.27 (±0.01 at 90 per cent level of confidence) that departs significantly from the spatially resolved XMM-Newton estimates (only in the outer radius, between 200 and 500 h^{−1} kpc, where the Fe/H decreases by about a factor of 2 with respect to the central estimate, it becomes consistent with the ASCA mean with a value of 0.32 ± 0.08). Moreover, the O/Fe ratio is about solar, whereas the Si/Fe and S/Fe ratios are roughly super-solar and sub-solar, respectively. The average Ni/Fe ratio in the ASCA sample is about 3.4A_⊙, well in agreement with the original ASCA determination in the data of the Perseus cluster by Dupke & Arnaud (2001) and consistent with the XMM-Newton constraints in Gastaldello & Molendi (2004) and with the BeppoSAX results for a sample of 22 objects (Fig. 6 in De Grandi & Molendi 2002). On the other hand, it is worth mentioning that the measurements of the Nickel abundance becomes reliable only in hot (kT ≥ 4 keV) systems where the excitation of (mainly) K-shell lines makes them detectable in the spectrum around 8 keV, in a region less contaminated from blends with Iron but highly af-
3 ACCUMULATING THE METALS

The total predicted Iron mass is obtained as

$$M_{\text{Fe,SN}} = M_{\text{Fe,1a}} + M_{\text{Fe,CC}}$$

$$= \sum_{\Delta t, \Delta V} m_{\text{Fe,1a}} \times r_{1a}(dt) \times dt \times dV$$

$$+ \sum_{\Delta t, \Delta V} m_{\text{Fe,CC}} \times r_{\text{CC}}(dt) \times dt \times dV$$ (2)

where we assume $m_{\text{Fe,1a}}$ and $m_{\text{Fe,CC}}$ as quoted in Table 1 (from Nomoto et al. 1997) and an interval time at given redshift equals to $dt(z, z_1) = H_0^2 \int_{z_1}^{z} (1 + z)^{-1} \Omega_m(1 + z)^3 + (1 - \Omega_m - \Omega_{\Lambda}) (1 + z)^2 + \Omega_{\Lambda}^{\Lambda} - 0.5 \ dz$.

As cluster volume, we define the volume corresponding to the spherical region that encompasses the cosmic background density, $\rho_b = 3H_0^2/(8\pi G) \times \Omega_m \approx 4 \times 10^{10} M_\odot$.

$M_{\text{Fe,SN}}$, for the assumed cosmology, with a cumulative mass of $M_{\text{vir}} \approx 6.8(kT/5k_{\odot})^{3/2} \times 10^{14} M_\odot$, as inferred from the best-fit results on the observed properties of X-ray clusters with $kT > 3.5$ keV in Arnaud et al. (2005) and adopting $M_{\text{vir}}/M_{\text{CC}} \approx 0.6$.

Figure 1. Accumulation history of the Iron mass from $z_p = 10$ to $z = 0$, as obtained from equations (2) and (3). The solid line shows the sum of SN Ia (dashed line) and SN CC (dotted line) contribution. Horizontal lines indicate the redshift region where the SN rates are actually measured (Dahlen et al. 2004). The accumulation history is here compared to the total Iron mass measured in samples of local (De Grandi et al. 2004) and high-$z$ (Tozzi et al. 2003) galaxy clusters for a typical object at 5 keV. Error bars on the mean observed value and scatter (shaded region) around it are shown (see text in Section 2). The dot-dashed line indicates the expected Iron mass for a typical 5 keV cluster with $M_{\text{vir}} = 10^{15} M_\odot$, a gas mass fraction of 10 per cent and Iron abundance of 0.3A_⊙.

Figure 2. Predictions (big dots) of the local metal yields compared with the X-ray measurements in Tamura et al. (2004; case for a medium-T cluster in Table 6 with estimates in the three radial bins 0 - 50, 50 - 200 and 200 - 500h^{-1} kpc; diamonds) and Baumgartner et al. (2005; 4.5 keV bin in Table 4; triangles). Error bars at 1σ level are indicated. The abundance measurements are relative to the Anders & Grevesse (1989) solar photospheric values quoted in Table 1.

Given the differences between the two data sets, and the fact that the XMM-Newton estimates are spatially resolved and thus sensitive to the presence of any gradient that instead is washed out in the global measurement shown here from ASCA, they are considered independently in the following analysis.
unit formed stellar mass and is function of the delay time distribution function \( \phi(t_d) \) that represents the relative number exploded at a time \( t_d \) since a single burst of star formation; \( t_F \) is the time of formation of the first stars and corresponds to \( z_F = 10 \); the normalization \( k \) is the number of CC progenitors per unit of formed stellar mass; \( h \) is the Hubble constant in unit of 100 km s\(^{-1}\) Mpc\(^{-1}\). In the following analysis, we adopt a “narrow” Gaussian form for \( \phi(t_d) \), with a delay time \( \tau = 4 \) Gyr and \( \sigma_{t_d} = 0.2 \tau \) that better fit both the local (\( z \lesssim 0.1 \)) rates and the GOODS data (Stronger et al. 2004, Dahlen et al. 2004) and fix \( \nu = 0.0010 \). We assume \( k = 0.0069 M_\odot^{-1} \) as appropriated for CC progenitors masses in the range \( 8M_\odot \lesssim M \lesssim 50M_\odot \) with a Salpeter (1955) Initial Mass Function (IMF). We show in Fig. 4 the relative rates of SNe CC and Ia as function of redshift: this ratio ranges between 2 and 3 up to \( z \approx 1 \) and increases steeply at higher redshifts, with the “narrow” Gaussian function that provides a SN Ia rate at \( z \approx 2 \) lower by an order of magnitude than the other delay time distribution functions.

Regarding the adopted delay time, we mention here that Gal-Yam & Maoz (2004) and Maoz & Gal-Yam (2004) support the argument that some current data on the cosmic (field) star formation history require for the observed rate of SNe Ia a delay time larger than 3 Gyr. Combining this with the low observed rate of cluster SN Ia at \( z < 1 \), they conclude that the measured amount of Iron in clusters cannot be produced mainly by SNe Ia explosions but, more probably, must be produced via outputs of SNe CC originating from a top-heavy IMF. The reader is referred to the above-mentioned work for a detailed discussion on the effects of the assumed IMF on the SN rates. Our approach here is to use the best phenomenological models of cosmic star formation history to infer the corresponding cluster metal accumulation history and to compare some predictions with the observational constraints available.

To produce the cluster metal accumulation history, we have to take into account the fraction of the total produced Iron mass that remains locked up in the stars. The fraction of the total Iron that is then released to the ICM is estimated by considering that \( M_{\text{Fe, tot}} \approx Z_{\text{ICM}} M_{\text{ICM}} + Z_{\text{star}} M_{\text{star}} \). We adopt \( Z_{\text{ICM}} \approx 0.3 Z_\odot \) (see Fig. 2, Table 2 and 3 in Portinari et al. 2004). Therefore, \( M_{\text{Fe, ICM}} = M_{\text{Fe, tot}}/(1 + f_2) \), where \( f_2 = M_{\text{star}}/M_{\text{ICM}} \times Z_{\text{star}}/Z_{\text{ICM}} \approx 0.59 \). Considering its weak dependence upon time (see, e.g., Table 2 and Fig. 3 in Portinari et al. 2004), we neglect the evolution of the locked-up fraction.

In Fig. 4 we plot the results of the expected Iron mass compared to the observational results discussed in Section 2. The predicted amount is well in agreement with the observed Iron mass in local clusters. At a median redshift of 0.05, the De Grandi et al. sample has a mean \( M_{\text{Fe}} \) associated to a 5 keV object that is between 30 (when the \( M_{\text{vir}} - T \) relation from simulations is adopted) and 60 (with the observed \( M_{\text{vir}} - T \) relation) per cent higher than the Iron mass accumulated in the ICM through SN activities from \( z = 10 \). The latter value is, however, well within the scatter in the observed distribution. At higher redshift, the observed central value in the Tozzi et al. sample of Fe abundance measurements is a factor of about 3 higher than the predicted one.

It is worth noticing that this result does not depend significantly upon either the delay time distribution function adopted to calculate \( r_{\text{fe}} \) or the SN CC and Ia compilations assumed. The changes in the total Iron mass accumulated at \( z = 0.05 \) are in the order of 10 per cent when different \( \phi(t_d) \) are considered and of about 40 per cent (i.e. the ratio of the observed and the predicted...
values ranges between 1.0–1.2 and 1.4–1.8; see Table 2 when we use the calculations of SN CC explosions in two extreme cases presented in Woosley & Weaver (1995) and described at the end of this Section.

Note that, if the SN Ia rate in number per comoving volume and rest-frame year is converted to supernova unit (1 SNu = 1 SN per 100 year per 10^15 hL⊙ Mpc^-3) which evolves as (1 + z)^1.9 (see Dahlen et al. 2004 for the caveats in using such conversion for rates estimated on cosmological distances), we obtain a local (z ∼ 0.05) rate of 0.25 and 0.79 SNu for SN Ia and CC, respectively. By integrating the SNu values over the cosmic time, we measure a local M_{Fe}/L_{BB} of ~ 0.0020 and 0.0010h^2_0 as due to SN Ia and CC, respectively, with a dependence upon the redshift very similar to what is shown in Fig. 1. The sum of these values is still a factor between 3 and 5 lower than the present estimate in galaxy clusters: this estimate, however, is affected from the extension of the cluster region considered to measure B-band luminosities and Iron mass distribution (see discussion in the uncertainties of these measurements in De Grandi et al. 2004, Sect.3.2). Therefore, even though we solve most of the discrepancy between predicted and measured Iron mass in typical galaxy clusters through models of SN rates that make use of the number of SN per comoving volume and rest-frame time, some difficulties remain in recovering the observed M_{Fe}/L_{BB} ratio through a direct, but not straightforward (given the evolution with redshift of the B-band luminosity density), conversion to the number of SN per unit of B-band luminosity (e.g. Arnaud et al. 1992, Renzini et al. 1993). Regarding the latter issue, note that the suggested solution of an increase of the SN Ia rate in E/S0 galaxies by a factor of 5–10 at higher–z is partially taken into account in the models presented here (see, e.g., Fig. 3), where the SN Ia rate is enhanced by a factor of ∼ 5 from z = 0 to z = 0.8, but then decreases rapidly beyond it.

We can now extend these considerations to the enrichment history of the metals other than Fe. To infer these, we adopt, as done in the X-ray analyses presented above, the solar abundances tabulated in Anders & Grevesse (1989) and the most recent and widely used theoretical metal yields of Nomoto et al. (1997) for (i) SNe CC integrated between 10 and 50M⊙ for a Salpeter IMF (see Nakamura et al. 1999 on the uncertainties related to the adopted mass cut that can change the Nickel yield by a factor of 2) and (ii) SNe Ia exploding with fast deflagration according to the W7 model. All the numerical values considered here are presented in Table 1. We note that the values presented in Nomoto et al. (1997) are plotted relative to the solar photospheric abundance in Fe, O, Si, S and Ni, respectively. We have, however, adopted the Anders & Grevesse values for consistency between models and observational constraints.

Given a metal i, its total mass is estimated as

\[ M_i = M_{i,1a} + M_{i,CC} \]

\[ = \sum_{dt, dV} m_{i,1a} \times r_{1a}(dt) \times dt \times dV + \sum_{dt, dV} m_{i,CC} \times r_{CC}(dt) \times dt \times dV \]

\[ = (M_{Fe,1a} Y_{1a} + M_{Fe,CC} Y_{CC}) \frac{W_i A_i}{W_{Fe} A_{Fe}}, \]

(4)

where the synthesized masses for each element of interest, m_i, or the corresponding abundance yields, Y, are presented in Table 1.

One direct way to check the consistency of these models is to compare the ratio between some of the most prominent elements detectable in X-ray spectra and the Iron. To this purpose, we overplot in Fig. 2 the abundance ratios inferred from the models to the observational constraints on the O/Fe, Si/Fe, S/Fe and Ni/Fe discussed in Section 2. The agreement is remarkably good for what concerns the XMM-Newton means and the ASCA Ni/Fe measurement. A larger departure appears between the model prediction and the result for the S/Fe estimate from ASCA. We can evaluate the agreement by calculating the \( \chi^2 \) given the observational constraints (with the relative errors) and the predicted values. We obtain a \( \chi^2 = 3.1 \) (3 degrees of freedom) for the XMM-Newton data, which is statistically acceptable \( \left[P(\chi^2 > \chi^2_{obs}) = 0.63\right] \) and is, however, the largest value measured for any delay time distribution functions: the “wide” Gaussian and the e−-folding form (see caption of Fig. 2) give a \( \chi^2 \) of 2.2 and 2.3, respectively (see Table 2).

It is worth noting that the Si/Fe ratio alone contributes about 2.2 to the total \( \chi^2 \), owing to the over-predicted amount of Silicon by ~ 40 per cent. On the other hand, the ASCA measurements provide a \( \chi^2 \) of about 10.0 [3 degrees of freedom, \( P(\chi^2 > \chi^2_{obs}) = 0.098\)] mainly due to the over-prediction of the S/Fe ratio by 80 per cent. We have also considered alternative SN CC and Ia compilations to the Nomoto et al. one, adopted here as reference. Following the discussion in Gibson, Loewenstein & Mushotzky (1997) on the uncertainties related to the physics of exploding massive stars, we consider two extreme conditions for the explosion of SN CC as indicated in Woosley and Weaver (1995), namely case A with metallicity equals to 10^-4 solar and case B with solar metallicity. Both the models provide best-fit results worse than the Nomoto et al. one, with a \( \chi^2 \) of 9.3 and 3.1 (case A and B, respectively) when compared to the Tamura et al. abundance ratios and 42.5 and 21.0 when compared to the Baumgartner et al. values (see Table 2). Moreover, we consider SN Ia models with a delayed detonation induced from deflagration at low density layers (model WDD2 in Nomoto et al. 1997) that seems to reproduce well the observed yields in the outer regions of M87 (Finoguenov et al. 2002). This model doubles the amount of Si (\( m_{Si} = 0.27 M_{⊙} \), \( Y = 1.01\)) and S (\( m_{S} = 0.17 M_{⊙} \), \( Y = 1.20\)) and reduces the Ni ejecta by 70 per cent (\( m_{Ni} = 0.04 M_{⊙} \), \( Y = 1.40\)) with respect to W7, amplifying any mismatch with the observational mean values so that the \( \chi^2 \) increases to ~ 8 and 38 when model predictions are compared with data from Tamura et al. and Baumgartner et al., respectively. We thus exclude the possibility that this model of SN Ia explosions can explain the present results on the overall enrichment history of galaxy clusters better than W7.

We can now trace back the abundance ratios as function of redshift (see Fig. 4 and 5) and, given this history of the metals accumulation in galaxy clusters, plot in Fig. 6 the relative contribution in mass of the SN Ia products to the total material of each elements investigated (i.e. O, Si, S, Fe and Ni) available in the cluster baryon budget as function of redshift.

Locally, 51 per cent of Iron, 1 per cent of Oxygen, 14 per cent of Silicon, 21 per cent of Sulfur and 75 per cent of Nichel are produced from SN Ia explosions. These values change only by few (≤ 3) per cent by adopting different delay time distribution functions and by ≤ 10 per cent when the two other extreme cases of SN CC explosion are considered. We conclude that these predictions for nearby clusters are particularly stable and robust. As expected from the relative increase of SNe CC, the SN Ia contribution to the metal budget decreases significantly at higher redshifts, becoming
 responsible for less than half of the metal masses observed locally at \( z \approx 1 \). More interestingly, the predicted evolution in the Iron abundance, although significantly steepens up to \( z \approx 1 \) where the expected value is half of the local one, is still consistent with observational constraints obtained from a sample of Chandra exposures of 49 clusters at redshift \( z > 0.3 \) (Fig. 5).

4 SUMMARY AND DISCUSSION

We summarize here our main findings on the history of the metals accumulation in the ICM. By using the rates of SNe Ia and CC as observed (at \( z < 1.6 \) and \( z < 0.7 \), respectively) and modelled from the cosmic star formation rate derived from UV-luminosity densities and IR data sets (Dahlen et al. 2004, Strolger et al. 2004) and adopting theoretical yields (as described in Table 1), we infer how the metals masses in the ICM are expected to accumulate as a function of the redshift.

We find that these models predict that the total Iron mass accumulated in massive galaxy clusters through SN activities is between 24 and 75 per cent \((235-359 \text{ per cent})\) lower than the Iron mass estimated in local \((\text{high} - z)\) systems as determined through the equivalent width of the emission lines detected in X-ray spectra \((\text{e.g. De Grandi et al. 2004, Tozzi et al. 2003})\). This discrepancy is reduced by about 20 per cent when the cluster volume used to accumulate the SN products as a function of time is defined by adopting an average virial mass from numerical simulations instead of the value extrapolated from the observed X-ray scaling relationships \((\text{e.g. Ettori et al. 2004b, Arnaud et al. 2005})\). Because of this kind of uncertainty in relating the cluster gas temperature to the associated virial and Iron masses, we conclude that the agreement between the expected and measured Iron mass, even though marginal, is acceptable within the observed scatter. Moreover, we can reproduce the relative number abundance of the most prominent metals detectable in an X-ray spectrum, such as Oxygen, Silicon, Sulfur and Nickel with respect to the Iron as estimated for nearby bright objects observed both with ASCA (Baumgartner et al. 2005) and XMM-Newton (Tamura et al. 2004). We also show that the predicted evolution in the Iron abundance, which should decrease by a factor of 2 at \( z \approx 1 \) with respect to the local value, is in good agreement with the current observational constraints obtained from a sample of 49 clusters at \( z > 0.3 \) (see Fig. 5).

By using these models to describe the ICM enrichment, we can infer the relative SN contribution to the amount of elements present in galaxy clusters as function of the cosmic time. At increasing redshift, the products from SNe CC become dominant, owing to the steep rise of their relative rate with respect to SNe Ia. The transition occurs between \( z = 0.5 \) and 1.4, with an enhancement of the \( \alpha \)-elements with respect to Fe \((\text{e.g. O/Fe and S/Fe ratios increase by a factor of more than 2})\) and a drastic decrease of the Ni/Fe ratio (see Fig. 4). Then, the fractions of metals mass due to SN Ia outputs, which are locally about 51, 75, 1, 14 and 21 per cent of the total for Iron, Nickel, Oxygen, Silicon and Sulfur, respectively, halve at \( z \approx 1 \) (Fig. 6), almost independently from the adopted delay time distribution functions and models for SN CC explosions. When the assumed SN rates \((\text{number per co-moving volume per rest-frame year})\) are converted to units of the B-band luminosity \((\text{but see caveats in Dahlen et al. 2004})\), which is well mapped only in nearby galaxy clusters, we show that the expected total \( M_{\text{Fe}}/L_B \) is still below the local measurement by a factor between 3 and 5 and that SN Ia metal production contributes by \( \approx 70 \) per cent. We conclude that this well-known \((\text{e.g. Arnaud et al. 1992, Renzini et al. 1993})\) underestimate of the local \( M_{\text{Fe}}/L_B \) value cannot be explained with an increase in the SN rates at higher redshift, according to the present models.

The changes by a factor of 2 in the abundance ratios at \( z > 0.5 \) arising from the predominance of the enrichment through SNe CC might be investigated in the near future with X-ray spectroscopically resolved metal abundance estimates in high-redshift galaxy clusters. We are attempting this with our Chandra and XMM-Newton data set of high- \( z \) objects (Tozzi et al. 2003, Ettori et al. 2004a), with expected relative uncertainties on the abundance ratios of larger than \( \approx 20 \) per cent at the 1\( \sigma \) level (see, for example, Fig. 5). These X-ray satellites offer the best compromise available at present between field-of-view, effective area, and the spatial and spectral resolution required to pursue such a study. Only

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Table 2. Tests performed on the different SN Ia \((W7, \text{WDD2})\) and CC \((N97, \text{WW95A, WW95B})\) models and delay time distribution function \( \phi(t_d) \) (narrow Gaussian, wide Gaussian, exponential form) adopted. The first column indicates the change with respect to the favored model shown in the first row: W7 deflagration model of SN Ia products, Nomoto et al. 1997 \((N97)\) compilation of SN CC outputs and a “narrow” Gaussian delay time distribution function. The 5 tests done are: comparison between the observational constraints \((\text{from De Grandi et al. 2004 and Tozzi et al. 2003})\) on the total amount of Iron mass, \( M_{\text{Fe}} \), produced at the median redshift of 0.05 and 0.63 in a typical cluster of 5 keV and the predicted value, \( M_{\text{Fe}} \), both using a \( M_{\text{vir}} - T \) relation from simulations \((\text{low end})\) and from observations \((\text{high end}; \text{2nd and 3rd column})\); comparison of the relative change of the Iron abundance with redshift with 49 measurements done between redshift 0.3 and 1.3 \((\text{Fig. 5}; \text{4th column})\); comparison of the abundance ratios observed in a sample of nearby clusters with XMM-Newton \((\text{O/Fe, S/Fe, Si/Fe; Tamura et al. 2004; 5th column})\) and ASCA \((\text{Si/Fe, S/Fe, Ni/Fe; Baumgartner et al. 2005; 6th column})\).

| models | \( \chi^2 \text{(dof)} \) vs \( Fe(z) \) | \( \chi^2 \text{(dof)} \) vs XMM | \( \chi^2 \text{(dof)} \) vs ASCA |
|--------|---------------------|----------------------|----------------------|
| \((W7, N97)\) | 1.29–1.58 | 2.58–3.16 | 0.64 (5) | 3.1 (3) | 10.0 (3) |
| \((WDD2, ..., ...)\) | 1.33–1.62 | 2.64–3.22 | 0.64 (5) | 8.1 (3) | 37.5 (3) |
| \((..., WW95A, ...)\) | 1.43–1.75 | 2.94–3.59 | 0.66 (5) | 9.3 (3) | 42.5 (3) |
| \((..., WW95B, ...)\) | 1.02–1.24 | 1.92–2.35 | 0.66 (5) | 3.1 (3) | 21.0 (3) |
| \((..., ..., e--fol)\) | 1.20–1.47 | 2.48–3.03 | 0.68 (5) | 2.2 (3) | 8.9 (3) |
| \((1.22–1.49)\) | 2.33–2.85 | 0.74 (5) | 2.3 (3) | 9.0 (3) |
Brief history of the metal accumulation in the ICM

Figure 5. (Upper panel) Distribution of the metal abundance as a function of redshift for a sample of Chandra exposures of 49 galaxy clusters at $\text{z} > 0.3$ and gas temperatures between 3.4 and 15.5 keV (Balestra, Tozzi, Rosati, Ettori et al. in preparation, which will present the metallicity measurements for a sample larger by a factor of $\sim 3$ than the one presented in Tozzi et al. 2003, with upgraded calibration files and extended statistical analysis). The diamonds refer to the median distribution of 10 Iron abundance measurements per redshift bin. (Lower panel) Predicted and observed Iron abundance as a function of redshift. The diamonds refer to the median distribution shown in the upper panel. The normalization of the predicted evolution is here fixed equal to the first measured bin at $\text{z} \approx 0.4$. The lines refer to different SN explosion models and delay time distribution functions with respect to the reference values indicated by the solid line (dashed line: Woosley & Weaver SN CC models, case A -thin line- and B -thick line-; dotted line, from the thinnest to the thickest line: WDD2 SN Ia model, wide Gaussian and $e-$folding form).

Figure 6. Metal mass fraction resulting from SN Ia ejecta as a function of redshift.

with XEUS$^1$ and its sensitivity greater by two orders of magnitude than that of XMM-Newton and a spectral resolution of the order of 10 eV or less, will it be possible to investigate with significantly higher accuracy the metal budget of the ICM in high-$\text{z}$ systems.

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