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ROLE OF CLUSTERS OF GALAXIES IN THE EVOLUTION OF THE METAL BUDGET IN THE UNIVERSE.

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ABSTRACT

Using the guidelines on SN element production provided by XMM-Newton, we summarize the results of ASCA observations on the element abundance in groups and clusters of galaxies. We show that while the metal production in groups could be described by a stellar population with a standard local IMF, clusters of galaxies require a more top-heavy IMF. We attribute an excess heavy element production to an IMF evolution with redshift. Dating the galaxy formation in clusters by observations of the star-formation rate, we conclude that the IMF variations have occurred preferentially at $z \gtrsim 4$. We further combine our metallicity measurements with the mass function of clusters to estimate the role of clusters in the evolution of the metal content of the Universe. We argue that at no epoch stars are a major container of metals, unless groups of galaxies are not representative for the star-formation. This lends further support for the reduced (0.6 solar) mass-averaged oxygen abundance in the stellar population.

Subject headings: galaxies: intra-galactic medium; clusters: cosmology; cosmic star-formation

1. INTRODUCTION

The amount of baryons found in clusters of galaxies by X-ray observations is similar to the amount of baryons locked in stars (Fukugita, Hogan, Peebles 1998, hereafter FHP). The high element abundance found in the cluster gas makes cluster metals a significant entry in the total metal budget of the Universe. Moreover, the flat radial abundance profiles of alpha-chain elements (O, Mg, Si) in clusters suggest that the enrichment by SN type II (which are responsible for 90% of metal mass production, as opposed to only 25% SN II contribution to Fe) occurred before the cluster collapse (Finoguenov et al. 2000, 2001a, 2002b). Comparison with the predictions of cluster formation in a low density Universe (as inferred by recent observations) suggests that this enrichment should occur at redshifts greater than 3. In comparison with the expectations for the total metal budget at that time (e.g. Pagel 2002), clusters contain a significant fraction of the metals, produced at high redshift. Direct observations at high redshifts have not yet revealed the objects that account for metal production associated with the observed star-formation rate density (Pettini et al. 1999).

In this *Paper* we will consider a detailed analysis of the cluster contribution to the metal balance in the Universe by combining the REFLEX (Böhringer et al. 2001) results on the cluster mass function with ASCA (Tanaka, Inoue, Holt 1984) results on the cluster metal abundance and a preheating approach to explain the properties of groups of galaxies. Suggesting cluster metals as an explanation for the missing metal problem at high z, places the requirement on the top-heavy IMF needed to explain the cluster metals at the redshift where such deviations have recently been suggested from observations (Hernandez & Ferrara 2002). Knowledge of IMF provides a key ingredient for understanding the light-to-star-formation conversion, as well as the association of a stronger feedback to high-redshift star-formation.

We adopt $H_\circ = 70$ km s^{-1} Mpc^{-1} to provide an unbiased comparison between measured and theoretical values. The dependence of the luminosity distance (D_L) on the deceleration parameter ($q_\circ = 0.5$ in our study) has a negligible effect (less than 5%) on the results, as this is a fossil record study of nearby systems.

2. DATA

We collect the measurements of the ICM heavy element abundance, gas content, and optical light for a sample of 44 groups and clusters from Finoguenov et al.(2000; 2001; 2002a). Our sample constitutes $\sim 70\%$ of HIFLUGS, a complete sample of bright clusters of galaxies and thus could be taken as representative. Given the limited number of systems, we divide the sample into three categories, that approximately correspond to a general census for groups, poor and rich clusters.

A comparison among the systems is done at radii of equal gravitational matter overdensity, which have been shown to correspond to similar morphological mixes of galactic types and heavy element abundance content of the ICM (Dressler et al. 1997; Cen & Ostriker 1999; Finoguenov et al. 2001a). This scaling is also preferred from the point of view of cluster hydrodynamics (Evrard, Metzler, Navarro 1996). In view of our goal to understand the metal budget, it is crucial to provide measurements at as large radii as possible. Given the coverage of the clusters in our sample, we select the radii of equal overdensity corresponding to $0.4 r_{100}$ radius, where r_{100} is a virial radius in a flat $\Omega_{m,\circ} = 0.3$ ΛCDM universe (Pierpaoli, Scott, White 2001). For this comparison the r_{100} is estimated by rescaling the $r_{500} - T$ relation of Finoguenov, Reiprich, Böhringer (2001b), assuming a NFW mass density profile (Navarro, Frenk & White 1996).

In Fig.1 we show the properties of the sample. The sample is binned and averaged according to the X-ray temperature, taken as a measure of the mass of the system

($kT \sim M_{total}^{1.6}$, e.g. Finoguenov et al. 2001b). The three bins, shown in Fig.1 correspond to the virial masses in the 0.3–1, 1–4, 4–14 $10^{14} M_{\odot}$ intervals. We plot the total gravitational mass-to-light ratio, gas mass-to-light ratio, and the values for Υ_{Fe} and Υ_{Si}, where Υ_{Fe} and Υ_{Si} are Fe and Si mass to L_B ratio, normalized to the solar values of 0.00128 and 0.000702, respectively (calculated using the meteoritic values from Anders & Grevesse 1989). We use the cumulative values for gas, Fe, and Si mass, as well as optical light, obtained using the spatially resolved measurements, as presented in Finoguenov et al. (2000, 2001a,b). Deviations of the points around the mean value have been studied by Finoguenov et al. (2001a). A significant spread of values was found for the SN Ia products and was successfully interpreted as an effect arising from the spread in the cluster formation epochs, characteristic for the conventional low Ω_m cosmologies, assuming the present-day SN Ia rate and the evolution of the SN Ia rate in agreement with existing measurements (Finoguenov et al. 2001a and references therein). At 0.4 r_{100} the cluster gas reaches the 0.10 fraction of the total mass, thus accounting already for more than 75% of the primordial baryon fraction with an additional $5-10$% of the primordial baryon fraction being presently locked in stars. Thus, we do not expect the gas fraction to be by more than 20% different at larger radii. Large amount of observational data on outskirts of groups and clusters of galaxies progressed our understanding on the non-gravitational effects (Tozzi & Norman 2001; Finoguenov et al. 2003a; Voit et al. 2003). Numerical simulations that allow for a wide spread of SN II products at the epoch of star-formation show that it does not prevent the gas from collapse on the potential wells of systems studied here (e.g. Finoguenov et al. 2003a; Tornatore et al. 2003). The lower fraction of gas reported here is understood as a larger extent of the gas halo around the groups in the virial units. Comparison of the distributions of the SN II and SN Ia products in Finoguenov et al. (2000) in terms of element abundance and mass-to-light ratio, suggests that the SN II products have been released into the ICM before the cluster collapse, while SN Ia products trace well the different spatial distribution between the gas and the stars inside the cluster (see also De Grandi & Molendi 2001). Since, as will be seen below, early-type galaxies account for most of the star-formation that happened inside the radius, where we observe the metals and the end of star-formation in ellipticals precedes the formation of the cluster (Thomas, Maraston Bender 2002), a release of the bulk of the SN II products should have happened before the accretion shock heating in clusters changed the relative gas-to-stellar mass distribution. To account for this difference (except in Fig.1, where the observed values are plotted), we use the presently observed gas mass in clusters to account for the contribution of SN Ia, while for SN II, we take the 0.12[1] (precollapse) gas fraction to estimate the SN II contribution to the Fe abundance (resulting in a factor of 1.8 higher SN II metal enrichment in groups).

The release of the bulk of SN II products prior to cluster virialization is a key assumption of the present work and all the conclusions derived here rely on it. This implies a dominant role of early galactic winds in the release of SN II products, as opposite to cluster environmental effects. Modeling of the cosmic star-formation rate requires the ejection of energy at early epochs ($z > 4$) to prevent overproduction of stars (e.g. Kaiser 1986; Tornatore et al. 2003; Benson et al. 2003) and at $z \sim 3$ to reproduce the properties of the star-formation in early-type galaxies (Tornatore et al. 2003; Oh & Benson 2003).

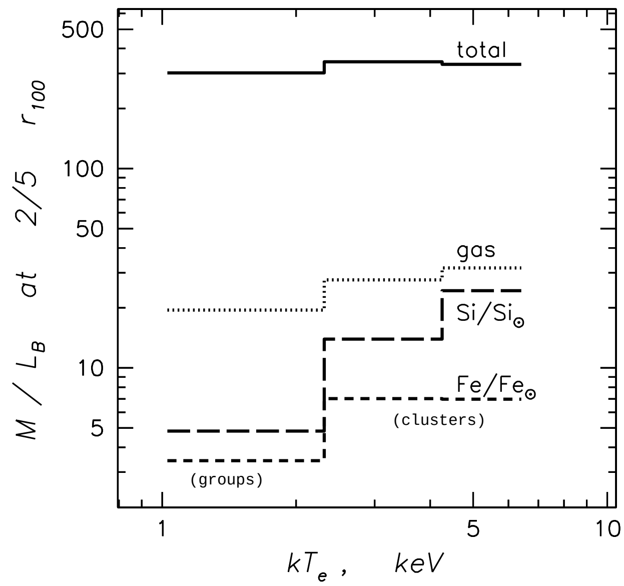

FIG. 1.— M-to-L_B ratios (Υ) in groups and clusters of galaxies vs the temperature of the ICM. The ratios of the cumulative values within $0.4 r_{100}$ are shown. The solid line indicates the ratios for the total gravitational mass, dotted line – for the gas. The short and long dashed lines represent respectively the values for Υ_{Fe} and Υ_{Si}, expressed in solar units.

Galaxies can be subdivided onto disks and bulges, that have different formation histories. Since our key assumption on the early release of SN II products is valid for bulges, but not valid for disks, we need to determine the relative importance of bulges and disks. To obtain the morphological fractions of galaxies, we relate the galaxy surface density Σ in units chosen by Dressler et al. (1997) to mass overdensity δ by

$$log_{10}(\Sigma) = 0.58 \times log_{10}(\delta) - 0.40, \quad (1)$$

using Eq.1 in Finoguenov et al (2000), the NFW profile, using the measurements of radii of an overdensity of 500 from Finoguenov et al. 2001b, and accounting for different assumptions in the Hubble constant. While we use the Dressler relation established for local clusters, and it has been shown by Helsdon & Ponman (2003), that, accounting for the difference in the projection to Σ (which we implicitly do by adopting a scaling with δ), groups statistically obey the same relation. Using the Eq.1, morphological fractions of E:S0:Sp within a radius of $0.4 r_{100}$ are found to be 0.27:0.46:0.27. To obtain the luminosity density fractions, we multiply the morphological fractions by 1.9, 1.3, and 1.2 for E, S0, and Sp galaxy types, correspondingly, and renormalize. These conversion factors are taken from Arnaud et al. (1992) and were rescaled from V to B band by multiplying the correction for Sp by 1.2 (*e.g.* Postman & Geller 1984). The next step is to calculate the relation between the observed light and the integrated initial mass of the stars, which we denote as $M_{*,o}$

[1]a somewhat larger value, 0.14, would be more consistent with the recent WMAP result (Spergel et al. 2003)

(and its ratio to the present L_B light as $\Upsilon_{*,o}$), assuming conversion factors of 6.5 and 1.5 for bulges and disks, respectively (thereby assuming a Salpeter IMF[2]) as well as a disk fraction in different galaxies as in FHP. This translates into the following luminosity fractions of bulges and disks: $L_B(spheroidal) : L_B(disk) = 0.74 : 0.26$ at 0.4 r_{100}, with the following contribution to $\Upsilon_{*,o} = 4.8 + 0.4 = 5.2$. We find therefore, that the cumulative initial stellar fraction of total baryons amounts to 12%, similar to the K-band estimates (Lin, Mohr, Stanford 2003). Recent observations of diffuse extra-galactic emission in Coma of $L_B \propto 10^{11} L_\odot$, suggests a contribution from IGSP (intergalactic stellar population) of 20% for the cluster total blue light (Gregg & West 1998) and is therefore negligible. Part of this limit could be attributed to the contribution of dwarfs. In the model of Gibson & Matteucci (1997), the expected range of $\Upsilon_{*,\mathrm{o}}$ from dwarf galaxies lies in the interval $2-6$, making a 10–20% change with lower values more probable.

To estimate the amount of metals associated with the present-day stellar population, we take $\Upsilon_* = 4$ for bulges, $\Upsilon_* = 1$ for disks, corresponding to the dynamical mass-to-light measurements (e.g. van der Marel 1991), and a solar Fe abundance. We distinguish them from the initial cumulative values by omitting the subscript 'o'.

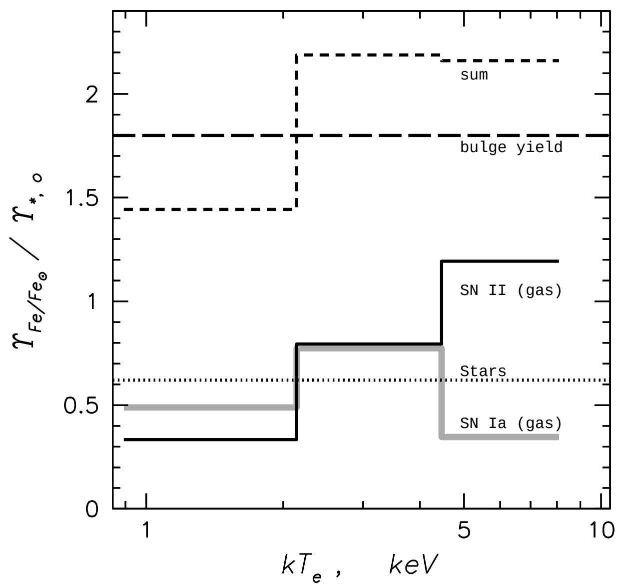

FIG. 2.— The Fe enrichment schemes in units of stellar yields. The bulge Fe enrichment amounts of 1.8 solar (Pagel 1987) and is shown by the long-dashed line. The stellar component in clusters is shown by the dotted line (assuming a solar value for the Fe abundance). The solid black (grey) line indicates the SN II (SN Ia) contribution to the Fe enrichment in groups and clusters. Cluster values are cumulative within a radius of 0.4 of r_{100}.

To determine the relative enrichment from different supernova types, we adopt the yields $y_{Si} = 0.12 M_\odot$, $y_{Fe} = 0.05 M_\odot$ for a SN II and $y_{Si} = 0.15 M_\odot$, $y_{Fe} = 0.74 M_\odot$ for a SN Ia, confirmed by analysis of clusters (Finoguenov et al. 2000). First XMM-Newton results on the SN Ia enrichment in the cores of bright cluster galaxies revealed larger Si/Fe ratio for SN Ia (Finoguenov et al. 2002b). However, with a larger gas-to-light ratio this ratio was found to approach the W7 yields, assumed here (Finoguenov et al. 2002b; Matsushita, Finoguenov, Böhringer 2003). Thus, for the region of study here, it is appropriate to assume the W7 SN Ia yields. Changing the assumed values within the uncertainty of the SN yields, does not change the separation onto SN II/Ia for clusters and has a small effect for groups. The presented separation using the W7 model maximizes SN II enrichment in groups. The uncertainty of the SN Ia and SN II contribution to $\Upsilon_{*,\mathrm{Fe}}$ is 20%. To guide the reader, the highest Fe yield from SN II observed in clusters correspond to a SN II contribution to the observed Fe abundance of 0.14 of photospheric solar units of 4.68×10^{-5} (0.20 in meteoritic solar units of 3.23×10^{-5}) for iron number abundances relative to H.

In Fig.2 we show the cumulative contributions from SN Ia and SN II to Fe mass within 0.4 of r_{100}. As can be seen in Fig.2, that although the effective iron yield is nearly the same between groups and clusters of galaxies and is similar to the bulge iron yield (Pagel 1987), the SN II contribution increases by a factor of 3–4 between groups and clusters of galaxies, which implies that there is no universal Silicon yield. In the following we will conventionally express this result in terms of the Oxygen yield, adopting the solar O/Si ratio from SN II in the ICM, as observed by XMM-Newton (e.g. Finoguenov et al. 2002b). The value for the effective Oxygen yield ($\Upsilon_{\mathrm{O}}/\Upsilon_{*,\mathrm{o}}$) amounts to 1.4 solar for groups and 4.1 solar for clusters, taking the measurements of the SN II element abundance pattern in the cluster gas of Finoguenov et al. (2002b). For comparison, the Salpeter IMF is characterized by one SN II per 100 solar mass of stars. For O and Fe yields of $1.7 M_\odot$ and $0.07 M_\odot$ per SN II, respectively, one finds a yield of 1.2 solar for O and 0.4 solar for Fe matching our results for the groups.

In the calculation of the effective O yield we assume a stellar Oxygen abundance of 0.6 solar, implied by the O abundance in early-type galaxies, as seen in the XMM-Newton EPIC and RGS observations centered on bright galaxies in groups and clusters (Peterson et al. 2002; Xu et al 2002; Matsushita et al. 2003; Buote et al 2003), which is compatible with the recent revision of the solar O abundance, which yields a value of 0.56 ± 0.06 (Allende Prieto, Lambert, Asplund 2001). A similar value is obtained from the chemical enrichment modeling of the LMC (Pagel & Tautvaisiene 1998). Higher values, however, are implied from the Mg abundance measurements (Edmunds & Phillipps 1997). The apparent contradiction between the measurements of the O yield from dwarf galaxies and the O yield implied by the Milky Way chemical enrichment schemes has been long known as an O yield problem (e.g. Pagel & Tautvaisiene 1998). First XMM-Newton results also reveal a variation in the Mg/O ratio (Matsushita, et al. 2003). All currently published XMM-Newton results on the O/Mg ratio in ISM/ICM seem to fit into a scheme, where a subsolar O/Mg ratio is characteristic of the stellar population (Xu et al. 2002; Matsushita et al. 2003; Peterson et al. 2002; Buote et al. 2003) and a solar O/Mg ratio is a characteristic of the ICM (Matsushita et al. 2003; Buote et al. 2003), with a difference in the ratios being a factor of 2. In calculating the metal budget, O plays a major role due to the high abundance of this element and as we will discuss below, the conclusion whether most of the metals (by mass) are in stars or gas, crucially depend on it. According to both X-ray gas — galaxy comparison and metal-poor vs metal rich stars, early chemical enrichment

[2]such an assumption for $\Upsilon_{*,o}$ correspond more to a Scalo IMF for solar metallicity stars (Maraston 1998)

has been characterized by an O/Mg ratio different by a factor of two. Such a behavior of the O/Mg ratio, probably originating from different averaging over the mass of SN II progenitors, makes it a tracer of the IMF, independent of the total element production. However, in this picture the Milky Way enrichment scheme is inconsistent with any scheme of early-type galaxy formation and cluster enrichment. Currently there are two approaches to model the end of star-formation in early-type galaxies, via ejection of the gas (e.g. Matteucci 1994) or strangulation of the gas accretion (White & Rees 1978; Finoguenov et al. 2003a; Oh & Benson 2002; Tornatore et al. 2003). The first scenario predicts stellar metallicities to form before or in parallel with the gas metallicities. The second scenario allows the gas metallicity to form much ahead of the stellar metallicity, as preheating of the gas surrounding the galaxy associated with its chemical enrichment prevents this gas from accretion onto the galaxy causing a global feedback effect. Thus, usage of the O/Mg ratio as a separate argument in favor of a variable IMF supports the results only within a certain scheme of galaxy formation.

3. IMF EVOLUTION WITH THE REDSHIFT

As discussed in the previous section, there is a difference in the effective O yields implied by the analysis of groups and clusters of galaxies. So far all interpretations of the differences in the content of SN II products between X-ray groups and clusters of galaxies focused on the escape of metals from groups (Fukazawa et al. 1998; Finoguenov et al. 2001a). High effective O yields, characteristic to clusters, cannot be obtained with the standard IMF (e.g. Kroupa, Tout, Gilmore 1993), appropriate for the star-formation processes observed at $z = 0$. In the X-ray regime we probe the systems covering two decades in mass ($10^{13} - 10^{15} M_\odot$). With only one decade more, including the groups with virial masses of $10^{12} M_\odot$ in the 2dF galaxy redshift survey, Martínez et al. (2002) account for most mass in the local Universe. Thus, X-ray groups are a link between the clusters and the field and a similarity in the chemical enrichment between groups and the field is hardly by chance. Finoguenov, Briel, Henry (2003b) find that the chemical enrichment of the X-ray filaments, which are a bona fide example of the field environment, is similar to that of groups. Based on these arguments, we consider variations in the IMF to occur only in massive clusters of galaxies and associate such changes to the high-redshift epoch of star-formation in clusters, following the theoretical work on the IMF (Padoan, Nordlund, Jones 1997; Larson 1998).

In the hierarchical clustering model we expect a growth of galactic halos of the same mass to occur earliest in the system of largest total mass, such as a protocluster. This scheme has been strongly suggested by the tightness of the scatter in the color-magnitude relation for cluster galaxies (Bower, Kodama, Terlevich 1998). To estimate the redshift of the star-formation in clusters we will use the extinction-corrected Madau plot in ΛCDM Universe (e.g. Somerville, Primack, Faber 2001) and an assumption that the star-formation density at high redshift is dominated by the formation of the protocluster galaxies[3], followed by proto-group galaxies and only then followed by the field. Numerical simulations as well as considerations using the mean stellar ages imply that the star-formation should decline at $z > 5$ (e.g. Springel, Hernquist 2003). We adopt a decline of star-formation inversely proportional to z at $z > 3$, so at $z = 6$ the star-formation rate is decreased by a factor of two compared to $z = 3$, which is consistent with current observational restrictions, discussed in Springel, Hernquist (2003; see references therein). We assume a linear rise in the star-formation rate with z at $z < 1$ with a plato in the $1 - 3$ interval at the level of $0.07 M_\odot$ yr^{-1} Mpc^{-3}. We note, that the conversion of luminosity density to the star-formation rate for some of the methods rely on the assumption of the Salpeter IMF, potentially leading to an overestimate of the star-formation rate, which could be of some importance for most massive clusters, where IMF variation are most strong.

$$\Omega_{*,\,\mathrm{cluster}} = \int_{t(z^{\mathrm{cluster}}_{\mathrm{upper\ limit}})}^{t(z=\infty)} \dot\rho_*(z(t))dt/\rho_{crit} \qquad (2)$$

where we estimate $\Omega_{*,\,\mathrm{cluster}}$ using the results from a complete X-ray survey of clusters of galaxies (REFLEX) on the cluster number abundance (Reiprich & Böhringer 2002), assuming stellar fraction of baryons of 12%, derived at $0.4 r_{100}$. Since the number abundance of clusters is a strong function of their mass, as compared to changes in the element abundance, we subdivided our sample onto four bins for further analysis. In the following we will use the terminology group and cluster to indicate trends with the mass of the system.

The above calculation provides an upper limit on the epoch of star-formation, as we neglect the part of the star-formation proceeding in parallel. To provide an estimate of the lower limit, we assume that most of the star-formation in the systems we study happened at $z > 2.5$,

$$\Omega_{*,\,\mathrm{cluster}} = \int_{t(z=2.5)}^{t(z^{\mathrm{cluster}}_{\mathrm{lower\ limit}})} \dot\rho_*(z(t))dt/\rho_{crit} \qquad (3)$$

At the peak star-formation rate of $0.07 M_\odot$ yr^{-1} Mpc^{-3} it takes only one Gyr to reproduce the stellar population in the groups and clusters of galaxies in the system mass range of the REFLEX sample, so the choice of the lower limiting redshift is very important, e.g. at $z < 2$ redshift-dependent effects could play no role in our sample. An independent check of our choice of the star-formation redshift is given by the relative importance of dwarf galaxies (Zabludoff, Mulchaey 2000), the tightness of the color-magnitude relation (Bower et al 1998), consideration of the feedback epoch (Finoguenov et al. 2002a), the delay between the formation epochs of bulges and ellipticals, and studies of the star-formation in the high-redshift progenitors of early-type galaxies (e.g. McCarthy et al. 2001). These arguments predict the star-formation epoch for early-type galaxies at around $z \sim 3$, therefore supporting our estimate of the redshift range. As was calculated above, recent episodes of star-formation, as traced by disks, account only for 7% of the total star-formation in clusters.

[3] Although, elliptical galaxies are thought to form most of their stars via starburst, deviating from the original method of Madau suitable for quiescent star formation, ellipticals should at least be present in the Madau plot based on the IR band studies.

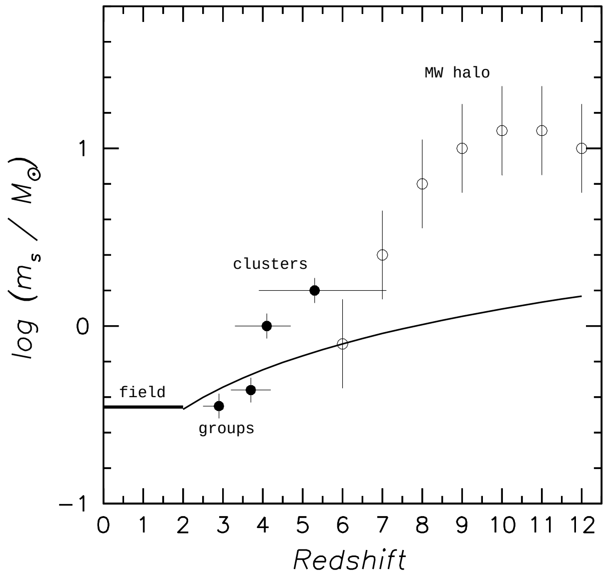

FIG. 3.— Inferred values of the scale mass of the IMF (m_s), as a function of redshift. Open circles denote the data from Hernandes & Ferrara (2001), filled circles denote the position of groups and clusters of galaxies. The solid curve gives the redshift evolution of the Jeans mass of cold star forming clouds, identified with m_s, resulting from the temperature evolution of the cosmic microwave background.

We describe the IMF ($N(m)$) variation by the typical mass, m_s, given by equation

$$dN/dlog\, m \sim (1+m/m_s)^{-1.35} \qquad (4)$$

from Hernandez & Ferrara (2001). The value of m_s, which is identified with the Jeans mass of cold star forming clouds, is judged from the amount of metals produced by stars in the $12-40 M_\odot$ range, compared to the stellar mass in the $0.6-1.1 M_\odot$ range. Such a choice of stellar mass range is made to be consistent with definition of Hernandez & Ferrara (2001). For the low mass range, it is important to calculate the resulting luminosity using the assumed IMF to weight the stellar tracks. The stars below $0.6 M_\odot$ do not contribute to the stellar light (e.g. Maraston 1998), so we do not consider them in our calculation. We have checked that using the $0.9-1.1 M_\odot$ range does not strongly change our derived values of m_s. Although, we do not calculate the light, the narrow range of mass for the low mass stars allows us to neglect the effect of differential averaging. As we have shown above, the amount of elements found in groups corresponds closely to the Salpeter IMF, which in the formulation of Hernandez & Ferrara (2001) corresponds to $m_s = 0.35 M_\odot$. We preset this mass scale for groups to provide an unbiased comparison to the data in Hernandez & Ferrara (2001). The obtained values of m_s for groups and clusters lie in the $0.35-1.6 M_\odot$ range, validating our simplified assumption on the equal Fe yield per SN II. We present the results of this analysis in Fig.3. Filled circles indicate our data. The points derived from the modeling of the element abundance in low-metallicity stars in the halo of the Galaxy by Hernandez & Ferrara (2001) are shown as open circles. One can see that the continuous change of the IMF between groups and clusters of galaxies lies on the continuation of the points derived from the low-metallicity stars. Faster-than-Salpeter fading of the light, deduced in LBG observations (Ferguson, Dickinson, Papovich 2002) further supports our conclusion on the biased IMF at high redshift ($z \sim 6$). The assumption of a top-heavy IMF to operate at high redshift is supported by the recent WMAP constraints on the reionization epoch (Cen 2003).

Our results limit the occurrence of the biased IMF to $z > 4$ and confirm the findings of Hernandes & Ferrara (2001) that changes in the IMF grow exponentially with the redshift, exceeding the effect, predicted based on the increase of the CMB temperature (Padoan et al. 1997). The fact that the enrichment of the intracluster gas is comparable to that of the halo stars, argues against strong effects of the environment on the physics of the star-formation.

Additional constraints on the assumed IMF shape, arise from the effects on the dynamical mass-to-light ratios in galaxies (Zepf & Silk 1996), variations in the SN Ia rates with redshift (Smecker & Wyse 1991), and C/O and N/O ratios in the metal poor stars (Gibson & Mould 1997). From the point of view of X-ray observations of clusters, the introduction of a varying IMF has only a 6% effect on increasing Υ_* and 20% on $\Upsilon_{*,\,o}$. Finoguenov et al. (2001a) showed that the observed amount of SN Ia products in clusters could be understood if the release of SN Ia products into the IGM occurs only when galaxies fall onto the cluster. This scenario explains the lack of the SN Ia products in most massive clusters. Alternative solution offered in Lin et al. (2003) consists in indication from a more precise K-band light measurements that in the massive clusters the stellar mass content is lower, that would solve the problem of SN Ia products, while it would make a need for a top-heavy IMF even stronger.

Consideration of C/O and N/O ratios should account for the variation in the O yield in SN II chemical enrichment. With improvement in the sensitivity and energy resolution at low energies, X-ray observations become sensitive to the measurement of the C and N abundance and a proper comparison will soon be possible.

4. METAL CONTENT OF THE UNIVERSE

To provide an insight into the role of clusters in the metal (all the elements excluding H and He) budget of the Universe, we compare the metal content in clusters with observations of other major metal entries. We use the results from a complete X-ray survey of clusters of galaxies (REFLEX) on the cluster number abundance (Reiprich & Böhringer 2002) and combine them with our metallicity measurements to calculate Ω_Z. Detailed measurements of the cluster mass and comparing the measurements using the virial units, strongly reduces the amount of baryons associated with massive virialized structures, compared to estimates of FHP. In addition, in calculating the metal budget, we take into account a decrease in the metallicity with decreasing mass of the system, substantially reducing the implied metal budget, compared to estimates of Pagel (2002). We use an estimate of the epoch of cluster enrichment, considered in the previous section, which puts cluster metals in place at $z \sim 3$ and implies no evolution of the cluster metal content since then. SN II are more frequent in the Universe (SNe Ia:II is 1:7 in the Milky Way) and produce more metal mass per event, compared to SN Ia. To go from Fe abundance to Z, we use our separation into SN II and Ia contributions, take only the SN II part and multiply it by the SN II metal-to-iron mass ratio. We take the SN II yields from Nomoto et al. (1997), corrected for yields of S and Fe, as implied by X-ray observations (e.g. Finoguenov et a. 2002b). In this calculation O makes up 75% of metals, with Ne, Mg and Si contributing another 21%. In the calculation of the lower limit we ignore the mass of C and N, the elements not yet measured in the ICM. We provide an upper limit on the metal mass in clusters including C and N at solar ratios to O, which increases the total mass of metals in clusters by 30%.

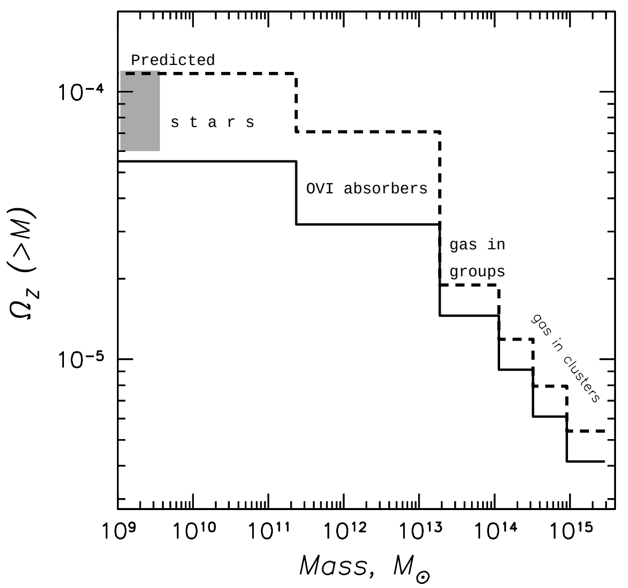

FIG. 4.— Local cumulative $\Omega_Z(>M) - M$ relation. Solid and dashed lines indicate a low and upper limit on the metal content, as explained in the text and detailed in Tab.1. Grey shade is indicating the range of predicted values.

Stars are known as an important metal entry at low redshift (Pagel 2002) and as we have shown above, also at high redshift, yet at progressively lower importance. To determine the Ω_Z of the stars at $z = 0$, we take a typical O abundance of 0.6 solar, as discussed above, and a 5–10% present-day stellar fraction of baryons in the field, obtained from the K-band observations (Balogh et al. 2001; Huang et al. 2002). At $z = 2.5$ we take an estimate of Dunne, Eales, Edmunds (2002), scaling it by 0.6 for self-consistency on the assumption of the O abundance in stars. We also consider two major baryon reservoirs, Ly_α and OVI absorbers. Ly_α absorbers account for most of the baryons at $z = 2.5$, contributing 0.3×10^{-5} to Ω_Z (Pagel 2002). At $z = 0$ Ly_α absorbers make up $32 \pm 6\%$ of Ω_b (Penton et al. 2002; McLin et al. 2002; Stoke et al. 2002). To estimate their metal contribution, we assume that Ly_α absorbers at $z = 0$ are a survived fraction of their $z = 3$ counterparts (Cen & Ostriker 1999) and that their metallicity does not evolve. To estimate the amount of metals associated with the OVI absorbers, we use a lower limit by Tripp, Savage, Jenkins (2000) and a value implied by ionization balance measurement of Mathur, Weinberg, Chen (2002). No assumption on the O abundance is needed to calculate the contribution of the OVI absorbers to the metal budget, while for the baryon budget, we assume $0.14 O_\odot$ (Finoguenov et al. 2003b). Both the metal and baryon inventory are detailed in Tab.1.

TABLE 1
INVENTORY OF METALS AND BARYONS IN THE UNIVERSE

Component	Ω_Z, 10^{-5}	Ω_b, 10^{-2}	Refs
$z = 0$			
Stars	2.3 – 4.6	0.2 – 0.4	(1,2,3)
X-ray gas, clusters	1.4 – 1.8	0.2	(1)
OVI absorbers	1.8 – 5.2	0.7 – 2.0	(1,8,9,10)
Ly_α forest	0.1	1.0 – 1.5	(6,7)
Total	5.6 – 11.7	2.1 – 4.1	(1)
Predicted	6 – 12	3.9	(1, 5, 11)
$z = 2.5$			
Damped absorbers	0.1	0.1	(5,11)
Ly_α forest	0.1 – 0.3	1 – 5	(5,11)
protocluster gas	1.4 – 1.8	0.2	(1)
ISM, dust	0.8 – 1.7	0.1 – 0.2	(4,1)
Total	2.4 – 3.9	1.4 – 5.5	(1)
Predicted	1.6 – 3.2	3.9	(1, 5, 11)

References: (1) this work; (2) Balogh et al. 2001; (3) Huang et al. 2002; (4) Dunne, Eales, Edmunds 2002; (5) Pagel 2002; (6) Stoke et al. 2002; (7) Cen & Ostriker 1999; (8) Tripp, Savage, Jenkins 2000; (9) Mathur, Weinberg, Chen 2002; (10) Finoguenov et al. 2003b; (11) Fukugita, Hogan, Peebles 1998

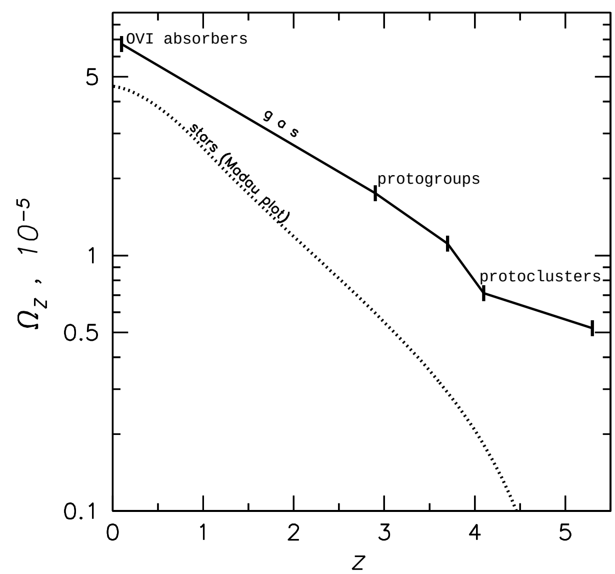

FIG. 5.— Evolution of Ω_Z with redshift. Black line represents the gas with labels indicating the major metal carrier at the redshift. The dotted line shows the contribution to Ω_Z from the stellar population. The Madau plot is normalized to the local K-band stellar baryon content and a mass-average stellar oxygen abundance is assumed to be 0.6 solar.

The entries in Table 1 include the proposed solutions for both the missing metals at high redshift (dust and/or warm gas in protoclusters) as well as missing baryons in the local Universe (OVI absorbers; Ly_α absorbers). So within the uncertainty of measurements, neither baryons nor metals are missing at either $z = 0$ or $z = 2.5$. In this comparison we do not list the groups with masses below the detection threshold of the REFLEX sample. Part of these systems, that have lowest masses should be observed as OVI absorbers and therefore we should not account for them twice. The exact separation between X-ray emitting and OVI absorbing systems is not entirely settled due to insufficient observational data on both sides. Since we adopt an optimistic estimate of the amount of baryons, associated with OVI absorbers, we consider it also as including the low-mass groups. There could be some metals left unaccounted, if they are associated with the groups, missed by both the OVI absorbers and REFLEX.

Fig.4 shows the cumulative distribution of the metals over the mass of the system and Fig.5 outlines the evolution of various components of Ω_Z with redshift. We specify two components, stellar and gaseous. For stars we use the Madau-plot, normalizing it to the local K-band estimate of the stellar content. For the metals in the gas we label the dominant component at each epoch. At any epoch, metals are contained mostly in the gas and not in the stars. This will no longer be true, once we assume a solar O abundance for the stars and would indicate that groups of galaxies are no longer representative of the star-formation processes.

5. CONCLUSIONS

We present the analysis of ASCA observations on the element abundance measurements in groups and clusters of galaxies, determined at $0.4r_{100}$. Using the results on the volume abundance of groups and clusters of galaxies, provided by the REFLEX survey, we study the role of metals associated with groups and clusters in the redshift evolution of the metal content in the Universe.

- Detailed considerations of the amount of star-formation reveal that the element production in groups is consistent with predictions for the Salpeter IMF. Prevalence of the Salpeter IMF on the mass scales just a factor of 10 smaller, argues in favor of the assumption made here that groups do not loose SN II products.

- The deviation in the chemical enrichment between groups and clusters of galaxies, when described as an IMF variation with redshift, requires the occurrence of strong IMF evolution at $z \gtrsim 4$.

- The star-formation is guided by the IMF variation with redshift, rather than environment, since our conclusions on the IMF evolution agrees well with independent method of Hernandez & Ferrara 2001, applied to the Milky Way halo.

- Proto-groups and proto-clusters of galaxies are an important reservoir of metals at high redshift, and together with the dusty ISM of galaxies provides a solution to the missing metal problem.

- If star-formation in groups could be taken as representative, a low (0.6 solar) mass-average O abundance in stars should be assumed. This suggestion also finds support in many recent chemical enrichment studies (e.g., Pagel & Tautvaisiene 1998; Allende Prieto et al. 2001).

The importance of the above suggestions for a variable IMF at high-redshift to early feedback and redshift-dependent corrections for the star-formation rate, calls for direct confirmation of these results, that will be available with XEUS, either in X-ray absorption or emission.

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