What Heavy Elements in Clusters of Galaxies Tell About Clusters and Galaxies

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Abstract. Clusters of galaxies allow a direct estimate of the metallicity and metal production yield on the largest scale so far. The ratio of the total iron mass in the ICM to the total optical luminosity of the cluster (the iron mass-to-light-ratio) is the same for all clusters which ICM is hotter than \( \sim 2 \text{ keV} \), and the elemental proportions (i.e. the \( \alpha/Fe \) ratio) appear to be solar. The simplest interpretation of these evidences is that both the IMF as well the relative contributions of SN types are universal. Currently available abundances in cooler clusters and groups are much more uncertain, possibly due to insufficiently accurate atomic physics data for multielectron ions, or to the ICM being multi-phase, or to a combination thereof. This uncertainty automatically extends to the reality of radial abundance gradients so far reported in cool clusters. It is emphasized that most metals reside in the ICM rather than in galaxies, which demonstrates that energetic winds operated early in the evolution of massive galaxies, the likely producers of most metals now in the ICM. The ICM metallicity is also used to set a semiempirical constraint of \( \sim 0.1 \text{ keV} \) per particle to the ICM preheating due to supernova driven galactic winds. A lower limit of the universe global metallicity at \( z = 3 \) is also derived.

1 Introduction

Clusters of galaxies offer many interesting opportunities to astrophysical and cosmological research. One of them is the study of the cosmic chemical evolution on the largest scale so far. In turn, the heavy element content of clusters results in interesting constraints on the formation and evolution of clusters as well as of their population of galaxies.

Current estimates of iron content of the intracluster medium (ICM) are presented in Section 2, together with those of the abundance of the \( \alpha \)-elements. Section 2 also deals with the reported radial abundance gradients in cool clusters, as well as with the relative share of iron and the other heavy elements now in the ICM and locked into stars and galaxies. Section 3 deals with the origin of the ICM metals, identifying in the old, giant spheroids the main producers. Section 4 offers an estimate of the ICM preheating by early supernova driven galactic winds, while Section 5 provides references for further reading concerning the implications for the globe metallicity of the universe at low as well as high redshift.
2 Iron and \( \alpha \)-Elements in the ICM

As Larson and Dinerstein (1975) predicted and X-ray observations confirmed (Mitchell et al. 1976), the ICM is rich in heavy elements. Actually, it has the larger share of them compared to cluster galaxies.

2.1 Iron

Fig. 1 shows the iron abundance in the ICM of clusters and groups as a function of ICM temperature from an earlier compilation (Renzini 1997, hereafter R97). Data cluster along two sequences in Fig. 1: for \( kT \gtrsim 3 \) keV the ICM iron abundance is constant, i.e. independent of cluster temperature. Abundances for clusters in this horizontal sequence come from the Iron-K complex at \( \sim 7 \) keV, which emissions are due to transitions to the K level of H-like and He-like iron ions. Conversely, at lower temperatures data delineate an almost vertical sequence, with a fairly strong abundance-temperature correlation reaching extremely low iron abundances in groups cooler than \( \sim 1 \) keV. Iron abundances in the vertical sequence from the Iron-L complex at \( \sim 1 \) keV, which emission lines are due to transitions to the L level of iron ions with three or more electrons. In these cooler clusters iron is indeed in such lower ionization stages, and the iron-K emission disappears. Such low abundances were regarded with suspicion in R97, being possibly the result of systematic inaccuracies in the atomic physics data used to model the iron-L complex.

Fig. 2 is the same of Fig. 1 with one difference. Clusters and groups in R97 with \( kT < 2 \) keV have been substituted by a set of 11 groups from Buote (1999). Buote argues that the atomic physics may be correct, but gets substantially higher (perhaps more realistic) abundances when using 2-temperature fits. It remains to be established whether the apparent correlation of the iron abundance with temperature is real or instead is an artifact of inadequate diagnostics at low temperatures. For this reason conclusions concerning abundances derived from iron-K should be regarded as more secure than those for cooler clusters.

Fig. 3 shows the iron-mass-to-light-ratio (Fe\( M/L \)) of the ICM, i.e. the ratio \( M_{\text{Fe}}^{\text{ICM}}/L_B \) of the total iron mass in the ICM over the total B-band luminosity of the galaxies in the cluster. Again, objects with \( kT < 2 \) keV in R97 have been omitted, with the exception of 4 objects from Buote (1999) for which a measure of the ICM mass was available from the R97 compilation.

The drop of the Fe\( M/L \) in poor clusters and groups (i.e. for \( kT \lesssim 2 \) keV) noticed in R97 can be traced back to a drop in both the iron abundance (which however may not be real) and in the ICM mass to light ratio. Such groups appear to be gas poor compared to clusters, which suggest that they may be subject to baryon and metal losses due to strong galactic winds driving much of the ICM out of them (Renzini et al. 1993; R97: Davis et al. 1998). For the rest of this paper I will concentrate on clusters with \( kT \gtrsim 2 - 3 \) keV.
Figure 1: A compilation of the iron abundance in the ICM as a function of ICM temperature for a sample of clusters and groups (R97), including several clusters at moderately high redshift with \( <z> \simeq 0.35 \), represented by small filled circles.

Figure 2: The same as Fig. 1 with clusters and groups with \( kT \lesssim 2 \) keV having been replaced by 11 groups from Buote (1999), which temperatures and abundances are determined from 1- and 2-temperature fits (filled squares and open triangles, respectively).
Figure 3: The iron mass to light ratio of the ICM of clusters and groups (for $H_0 = 50$) as a function of the ICM temperature (R97).

Fig.s 1-3 show that both the iron abundance and the Fe\textit{M/L} in rich clusters ($kT > \sim 3$ keV) are independent of cluster temperature, hence of cluster richness and optical luminosity. For these clusters one has $Z_{\text{ICM}}^{\text{Fe}} = 0.3 \pm 0.1$ solar, and $M_{\text{ICM}}^{\text{Fe}}/L_B = (0.02 \pm 0.01)$ for $H_0 = 50$. The most straightforward interpretation is that clusters did not lose iron (hence baryons), nor differentially acquired pristine baryonic material, and that the conversion of baryonic gas into stars and galaxies has proceeded with the same efficiency and the stellar IMF in all clusters (R97). Otherwise, we should observe cluster to cluster variations of the iron abundance and of the Fe\textit{M/L}.

The absence of such variations also argues for the iron now residing in the ICM having been ejected from galaxies by supernova- (or AGN-) driven galactic winds, rather than having been stripped by ram pressure (Renzini et al. 1993; Dupke & White 1999). Indeed, ram pressure effects become much stronger with increasing cluster richness, hence galaxy velocity dispersion and ICM temperature. Correspondingly, if ram pressure would play a major role in getting iron out of galaxies one would expect the ICM abundance and Fe\textit{M/L} to increase with $kT$, which is not observed.

2.2 The $\alpha$-Elements

From ASCA X-ray observations the ICM abundances of some of the $\alpha$-elements (O, Ne, Mg, and Si) have also been derived, yielding an average $<\alpha/\text{Fe}> \simeq +0.2$
(Mushotzky et al. 1996). This modest $\alpha$-element enhancement suggested an ICM enrichment dominated by SNII products. However, the $\alpha$-element overabundance vanishes when consistently adopting the “meteoritic” iron abundance for the sun, as opposed to the “photospheric” value (Ishimaru & Arimoto 1997), with a formal average $<\alpha/Fe> \simeq +0.04 \pm 0.2$ (R97). Clusters of galaxies as a whole are therefore nearly solar as far as the elemental ratios are concerned, which argues for stellar nucleosynthesis having proceeded in much the same way in the solar neighborhood as well as at the galaxy cluster scale. This argues for a similar ratio of the number of Type Ia to Type II SNs, as well as a similar IMF (R97), suggesting that the star formation process (IMF, binary fraction, etc.) is universal, with little or no dependence on the global characteristics of the parent galaxies in which molecular clouds are turned into stars.

2.3 Radial Abundance Gradients, Are They Real?

The values of the Fe$M/L$ shown in Fig. 3 were derived as the product of the ICM mass times the central iron abundance. However, radial gradients in the iron abundance have been reported for several clusters (e.g. Fukazawa et al. 1994; Dupke & White 1999; Finoguenov, et al. 1999; White 1999), which would require a radial integration of $\rho(r)Z_{Fe}(r)dV$ to derive the total iron mass in the ICM. This is not currently feasible because ASCA data lack of the sufficient image quality to do a proper job.

Nevertheless, a cursory examination of the radial gradient so far reported reveals two intriguing trends. The first is that the presence of radial abundance gradients is confined to cool clusters and groups ($kT \lesssim 3$ keV, with hotter clusters – which incidentally are generally those with the best S/N ratios – never showing appreciable gradients. The second trend one can notice in the published data is that an abundance gradient is most often associated to a temperature gradient: iron abundances increase inwards as temperature drops towards the center to $\sim 2$ keV or below. These trends are illustrated in Fig. 4, showing the abundance-temperature relation for a representative set of clusters (Pellegrini 2000).

Given the uncertainties affecting the low temperature abundances – resulting from either problems with the atomic physics or from the complexities of a multi-temperature ICM – it seems prudent to conclude that the reality of the reported abundance gradients is far from being established. Although more or less plausible mechanisms could be invented to produce radial abundance gradients in clusters, it is nevertheless worth entertaining the possibility of the reported gradients being a mere artifact of inadequate diagnostics.

2.4 Most Metals are not in Galaxies

The metal abundance of the stellar component of cluster galaxies can only be inferred from integrated spectra coupled to synthetic stellar populations. Much of
the stellar mass in clusters is confined to passively evolving spheroids (ellipticals and bulges) for which the iron abundance may range from $\sim 1/3$ solar to a few times solar. Following R97, the ratio of the iron mass in the ICM to the iron mass locked into stars and galaxies is given by:

$$\frac{Z_{\text{Fe}}^{\text{ICM}} M_{\text{ICM}}}{Z_{\text{Fe}}^{\ast} M_{\ast}} \simeq 1.65 h^{-3/2},$$

(1)

or 4.6, 2.5, and 1.65, respectively for $h = 0.5$, 0.75, and 1 ($h = H_0/100$), and having adopted $Z_{\text{Fe}}^{\text{ICM}} = 0.3$ solar and $Z_{\text{Fe}}^{\ast} = 1$ solar. Note that with the adopted values for the quantities in equation (2) most of the cluster iron resides in the ICM, rather than being locked into stars, especially for low values of $H_0$. Therefore, it appears that there is at least as much metal mass out of cluster galaxies (in the ICM), as there is inside them (locked into stars). This sets a strong constraint by models of the chemical evolution of galaxies.

3 Origin of the Metals in the ICM

The constant Fe$M/L$ of clusters says that the total mass of iron in the ICM is proportional to the total optical luminosity of the cluster galaxies (Songaila et al. 1990; Ciotti et al. 1991; Arnaud et al. 1992; Renzini et al. 1993). This strongly argues for the iron (metals) now in the ICM having been produced by the (massive) stars of the same stellar population to which belong the low-mass

Figure 4: The metal abundance vs temperature within individual clusters from a compilation by Pellegrini (2000). Data points for a given cluster at various distances from the cluster center are connected by lines.
stars now producing the bulk of the cluster optical light. As well known, much of the cluster light comes from the old spheroidals (ellipticals and bulges), hence one can say that the bulk of cluster metals were produced by ellipticals and bulges when they were young.

It is now well established that the stellar populations in spheroidals – in clusters as well in the field – are very old, with the bulk of stars having formed at $z \gtrsim 3$ (for a recent review with extensive references see Renzini & Cimatti 1999). Therefore, the simplest interpretation of the data suggests that the bulk of the heavy elements in the ICM were produced and expelled from galaxies a long time ago, i.e. at $z \gtrsim 3$. If so, the ICM abundances should not show any significant evolution all the way to very high redshifts. Existing data are in agreement with this prediction (see Fig. 1), but do not reach much beyond $z \approx 0.5$. Future X-ray observatories could check this prediction.

It is also interesting to address the question of which galaxies have produced the bulk of the iron and the other heavy elements, i.e. the relative contribution as a function of the present-day luminosity of cluster galaxies. This has been recently investigated by Thomas (1999), from whom I reproduce here Fig. 5. This shows that the bright galaxies (those with $L \sim L^*$) produce the bulk of the cluster light, while the dwarf contribute a negligible amount of light in spite of dominating the galaxy counts by a large margin. Hence, most galaxies don’t do much, while the
brightest $\sim 3\%$ of all galaxies contribute $\sim 97\%$ of the whole cluster light. Given that it is most likely that the metals were produced by the same stellar population that now shines, one can safely conclude that also the bulk of the cluster metals have been produced by the giant galaxies (or - paying a tribute to a widespread belief - by the stars that are now in the giants). Dwarfs contribution to ICM metals may have been somewhat larger than their tiny contribution to the cluster light, since metals can more easily escape from their shallower potential wells (Thomas 1999), but this cannot alter the conclusion that the giants dominate metal production by a very large factor.

4 A Semiempirical Estimate of Preheating

The total amount of iron in clusters represents a record of the overall past supernova (SN) activity as well as of the past mass and energy ejected from cluster galaxies. The empirical values FeM/L was used to set a constraint on the so-called preheating of the ICM (Renzini 1994), a hot topic indeed at this meeting. The total SN heating is given by the kinetic energy released by one SN ($\sim 10^{51}$ erg) times the number of SNs that have exploded. It is convenient to express this energy per unit present optical light $L_B$, i.e.:

$$\frac{E_{SN}}{L_B} = 10^{51} \frac{N_{SN}}{L_B} = 10^{51} \left( \frac{M_{Fe}}{L_B} \right)^{TOT} \frac{1}{<M_{Fe}>} \simeq 10^{50} \text{ (erg}/L_\odot),$$

where as total (ICM+galaxies) FeM/L=0.03 $M_\odot/L_\odot$ is adopted, and the average iron mass release per SN event is assumed to be 0.3 $M_\odot$. This is the appropriate average if $\sim 3/4$ of all iron is made by Type Ia SNs, and $\sim 1/4$ by Type II and other SN types (see R97). Were all the iron made instead by SNIIs, the resulting SN energy would go up by perhaps a factor of 3 or 4. This estimate should therefore be accurate to within a factor of 2 or 3.

The presence of a large amount of iron in the ICM demonstrates that matter (and then energy) has been ejected from galaxies. The kinetic energy injected into the ICM by galactic winds, again per unit cluster light, is given by 1/2 the ejected mass times the typical wind velocity squared, i.e.:

$$\frac{E_w}{L_B} = \frac{1}{2} \frac{M_{ICM}}{L_B} \left( \frac{v_w^2}{Z_{Fe}} \right) \simeq 1.5 \times 10^{49} \frac{Z_{Fe}}{Z_{Fe}} \left( \frac{v_w}{500 \text{ km s}^{-1}} \right)^2 \simeq 10^{49} \text{ (erg}/L_\odot),$$

where the empirical FeM/L for the ICM has been used, the average metallicity of the winds $Z_{Fe}$ is assumed to be twice solar, and the wind velocity $v_w$ cannot be much different from the escape velocity from individual galaxies, as usual in the case of thermal winds. Again, this estimate may be regarded as accurate to within a factor of 2, or so.

A first inference from these estimates is that $\sim 5 - 10\%$ of the kinetic energy released by SNs survives as kinetic energy of galactic winds, thus contributing to
the heating of the ICM. A roughly similar amount should go into work to extract the gas from the potential well of individual galaxies, while the bulk $\sim 80 - 90\%$ has to be radiated away locally and does not contribute to the feedback.

The estimated $\sim 10^{49}$ erg/L$_\odot$ correspond to a “preheating” of $\sim 0.1$ keV per particle, for a typical cluster $M_{\text{ICM}}/L_B \simeq 40 M_\odot/L_\odot$. This is $\sim 20$ times lower than the (AGN induced) preheating some model require to fit the cluster $L_X - T$ relation (Wu et al. 1999). Not even if all the SN energy were to go to increase the thermal energy of the ICM would this extreme requirement be met. Crucial for the evolution of the ICM is however the entropy, hence the relative timing of galactic wind heating and cluster formation (Kaiser 1991; Cavaliere et al. 1993). The entropy increase associated to a given amount of preheating depends on the gas density when the heating takes place. Most of star formation in cluster elliptical galaxies – and therefore most SN activity and galactic winds – appears to be confined at very early times, i.e., at $z \gtrsim 3$. It remains to be seen whether such early preheating may render $\sim 0.1$ keV per particle sufficient to increase enough the entropy thus producing the observed $L_X - T$ relation. Alternative models less demanding than those of Wu et al. in terms of preheating are presented by Tozzi at this meeting (Tozzi & Norman 1999). Finally, if AGN preheating were as high as 2 keV/particle (averaged over the whole cluster) it may result in long term suppression of cluster cooling flows, in analogy with the scenario proposed for intermittent gas flows in ellipticals (Ciotti & Ostriker 1997).

5 Clusters as Fair Samples and the Metallicity of the High-$z$ Universe

In R97 and in some its subsequent updates (e.g. Renzini 1998, 1999) it is argued that clusters are representative of the local universe as a whole, as far as the fraction of baryons already turned into stars is concerned, hence of the global metallicity of the local universe ($\sim 1/3$ solar). Moreover, since stars in spheroids formed at $z \gtrsim 3$ and spheroids account for at least $1/3$ of the present day total mass in stars, it is concluded that the metallicity of the whole universe at $z \sim 3$ had to be $\sim 1/3$ of the present global value, hence $\sim 1/10$ solar. This simple argument supports the notion of a prompt initial enrichment of the early universe.
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