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

A. Finoguenov,1,2 A. Burkert,3 and H. Böhringer1

Received 2003 January 3; accepted 2003 May 8

ABSTRACT

Using the guidelines on supernova 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 initial mass function (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 heading: galaxies: abundances — galaxies: clusters: general — galaxies: evolution — intergalactic medium

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 supernovae (SNe) 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, David, & Ponman 2000; Finoguenov, Arnaud, & David 2001a; Finoguenov et al. 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 (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 initial mass function (IMF) needed to explain the cluster metals at the redshift, where such deviations have recently been suggested from observations (Hernandez & Ferrara 2001). 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 \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) to provide an unbiased comparison between measured and theoretical values. The dependence of the luminosity distance \( (D_L) \) on the deceleration parameter \( (q_0 = 0.5 \) 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 intracluster medium (ICM) heavy-element abundance, gas content, and optical light for a sample of 44 groups and clusters from Finoguenov et al. (2000, 2001a, 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 \( \Omega_{m,0} = 0.3 \Lambda \text{ CDM} \) universe (Pierpaoli, Scott, & White 2001). For this comparison, the \( r_{100} \) is estimated by rescaling the \( r_{500} - T \) relation of
Fig. 1.—$M$-$L_B$ ratios ($T_e$) in groups and clusters of galaxies vs. the temperature of the ICM. The ratios of the cumulative values within $0.4r_{100}$ are shown. Solid line: Ratios for the total gravitational mass. Dotted line: Gas. Short- and long-dashed lines: Values for $T_{Fe}$ and $T_{Si}$, respectively, expressed in solar units.

Finoguenov, Reiprich, & Böhringer (2001b), assuming a NFW mass density profile (Navarro, Frenk, & White 1996).

In Figure 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 ($kT \sim M_{vir}^{0.6}$; Finoguenov et al. 2001b). The three bins, shown in Figure 1, correspond to the virial masses in the $0.3-1$, $1-4$, and $4-14 \times 10^{14} M_\odot$ intervals. We plot the total gravitational mass-to-light ratio, gas mass-to-light ratio, and the values for $T_{Fe}$ and $T_{Si}$, where $T_{Fe}$ and $T_{Si}$ 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, 2001b). 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-$\Omega_m$ 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 $0.4r_{100}$, the cluster gas reaches the 0.10 fraction of the total mass, thus accounting 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 more than $20\%$ different at larger radii. Large amounts of observational data on outskirts of groups and clusters of galaxies progressed our understanding on the nongravitational 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 (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 account for most of the star formation that preceded 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 $0.12^{+1}_{-1}$ (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, 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 (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).

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 $\Sigma$ in units chosen by Dressler et al. (1997) to mass overdensity $\delta$ by

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

using equation (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 $\Sigma$ (which we implicitly do by adopting a scaling with $\delta$), groups statistically obey the same relation. Using the equation (1), morphological fractions of E:S0:Sp within a radius of $0.4r_{100}$ 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 (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 $M_{*,0}$ (and its ratio to the present $L_B$ light as $\Upsilon_{*,0}$), assuming conversion factors of 6.5 and 1.5 for bulges and disks, respectively (thereby assuming a Salpeter IMF\(^5\)) as well as a disk fraction in different galaxies as in FHP. This translates into the following luminosity fractions of bulges and disks:

$$L_B^{\text{spheroidal}} : L_B^{\text{disk}} = 0.74 : 0.26 \quad \text{at} \quad r_{100},$$

with the following contribution to $\Upsilon_{*,0} = 4.8 + 0.4 = 5.2$. 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 extragalactic emission in Coma of $L_B \propto 10^{11} L_\odot$ suggest a contribution from the 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 $\Upsilon_{*,0}$ 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 (van der Marel 1991) and a solar Fe abundance. We distinguish them from the initial cumulative values by omitting the subscript “0.”

To determine the relative enrichment from different supernova types, we adopt the yields $y_{\text{Si}} = 0.12 M_\odot$, $y_{\text{Fe}} = 0.05 M_\odot$ for a SN II and $y_{\text{Si}} = 0.15 M_\odot$, $y_{\text{Fe}} = 0.74 M_\odot$ 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 $\Upsilon_{*,\text{Fe}}$ is 20%. To guide the reader, the highest Fe yield from SN II observed in clusters corresponds to a SN II contribution to the observed Fe abundance of 0.14 of photospheric solar units of $4.68 \times 10^{-5}$ (0.20 in meteoritic solar units of $3.23 \times 10^{-5}$) for iron number abundances relative to H.

In Figure 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 Figure 2, 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 (Finoguenov et al. 2002b). The value for the effective oxygen yield ($Y_O/\Upsilon_{*,\text{O}}$) 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 $M_\odot$ of stars. For O and Fe yields of 1.7 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 (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 in which a subsolar O/Mg ratio is characteristic of the stellar population (Xu et al. 2002; Matsushita et al. 2003; Peterson...\(^5\)Such an assumption for $\Upsilon_{*,0}$ corresponds more to a Scalo IMF for solar-metallicity stars (Maraston 1998).
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 as to whether most of the metals (by mass) are in stars or gas crucially depends on it. According to both X-ray gas/galaxy comparisons and metal-poor versus metal-rich stars, early chemical enrichment has been characterized by an O/Mg ratio different by a factor of 2. 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 evolution of star formation in early-type galaxies via ejection of the gas (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 parallel to 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 of clusters, cannot be obtained with the standard IMF (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 ($10^{12}$–$10^{15} M_\odot$). With only one decade more, including the groups with virial masses of $10^{12}$ $M_\odot$ in the 2dF galaxy redshift survey, Martinez 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. On the basis of these arguments, we consider variations in the IMF to occur only in massive clusters of galaxies and associate such changes with 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 (Somerville, Primack, & Faber 2001) and an assumption that the star-formation density at high redshift is dominated by the formation of the protocluster galaxies, followed by protogroup 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 $z > 5$ (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 2 compared to $z = 3$, which is consistent with current observational restrictions discussed in Springel, & Hernquist (2003 and references therein). We assume a linear rise in the star formation rate with $z$ at $z < 1$ with a plateau 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 relies 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 is strongest. To calculate the maximal redshift by which the protocluster can form most of its stars, we integrate the Madau plot to match the amount of stars found in the local clusters,

$$\Omega_{s, \text{cluster}} = \int_{t(z=\infty)}^{t(z=\text{cluster})} \dot{\rho}_* [z(t)] dt / \rho_{\text{crit}} ,$$

where we estimate $\Omega_{s, \text{cluster}}$ using the results from a complete X-ray survey of clusters of galaxies (HIFLUGS) on the cluster number abundance (Reiprich & Böhringer 2002) assuming a 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 $z > 2.5$.

$$\Omega_{s, \text{cluster}} = \int_{t(z=2.5)}^{t(z=\text{lower limit})} \dot{\rho}_* [z(t)] dt / \rho_{\text{crit}} .$$

At the peak star formation rate of 0.07 $M_\odot$ yr$^{-1}$ Mpc$^{-3}$, it takes only 1 Gyr to reproduce the stellar population in the groups and clusters of galaxies in the system mass range of the HIFLUGS 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

---

6 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.
(Finoguenov et al. 2002a), the delay between the formation epochs of bulges and ellipticals, and studies of star formation in the high-redshift progenitors of early-type galaxies (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 for only 7% of the total star formation in clusters.

We describe the IMF \([N(m)]\) variation by the typical mass, \( m_\star \), given by the equation

\[
dN/d \log m \sim (1 + m/m_\star)^{-1.35}
\]

from Hernandez & Ferrara (2001). The value of \( m_\star \), 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 (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 \( m_\star \). 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 \( m_\star = 0.35 M_\odot \). We present this mass scale for groups to provide an unbiased comparison to the data in Hernandez & Ferrara (2001).

The obtained values of \( m_\star \) 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 Figure 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 Lyman break galaxy 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 Hernandez & Ferrara (2001) that changes in the IMF grow exponentially with the redshift, exceeding the effect predicted on the basis of the increase of the cosmic microwave background 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 \( T_{s\star} \) and 20% on \( T_{s\star,0} \). 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. An alternative solution offered in Lin et al. (2003) consists of a more precise K-band light measurement 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 (HIFLUGS) on the cluster number abundance (Reiprich & Böhringer 2002) and combine them with our metallicity measurements to calculate \( \Omega_Z \). Detailing 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 (Finoguenov et al. 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%.

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 \( \Omega Z \) 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\( \alpha \) and O vi absorbers. Ly\( \alpha \) absorbers account for most of the baryons at \( z = 2.5 \), contributing \( 0.3 \times 10^{-3} \) to \( \Omega Z \) (Pagel 2002). At \( z = 0 \) Ly\( \alpha \) absorbers make up 32% \( \pm 6\% \) of \( \Omega b \) (Penton, Stocke, & Shull 2002; McLin et al. 2002; Stocke et al. 2002). To estimate their metal contribution, we assume that Ly\( \alpha \) 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 O vi absorbers, we use a lower limit by Tripp, Savage, & Jenkins (2000) and a value implied by ionization balance measurement of Mathur, Weinberg, & Chen (2003). No assumption on the O abundance is needed to calculate the contribution of the O vi 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 Table 1.

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 (O vi absorbers, Ly\( \alpha \) 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 HIFLUGS sample. Part of these systems that have lowest masses should be observed as O vi absorbers and, therefore, we should not account for them twice. The exact separation between X-ray-emitting and O vi 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 O vi absorbers, we consider it also as including the low-mass groups. There could be some metals left unaccounted for, if they are associated with the groups, missed by both the O vi absorbers and HIFLUGS.

Figure 4 shows the cumulative distribution of the metals over the mass of the system, and Figure 5 outlines the evolution of various components of \( \Omega Z \) 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

![Fig. 4.—Local cumulative \( \Omega Z(> M) \)-M relation. Solid and dashed lines: Lower and upper limit on the metal content, as explained in the text and detailed in Table 1. Gray area: Range of predicted values.](image-url)
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 0.4r100. 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.

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 X-Ray Evolving Universe Spectroscopy, either in X-ray absorption or emission.

A. F. thanks Ralph Bender, Bernard Pagel, Cesare Chiosi, Andrea Ferrara, Claudia Maraston, Francesca Matteucci, Trevor Ponman, Laura Portinari, Alvio Renzini, Mike Shull, Daniel Thomas, and Simon White for useful discussions and comments. The authors are thankful to Michael Loewenstein for the comprehensive referee report. This work was supported in part by NASA grant 16613323 and the Smithsonian Institution. A. F. acknowledges receiving Max-Plank-Gesellschaft fellowship.

REFERENCES

Allende Prieto, C., Lambert, D. L., & Asplund, M. 2001, ApJ, 556, L63
Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Arnaud, M., Rothenflug, R., Boulade, O., Vigroux, L., & Vangioni-Flam, E. 1992, A&A, 254, 49
Balogh, M. L., Pearce, F. R., Bower, R. G., & Kay, S. T. 2001, MNRAS, 326, 1228
Benson, A. J., & Madau, P. 2003, MNRAS, submitted (astro-ph/0203121)
Böhringer, H., et al. 2001, A&A, 369, 826
Bower, R. G., Kodama, T., & Terlevich, A. 1998, MNRAS, 299, 1193
Buote, D. A., Lewis, A. D., Brighenti, F., & Mathews, W. G. 2003, ApJ, in press
Cen, R. 2003, ApJ, 591, L5
Cen, R., & Ostriker, J. P. 1999, ApJ, 519, L109
De Grandi, S., & Molendi, S. 2001, ApJ, 551, 153
Dressler, A., et al. 1997, ApJ, 490, 577
Dunne, J. A., Eales, S., & Edmunds, M. G. 2002, MNRAS, 335, 753
Edmunds, M. G., & Phillipps, S. 1997, MNRAS, 292, 733
Evrard, A. E., Metzler, C. A., & Navarro, J. F. 1996, ApJ, 469, 494
Ferguson, H. C., Dickinson, M., & Papovich, C. 2002, ApJ, 569, L65
Finoguenov, A., Arnaud, M., & David, L. P. 2001a, ApJ, 555, 191
Finoguenov, A., Borgani, S., Tornatore, L., & Böhringer, H. 2003a, A&A, 398, L35
Finoguenov, A., Briel, U., & Henry, J. P. 2003b, A&A, in press
Finoguenov, A., David, L. P., & Ponman, T. J. 2000, ApJ, 544, 188
Finoguenov, A., Jones, C., Böhringer, H., & Ponman, T. 2002a, ApJ, 578, 74
Finoguenov, A., Matsushita, K., Böhringer, H., Ikebe, Y., & Arnaud, M. 2002b, A&A, 381, 21
Finoguenov, A., Reiprich, T., & Böhringer, H. 2001b, A&A, 368, 749
Fukazawa, Y., et al. 1998, PASJ, 48, 13
Fukugita, M., Hogan, C. J., & Peebles, P. E. 1998, ApJ, 503, 518
Gibson, B. K., & Matteucci, F. 1997, MNRAS, 291, L5
Gibson, B. K., & Mould, J. R. 1997, ApJ, 482, 98
Gregg, M. D., & West, M. J. 1998, Nature, 396, 549
Helsdon, S. F., & Ponman, T. J. 2003, MNRAS, 339, L29
Hernandez, X., & Ferrara, A. 2001, MNRAS, 324, 484
Huang, J.-S., Glazebrook, K., Cowie, L. L., & Tinney, C. 2002, preprint (astro-ph/0209440)
Kaiser, N. 1986, MNRAS, 222, 323
Kroupa, P., Tout, C. A., & Gilmore, G. 1993, MNRAS, 262, 545
Larson, R. B. 1998, MNRAS, 301, 569
Lin, Y.-T., Mohr, J. J., & Stanford, S. A. 2003, ApJ, 591, 749
Maraston, C. 1998, MNRAS, 300, 872
Martinez, H. J., Zandivarez, A., Domínguez, M., Merchán, M. E., & Lambas, D. G. 2002, MNRAS, 333, L31
Mathur, S., Weinberg, D., & Chen, X. 2003, ApJ, 582, 82
Matteucci, F., Finoguenov, A., & Böhringer, H. 2003, A&A, 401, 443
Matteucci, F. 1994, A&A, 288, 57
McCarthy, P. J., et al. 2001, ApJ, 560, L131
McIn, K. M., Stoecke, J. T., Weymann, R. J., Penton, S. V., & Shull, J. M. 2002, ApJ, 574, L115
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Nomoto, K., et al. 1997, Nucl. Phys. A, 616, 79
Oh, S. P., & Benson, A. J. 2003, MNRAS, 342, 664
Padoan, P., Nordlund, A., & Jones, B. J. T. 1997, MNRAS, 288, 145

Fig. 5.—Evolution of ΩZ with redshift. Solid line: Gas with labels indicating the major metal carrier at the redshift. Dotted line: Contribution to ΩZ from the stellar population. The Madau plot is normalized to the local K-band stellar baryon content, and a mass-averaged stellar oxygen abundance is assumed to be 0.6 solar.
Pagel, B. E. J. 1987, The Galaxy (Dordrecht: Reidel), 341
———. 2002, in ASP Conf. Ser. 253, Chemical Enrichment of Intracluster and Intergalactic Medium, ed. R. Fusco-Femiano & F. Matteucci (San Francisco: ASP), 489
Pagel, B. E. J., & Tautvaisiene, G. 1998, MNRAS, 299, 535
Penton, S. V., Stocke, J. T., & Shull, J. M. 2002, ApJ, 565, 720
Peterson, J. R., et al. 2003, ApJ, 590, 207
Pettini, M., Ellison, S. L., Steidel, C. C., & Bowen, D. V. 1999, ApJ, 510, 576
Pierpaoli, E., Scott, D., & White, M. 2001, MNRAS, 325, 77
Postman, M., & Geller, M. J. 1984, ApJ, 281, 95
Reiprich, T. H., & Böhringer, H. 2002, ApJ, 567, 716
Somerville, R. S., Primack, J. R., & Faber, S. M. 2001, MNRAS, 320, 504
Snecker, T. A., & Wyse, R. F. G. 1991, ApJ, 372, 448
Spergel, D. N., et al. 2003, ApJS, 148, 175
Springel, V., & Hernquist, L. 2003, MNRAS, 339, 312

Stocke, J. T., Penton, S. V., & Shull, J. M. 2003, in ASSL Conf. Proc. 281, ed. J. L. Rosenberg, & M. E. Putnam (Dordecht: Kluwer), 57
Tanaka, Y., Inoue, H., & Holt, S. S. 1984, PASJ, 46, L37
Thomas, D., Maraston, C., & Bender, R. 2002, Ap&SS, 281, 371
Tornatore, L., et al. 2003, MNRAS, 342, 1025
Tozzi, P., & Norman, C. 2001, ApJ, 546, 63
Tripp, T. M., Savage, B. D., & Jenkins, E. B. 2000, ApJ, 534, L1
van der Marel, R. P. 1991, MNRAS, 253, 710
White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341
Voit, G. M., Balogh, M. L., Bower, R. G., Lacey, C. G., & Bryan, G. L. 2003, ApJ, 593
Xu, H., Kahn, S. M., Peterson, J. R., Behar, E., & Paerels, F. B. S. 2002, ApJ, 579, 600
Zabludoff, A. I., & Mulchaey, J. S. 2000, ApJ, 539, 136
Zepf, S. E., & Silk, J. 1996, ApJ, 466, 114