Carnegie Observatories Astrophysics Series, Vol. 3:
Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, 2004
ed. J. S. Mulchaey, A. Dressler, and A. Oemler (Cambridge: Cambridge Univ. Press)

The Chemistry of Galaxy Clusters

ALVIO RENZINI
European Southern Observatory

Abstract

>From X-ray observations of galaxy clusters one derives the mass of the intracluster medium along with its chemical composition. Optical/infrared observations are used to estimate the mass of the stellar components of galaxies, along with their chemical composition and age. This review shows that when combining all this information, several interesting inferences can be drawn, including: (1) galaxies lose more metals than they retain; (2) clusters and the general field have converted the same fraction of baryons into stars, hence the metallicity of the $z = 0$ Universe as a whole has to be nearly the same we see in clusters, $\sim$1/3 solar; (3) for the same reason, the thermal content of the intergalactic medium is expected to be nearly the same as the preheating energy of clusters; (4) a strong increase of the Type Ia supernova (SN) rate with lookback time is predicted if SNe Ia produce a major fraction of cosmic iron; (5) the global metallicity of the $z \approx 3$ Universe was already $\sim$1/10 solar; and (6) the Milky Way disk formed out of material that was pre-enriched to $\sim$1/10 solar by the bulge stellar population.

1.1 Introduction

In one of the rare cases in which theory anticipates observations, the existence of large amounts of heavy elements in the intracluster medium (ICM) was predicted shortly before it was actually observed (Larson & Dinerstein 1975). This came from (now old-fashioned) so-called *monolithic* models of elliptical galaxy formation, in which the observed color-magnitude relation is reproduced in terms of a metallicity trend. In turn, this trend is established by SN-driven galactic winds being more effective in less massive, fainter galaxies with shallow potential wells, compared to more massive galaxies harbored in deep potential wells. While these models may now be inadequate in quite many respects, their prediction was confirmed the following year by the discovery of the strong iron-K line in the X-ray spectrum of galaxy clusters (Mitchell et al. 1976).

This Carnegie Symposium on clusters of galaxies covers all the manifold aspects of these largest bound systems in the Universe. This review is meant to focus on one specific topic, the metal content of the clusters. I show that from this one can infer quite a number of intriguing consequences on galaxy formation and evolution on a wide scale, as well as on the evolution of some global properties of the baryonic component of the Universe. The following will be a *broad-brush* picture about facts and inferences, and is meant to stimulate a deeper look at each of the issues that will be cursorily touched upon here, and which include the following main topics:

- The metal content of clusters: ICM and galaxies
- The composition of the ICM "metallicity" (elemental ratios)
- The ICM/galaxies iron share in clusters
- Metal production: Type Ia and Type II SNe, and the cosmic evolution of their rate
- Metal transfer from galaxies to ICM: ejection vs. extraction
- Metals as tracers of the "ICM preheating"
- Clusters vs. field at $z = 0$
- The major epoch of metal production in clusters
- The metallicity of the Universe at $z = 3$
- The early chemical evolution of the Milky Way

The production and circulation of iron and other heavy elements on galaxy cluster scale has been widely discussed since their early discovery (e.g., Vigroux 1977; Matteucci & Vettolani 1988; Ciotti et al. 1991; Arnaud et al. 1992; Renzini et al. 1993; Loewenstein & Mushotzky 1996; Ishimaru & Arimoto 1997; Renzini 1997, 2000; Chiosi 2000; Aguirre et al. 2001; Pipino et al. 2002).

1.2 The Heavy Elements in Clusters: ICM and Galaxies

1.2.1 Iron

Iron is the best studied element in clusters of galaxies, as ICM iron emission lines are present in all clusters and groups, either warm or hot. Figure 1.1 shows the iron abundance in the ICM of clusters and groups as a function of ICM temperature from an earlier compilation (Renzini 2000). For $kT \gtrsim 3$ keV the ICM iron abundance is constant at $Z^{\rm Fe} \simeq 0.3 Z^{\rm Fe}_{\odot}$, independent of cluster temperature. Abundances for clusters in this *horizontal* sequence come from the iron-K complex at ~ 7 keV, whose emission is due to transitions to the K level of H-like and He-like iron ions. At lower temperatures the situation is much less simple. Figure 1.1 shows data from Buote (2000), with the iron abundance having been derived with both one-temperature and two-temperature fits. The one-temperature fits give iron abundances for those cool groups that are more or less in line with those of the hotter clusters. The abundances of the two-temperature fits, instead, form an almost vertical sequence, with a great deal of dispersion around a mean value of ~ 0.75 solar. Earlier estimates gave extremely low values for cooler groups, $kT \lesssim 1$ keV (Mulchaey et al. 1996). Compiling values from the literature, a strong dependence of the abundance on ICM temperature is apparent, being very low at low temperatures, steeply increasing to a maximum around $kT \approx 2$ keV, then decreasing to reach ~ 0.3 solar by $kT \approx 3$ keV (Renzini 1997; see also Mushotzky 2002).

Is this strong temperature dependence real? Perhaps some caution is in order. Besides the ambiguity as to whether one- or two-temperature fits are preferable, additional uncertainties for the iron abundances at $kT \lesssim 2$ keV come from their being derived from the iron-L complex at ~ 1 keV, whose emission lines are due to transitions to the L level of iron ions with three or more electrons. In these cooler groups/clusters iron is indeed in such lower ionization stages, and the iron-K emission disappears. The atomic configurations of these more complex ions are not as simple as those giving rise to the iron-K emission, and their (calculated) collisional

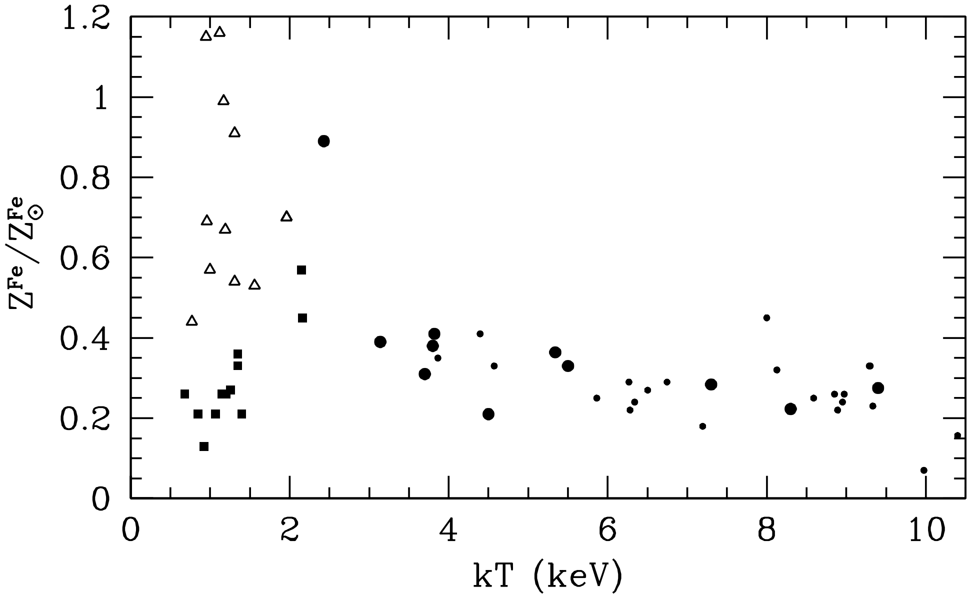

Fig. 1.1. A compilation of the iron abundance in the ICM as a function of the ICM temperature for a sample of clusters and groups, including several clusters at moderately high redshift with $\langle z \rangle \simeq 0.35$, represented by small filled circles. For temperatures less than about 2 keV, 11 groups are shown from Buote (2000), with temperatures and abundances determined from one- and two-temperature fits (filled squares and open triangles, respectively). (Adapted from Renzini 2000.)

excitation probabilities may be more uncertain. In summary, iron abundances derived from the iron-L emission should be regarded with a little more caution compared to those from the iron-K emission.

Abundances shown in Figure 1.1 refer to the cluster central regions. However, radial gradients in the iron abundance have been reported for several clusters, starting with *ASCA* and then *ROSAT* data (e.g., Fukazawa et al. 1994; Dupke & White 2000; Finoguenov, David, & Ponman 2000; White 2000; Finoguenov, Arnaud, & David 2001). From *Beppo-SAX* data, De Grandi & Molendi (2001) have conducted a systematic study of the radial distribution of iron (metals) in many clusters. Figure 1.2 shows that clusters break up into two distinct groups: so-called cool core clusters (formerly known as "cooling flow" clusters before the failure of the cooling flow model was generally acknowledged) are characterized by a steep metallicity (mostly iron) gradient in the core, reaching ~ 0.6 solar near the center, and non-cold core clusters (where no temperature gradient is found), which show no metallicity gradient. The origin of the dichotomy remains to be understood. The fact that metallicity gradients are found to be associated with large temperature gradients in the central regions may look suspicious, as noted for the strong dependence of $Z^{\rm Fe}$ on ICM temperature, but it appears to be well established.

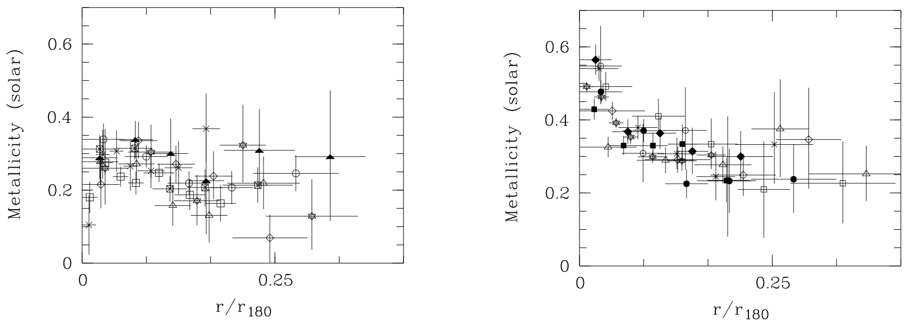

Fig. 1.2. Projected metallicity distributions for non-cold core clusters (left panel) and cold-core clusters (right panel), from *Beppo-SAX* data. The radial coordinate is normalized to the radius with an overdensity factor of 180. (From De Grandi & Molendi 2001.)

1.2.2 Elemental Ratios

X-ray observatories (especially *ASCA*, *Beppo-SAX*, and *XMM-Newton*) have such high spectral resolution that besides those of iron the emission lines of many other elements can be detected and measured. These include oxygen, neon, magnesium, calcium, silicon, sulfur, argon, and nickel. Most of these are α elements, predominantly synthesized in massive stars exploding as Type II SNe. As is well known, iron-peak elements are mainly produced by Type Ia SNe, and $50\% - 75\%$ of the iron in the Sun may come from them.

Early estimates from *ASCA* suggested a sizable α-element enhancement, $\langle[\alpha/\mathrm{Fe}]\rangle \simeq +0.4$ (Mushotzky (1994), later reduced to +0.2 (Mushotzky et al. 1996), and eventually found consistent with solar proportions $\langle[\alpha/\mathrm{Fe}]\rangle \simeq 0.0$ (Ishimaru & Arimoto 1997). More recently, Finoguenov et al. (2000) report near-solar Ne/Fe, slightly enhanced Si/Fe, and slightly depleted S/Fe, but with rather large error bars. From a systematic reanalysis of the *ASCA* archival data, Mushotzky (2002) reports a systematic increase of Si and Ni and a decrease of Ca with ICM temperature. Note that both silicon and calcium are α elements, and apparently they do not follow the same trend! No simple interpretation has so far emerged of these trends in terms of the relative role of the two SN types (Gibson & Matteucci 1997; Loewenstein 2001; Finoguenov et al. 2002).

I would conclude that no compelling evidence exist for other than near-solar [α/Fe] ratios in the ICM, when all α elements are lumped together. This argues for stellar nucleosynthesis having proceeded in much the same way in the solar neighborhood as well as at the galaxy cluster scale. In turn, this demands a similar ratio of the number of Type Ia to Type II SNe, as well as a similar stellar initial mass function (IMF), 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 (and their large-scale structure environment) in which molecular clouds are turned into stars. Alternatively, one can take at face value the variations of the abundance ratios with cluster temperature, as well as the overabundance of some α elements and the underabundance of others. One can then be forced to rather contrived conclusions, such as the mix of the two SN types, and perhaps even the nucleosynthesis of massive stars, depends on what the temperature of the ICM will be billions of years *after* star formation has ceased. On the other hand, one may argue that rich galaxy clusters are "special" places in many senses, and that ICM abundances reflect not only SN nucleosynthesis yields, but also how efficiently these are ejected, mixed into, and retained in the ICM. However, no simple understanding of the apparent empirical trends has yet emerged.

In summary, in the following I will assume that clusters, on a global scale, have solar elemental ratios and the total heavy element abundance is 0.3 solar, or 0.006 by mass.

1.2.3 The Iron Mass-to-Light Ratio

One useful quantity is the iron-mass-to-light-ratio ($M^{\rm Fe}/L$) of the ICM, the ratio $M^{\rm Fe}_{\rm ICM}/L_{\rm B}$ of the total iron mass in the ICM over the total *B*-band luminosity of the galaxies in the cluster. In turn, the total iron mass in the ICM is given by the product of the iron abundance times the mass of the ICM, $M^{\rm Fe}_{\rm ICM} = M_{\rm ICM} Z^{\rm Fe}_{\rm ICM}$. Figure 1.3 shows the resulting $M^{\rm Fe}/L$ from an earlier compilation (Renzini 1997). The drop of the $M^{\rm Fe}/L$ in poor clusters and groups (i.e., for $kT \lesssim 2$ keV) can be traced back to a drop in both the iron abundance (which, however, may not be real; see above) *and* in the ICM mass. Such groups appear to be gas poor compared to clusters, which suggests (1) that they may have been subject to baryon and metal losses due to strong galactic winds driving much of the ICM out of them (Renzini et al. 1993; Renzini 1997; Davis, Mulchaey, & Mushotzky 1999), (2) that such winds have *preheated* the gas around galaxies, thus preventing it to fall inside groups, or (3) that they have *inflated* the gas distribution. In one way or another, the *break* seen in Figure 1.3 is likely to be related to the break of self-similarity in the X-ray-temperature relation (see later).

For the rest of this paper I will mainly deal with clusters with $kT \gtrsim 2-3$ keV, for which the interpretation of the data appears more secure. Yet, several cautionary remarks are in order. The first is that the iron abundances used to construct Figure 1.3 did not take into account that some clusters have sizable iron gradients. In principle, X-ray observations can give both the run of gas density and abundance with radius, so to make possible to integrate their product over the cluster volume to get $M^{\rm Fe}_{\rm ICM}$. To my knowledge, so far this has been attempted only for one cluster (Pratt & Arnaud 2003). However, the extra iron contained within the core's iron gradient seems to be the product of the central cD galaxy, and may represent only a small fraction of the whole $M^{\rm Fe}_{\rm ICM}$ (De Grandi & Molendi 2002).

Another concern is that two of the three ingredients entering into the calculation of the $M^{\rm Fe}/L$ values shown in Figure 1.3 (namely $M_{\rm ICM}$ and $L_{\rm B}$) may not be measured in precisely the same way in the various sources used in the compilation. Both quantities come from a radial integration up to an ill-defined cluster boundary, such as the Abell radius, the virial radius, or to a radius of some fixed overdensity. Sometimes it is quite difficult to ascertain what definition has been used by one author or another, with the complication that in general X-ray and optical data have been collected by different groups using different assumptions. There is certainly room for improvement here. Finally, estimated total luminosities ($L_{\rm B}$) refer to the sum over all cluster galaxies and do not include the population of stars that is diffusely distributed throughout the cluster, which may account for at least $\sim 10\%$ of the total cluster light (Ferguson, Tanvir, & von Hippel 1998; Arnaboldi et al. 2003).

While keeping these cautions in mind, we see from Figure 1.3 that $M^{\rm Fe}/L$ runs remarkably flat with increasing cluster temperature, for $kT \gtrsim 2-3$ keV. This constancy of the $M^{\rm Fe}/L$ comes from both $Z^{\rm Fe}_{\rm ICM}$ and $M_{\rm ICM}/L_{\rm B}$, showing very little trend with cluster temperature [see Fig. 1.1 and Fig. 4 in Renzini (1997), where $M_{\rm ICM}/L_{\rm B} \simeq 25 h_{70}^{-1/2}$ $(M_\odot/L_\odot)$.] The resulting $M^{\rm Fe}/L$ is therefore

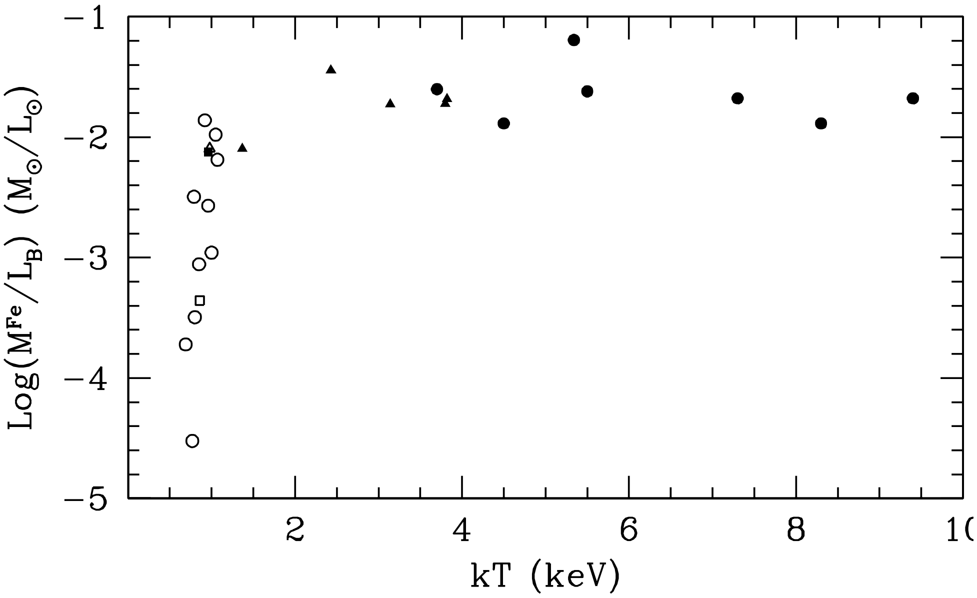

Fig. 1.3. The iron mass-to-light ratio of the ICM of clusters and groups as a function of the ICM temperature from an earlier compilation (Renzini 1997). Data are taken from the following sources: filled circles, Arnaud et al. (1992); filled triangles, Tsuru (1992); open triangle, David et al. (1994); open square, Mulchaey et al. (1993); filled square, Ponman et al. (1994); and open circles, Mulchaey et al. (1996). (Adapted from Renzini 1997.)

$$\frac{M_{\rm ICM}^{\rm Fe}}{L} = Z_{\rm ICM}^{\rm Fe}\frac{M_{\rm ICM}}{L_{\rm B}} \simeq 0.3 \times Z_{\odot}^{\rm Fe} \times 25 h_{70}^{-1/2} \simeq 0.01\, h_{70}^{-1/2}(M_{\odot}/L_{\odot}). \qquad (1.1)$$

That is, in the ICM there is about 0.01 solar masses of iron for each solar luminosity of the cluster galaxies. This value is $\sim 30\%$ lower than adopted in Renzini (1997) and shown in Figure 1.3, having consistently adopted here for $Z_{\odot}^{\rm Fe}$ the recommended *meteoritic* iron abundance (Anders & Grevesse 1989), $Z_{\odot}^{\rm Fe} = 0.0013$. Assuming solar elemental proportions for the ICM, the ICM *metal mass-to-light ratio* is therefore $\sim 0.3 \times 0.02 \times 25 h_{70}^{-1/2} = 0.15\,(M_{\odot}/L_{\odot})$, having adopted $Z_{\odot} = 0.02$ and for $h_{70} = 1$.

A very accurate analysis was performed recently for the A1983 cluster (Pratt & Arnaud 2003), paying attention to measure $M_{\rm ICM}$ and $L_{\rm B}$ within the same radius. The result is $M^{\rm Fe}/L = (7.5 \pm 1.5) \times 10^{-3} h_{70}^{-1/2}(M_{\odot}/L_{\odot})$, in fair agreement with the estimate above.

The most straightforward interpretation of the constant $M^{\rm Fe}/L$ 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 same stellar IMF in all clusters (Renzini 1997). Otherwise, there should be cluster-to-cluster variations of $Z_{\rm ICM}^{\rm Fe}$ and $M^{\rm Fe}/L$. All this is true insofar as the baryon-to-dark matter ratio is the same in all $kT \gtrsim 2$ keV clusters (White at al. 1993), and the ICM mass-to-light ratio and the gas fraction are constant. Nevertheless, there may be hints for some of these quantities showing (small) cluster-to-cluster variations (Arnaud & Evrard 1999; Mohr, Mathiesen, & Evrard 1999; Pratt & Arnaud 2003), but no firm conclusion has been reached yet.

1.2.4 The Iron Share Between ICM and Cluster Galaxies

The metal abundance of the stellar component of cluster galaxies is derived 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 $Z_*^{\rm Fe}$ may range from $\sim$1/3 solar to a few times solar. For example, among ellipticals metal-sensitive spectral features such as the magnesium index Mg_2 range from values slightly lower than in the most metal-rich globular clusters of the Milky Way bulge (which are nearly solar), to values for which models indicate a metallicity a few times solar (e.g., Maraston et al. 2003). The $M^{\rm Fe}/L$ of cluster galaxies is then given by:

$$\frac{M_{\rm gal}^{\rm Fe}}{L} = Z_*^{\rm Fe}\frac{M_*}{L_{\rm B}} \simeq 0.0046\,h_{70} \quad (M_\odot/L_\odot), \tag{1.2}$$

where we have adopted $M_*/L_{\rm B} = 3.5\,h_{70}$ (White et al. 1993) and $Z_*^{\rm Fe} = Z_\odot^{\rm Fe}$. The *total* cluster $M^{\rm Fe}/L$ (ICM+galaxies) is therefore $\sim 0.015 \quad (M_\odot/L_\odot)$, for $h_{70} = 1$, and the ratio of the iron mass in the ICM to the iron mass locked into stars and galaxies is

$$\frac{Z_{\rm ICM}^{\rm Fe} M_{\rm ICM}}{Z_*^{\rm Fe} M_*} \simeq 2.2 h_{70}^{-3/2}, \tag{1.3}$$

having adopted $Z_{\rm ICM}^{\rm Fe} = 0.3\,Z_\odot^{\rm Fe}$, $Z_*^{\rm Fe} = 1\,Z_\odot^{\rm Fe}$, and $M_{\rm ICM}/M_* = 9.3 h_{70}^{-3/2}$ as for the Coma cluster (White et al. 1993). So, it appears that there is ~ 2 times more iron mass in the ICM than locked into cluster stars (galaxies), perhaps even more if $Z_*^{\rm Fe}$ is subsolar due to an abundance gradient within clusters (Arimoto et al. 1997). In turn, this empirical iron share (ICM vs. galaxies) sets a strong constraint on models of the chemical evolution of galaxies. Under the same assumptions as above, the total metal mass-to-light ratio (ICM + galaxies) is therefore $\sim 0.15 h_{70}^{-1/2} + 0.07 h_{70} \simeq 0.2\,(M_\odot/L_\odot)$. This can be regarded as a fully empirical determination of the metal yield of (now) old stellar populations.

1.3 Metal Production: The Parent Stellar Population

The constant $M^{\rm Fe}/L$ of clusters means that the total mass of iron in the ICM is proportional to the total optical luminosity of the cluster galaxies (Songaila, Cowie, & Lilly 1990; Ciotti et al. 1991; Arnaud et al. 1992; Renzini et al. 1993). The simplest interpretation is that the iron and all the metals now in the ICM have been produced by the (massive) stars of the same stellar generation to which belong the low-mass stars now radiating the bulk of the cluster optical light. Since much of the cluster light comes from old spheroids (ellipticals and bulges), one can conclude that *the bulk of cluster metals were produced by the stars destined to make up the old spheroids that we see today in clusters*.

It is also interesting to ask 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. From their luminosity function it is easy to realize that the bright galaxies (those with $L \gtrsim L^*$) produce the bulk of the cluster light, while the dwarfs contribute a negligible amount of light, in spite of their dominating the galaxy counts by a large margin (Thomas 1999). In practice, most galaxies do not do much, while only the brightest $\sim 3\%$ of all galaxies contribute $\sim 97\%$ of the whole cluster light. Giants dominate the scene, while dwarfs do not count much. Following the simplest interpretation, according to which the metals were produced by the same stellar population that now shines, one can also conclude that the bulk of the cluster metals have been produced by the giant galaxies that contain most of the stellar mass. The relative contribution of dwarfs to ICM metals may have been somewhat larger than their small relative contribution to the cluster light, since metals can more easily escape from their shallower potential wells (Thomas 1999). Yet, this is unlikely to alter the conclusion that the giants dominate metal production by a very large margin.

1.4 Metal Production: Type Ia vs. Type II Supernovae

As is well known, clusters are now dominated by E/S0 galaxies, which produce only Type Ia SNe at a rate of $\sim (0.16\pm 0.06)h_{70}^2$ SNU (Cappellaro, Evans, & Turatto 1999), with 1 SNU corresponding to 10^{-12} SNe yr$^{-1}L_{\mathrm{B}\odot}^{-1}$. Assuming such rate to have been constant through cosmological times ($\sim$13 Gyr), the number of SNe Ia exploded in a cluster of present-day luminosity L_{B} is therefore $\sim 1.6\times 10^{-13}\times 1.3\times 10^{10}L_{\mathrm{B}}h_{70}^2 \simeq 2\times 10^{-3}L_{\mathrm{B}}$. With each SN Ia producing $\sim 0.7M_\odot$ of iron, the resulting M^{Fe}/L of clusters would be:

$$\left(\frac{M^{\mathrm{Fe}}}{L_{\mathrm{B}}}\right)_{\mathrm{SN\ Ia}} \simeq 1.4\times 10^{-3}h_{70}^2, \tag{1.4}$$

which falls short by a factor ~ 10 compared to the observed cluster M^{Fe}/L (0.015 for $h_{70} = 1$). The straightforward conclusion is that either SNe Ia did not play any significant role in manufacturing iron in clusters, or their rate in what are now E/S0 galaxies had to be much higher in the past. This argues for a strong evolution of the SN Ia rate in E/S0 galaxies and bulges, with the past average being $\sim 5-10$ times higher than the present rate (Ciotti et al. 1991). This may soon be tested directly by observations.

In the case of SNe Ia we believe to have a fairly precise knowledge of the amount of iron released by each event, while the ambiguities affecting the progenitors make theory unable to predict the evolution of the SN Ia rate past a burst of star formation (e.g., Greggio 1996). The case of Type II SN's is quite the opposite: one believes to have unambiguously identified the progenitors (stars more massive than $\sim 8M_\odot$), while a great uncertainty affects the amount of iron produced by each SN II event as a function of progenitor's mass, $M_{\mathrm{II}}^{\mathrm{Fe}}(M)$. The SN luminosity at late times can be used to infer the amount of radioactive Ni-Co (hence eventually iron) that was ejected, and an early study indicated small variations from one event to another ($0.04-0.10M_\odot$; Patat et al. 1994). This led Renzini et al. (1993) to assume $M_{\mathrm{II}}^{\mathrm{Fe}}$ to be a weak function of initial mass, with an average yield of $0.07M_\odot$ of iron per event (as in SN 1987A). More recent studies based on a larger sample of SN II events have actually detected very large differences from one event to another (ranging from $\sim 0.002M_\odot$ to $\sim 0.3M_\odot$; Turatto 2003). However, an average over 16 well-studied SNe II gives $\langle M^{\mathrm{Ni}}\rangle = 0.062M_\odot$ (Hamuy 2004), close to the adopted value.

The total number of SNe II, N_{II}, is obtained by integrating the stellar IMF from, for example, 8 to 100 $M_\odot$, with the IMF being $\psi(M) = 3.0L_{\mathrm{B}}M^{-(1+x)}$, where L_{B} is the luminosity of the stellar population when it ages to $\gtrsim 10^{10}$ yr (Renzini 1998b). Clearly, the flatter the IMF slope the larger the number of massive stars per unit present luminosity, the larger the number of SNe II, and the larger the implied M^{Fe}/L. Thus, integrating the IMF one gets

$$\left(\frac{M^{\rm Fe}}{L_{\rm B}}\right)_{\rm SN\ II} = \frac{M^{\rm Fe}_{\rm II}N_{\rm II}}{L_{\rm B}} \simeq \begin{cases} 0.003 & \text{for } x = 1.7 \\ 0.009 & \text{for } x = 1.35 \\ 0.035 & \text{for } x = 0.9. \end{cases} \tag{1.5}$$

Hence, if the Galactic IMF slope ($x = 1.7$; Scalo 1986) applies also to cluster ellipticals, then SNe II underproduce iron by about a factor of ~ 5. Instead, making all the observed iron by SNe II would require an IMF flatter than Salpeter's $x = 1.35$ (Renzini et al. 1993).

In summary, with an IMF with $1.35 \lesssim x \lesssim 1.7$ and a past average rate of SNe Ia in ellipticals $\gtrsim 5$ times the present rate, the iron content of clusters and the global ICM [α/Fe] ratio are grossly accounted for, with SNe Ia then having produced $\sim$1/2–3/4 of the total cluster iron, not unlike in standard chemical models of the Milky Way galaxy. This is not to say that this has been firmly proved, but it seems to me to be premature to abandon the attractive simplicity of a universal nucleosynthesis process (i.e., IMF and SN Ia/SN II ratio) for embarking toward more complex, multi-parametric scenarios.

1.5 Metals from Galaxies to the ICM: Ejection vs. Extraction

Having established that most metals in clusters are out of the parent galaxies, it remains to be understood how they were transferred from galaxies to the ICM. There are two possibilities: extraction by ram pressure stripping as galaxies plow through the ICM, and ejection by galactic winds powered from inside galaxies themselves. In the latter case the power can be supplied by SNe (the so-called star formation feedback) and/or by AGN activity. Three arguments favor ejection over extraction:

- There appears to be no trend of either $Z^{\rm Fe}_{\rm ICM}$ or the $M^{\rm Fe}/L$ with cluster temperature or cluster velocity dispersion ($\sigma_{\rm v}$), while the efficiency of ram pressure stripping should increase steeply with increasing $\sigma_{\rm v}$.
- Field ellipticals appear to be virtually identical to cluster ellipticals. They follow basically the same $\mathrm{Mg}_2-\sigma$ relation (Bernardi et al. 1998, 2003), which does not show any appreciable trend with the local density of galaxies. If stripping was responsible for extracting metals from galaxies one would expect galaxies in low-density environments to have retained more metals, hence showing higher metal indices for a given σ, which is not seen.
- Nongravitational energy injection of the ICM seems to be required to account for the break of the self-similar X-ray luminosity-temperature relation for groups and clusters (Ponman, Cannon, & Navarro 1999; see below). While galactic winds are an obvious vehicle for preheating, no preheating would be associated with metal transfer by ram pressure.

One can quite safely conclude that metals in the ICM have been *ejected* from galaxies by SN (or AGN) driven winds, rather than stripped by ram pressure (Renzini et al. 1993; Dupke & White 1999). Two kinds of galactic winds are likely to operate: *early winds* driven by the starburst forming much of the galaxy's stellar mass itself, and *late winds* or outflows where the gas comes from the cumulative stellar mass loss as the stellar populations passively age. Direct observational evidence for early winds exists for Lyman-break galaxies (Pettini et al. 2001), as well as for local massive starbursts (Heckman et al. 2000). Late winds are also likely to operate, as the stellar mass loss from the aging population flows out of spheroids, being either continuously driven by a declining SN Ia rate (Ciotti et al. 1991), or intermittently by recurrent AGN activity (Ciotti & Ostriker 2001).

1.6 Metals as Tracers of ICM Preheating

The total amount of iron in clusters represents a record of the overall past SN activity as well as of the past mass and energy ejected from cluster galaxies. The empirical values of $M^{\rm Fe}/L$ can be used to set a constraint on the energy injection into the ICM by SN-driven galactic winds (Renzini 1994). The total SN heating is given by the kinetic energy released by one SN ($\sim 10^{51}$ erg) times the number of SNe that have exploded. It is convenient to express this energy per unit present optical light $L_{\rm B}$,

$$\frac{E_{\rm SN}}{L_{\rm B}} = 10^{51}\,\frac{N_{\rm SN}}{L_{\rm B}} = 10^{51}\left(\frac{M^{\rm Fe}}{L_{\rm B}}\right)_{\rm tot}\frac{1}{\langle M^{\rm Fe}\rangle} \simeq 10^{50} \quad ({\rm erg}/L_\odot), \tag{1.6}$$

where the total (ICM+galaxies) $M^{\rm Fe}/L$=0.015 $M_\odot/L_\odot$ is adopted, and the average iron release per SN event is assumed to be $0.15 M_\odot$ (appropriate if SNe Ia and SNe II contribute equally to the iron production). This estimate should be accurate to within a factor of 2 or 3.

The kinetic energy injected into the ICM by galactic winds, again per unit cluster light, is given by 1/2 the ejected mass ($M^{\rm Fe}_{\rm ICM}/Z^{\rm Fe}_{\rm w}$) times the square of the typical wind velocity,

$$\frac{E_{\rm w}}{L_{\rm B}} = \frac{1}{2}\,\frac{M^{\rm Fe}_{\rm ICM}}{L_{\rm B}}\,\frac{\langle v^2_{\rm w}\rangle}{\langle Z^{\rm Fe}_{\rm w}\rangle} \simeq 1.5\times 10^{49}\,\frac{Z^{\rm Fe}_\odot}{Z^{\rm Fe}_{\rm w}}\cdot\left(\frac{v_w}{500\,{\rm km\,s^{-1}}}\right)^2 \simeq 10^{49} \quad ({\rm erg}/L_\odot), \tag{1.7}$$

where the empirical $M^{\rm Fe}/L$ for the ICM has been used and the average metallicity of the winds $Z^{\rm Fe}_{\rm w}$ is assumed to be 2 times solar. As usual in the case of thermal winds, the wind velocity $v_{\rm w}$ is of the order of the escape velocity from individual galaxies. Again, this estimate may be regarded as accurate to within a factor of 2 or so.

A first inference is that of order $\sim 5\% - 20\%$ of the kinetic energy released by SNe is likely to survive as kinetic energy of galactic winds, thus contributing to the heating of the ICM. A roughly similar amount goes into work to extract the gas from the potential well of individual galaxies, while the rest of the SN energy has to be radiated away locally and does not contribute to the feedback. This estimated energy injection represents a small fraction of the thermal energy of the ICM of rich (hot) clusters and so had only a minor impact on the history of the ICM. However, in groups it represents a nonnegligible fraction of the thermal energy of the ICM, thus affecting its evolution and present structure (Renzini 1994). The necessity of some nongravitational heating (or preheating) was recognized from the observed break of the self-similarity of the X-ray luminosity-temperature relation, especially when groups are included (Ponman et al. 1999).

The estimated $\sim 10^{49}$ erg/$L_\odot$ correspond to a preheating of ~ 0.1 keV per particle, for a typical cluster $M_{\rm ICM}/L_{\rm B} \simeq 25\, M_\odot/L_\odot$. This is $\gtrsim$10 times lower than the ~ 1 keV/particle preheating that some models require to fit the cluster $L_{\rm X}-T$ relation (Wu, Fabian, & Nulsen 2000; Borgani et al. 2001, 2002; Tozzi & Norman 2001; Pipino et al. 2002; Finoguenov et al. 2003). This estimate depends somewhat on the gas density (hence environment and redshift) where/when the energy is injected, because what matters is the entropy change induced by the preheating, $\Delta S = k\Delta T/n_{\rm e}^{2/3}$ (Kaiser 1991; Cavaliere, Colafrancesco, & Menci 1993); hence, the required energy decreases if it is injected at a lower gas density. Nevertheless, this extreme (1 keV/particle) requirement would be met only if virtually all the SN energy were to go to increase the thermal energy of the ICM. Such extreme preheating requirement points toward an additional energy (entropy) source, such as AGN energy injection (e.g., Valageas & Silk 1999; Wu et al. 2000). Note, however, that in powerful starbursts most SNe explode inside hot bubbles made by previous SNe, thus reducing radiative losses, and the feedback efficiency may approach unity (Heckman 2002). More recently it has been suggested that preheating requirements may be relaxed somewhat if the energy injection takes place at relatively low density, so as to boost the entropy increase with less energy deposition (Ponman, Sanderson, & Finoguenov 2003). For example, preheating could take place within the filaments, prior to their coalescing to form clusters. Numerical simulations are exploring this possibility (see the review by Evrard 2004), which may eventually reduce the energetic requirement to be more in line with a conservative (i.e., $\sim 0.1-0.3$ keV/particle) SN-driven galactic wind scenario.

1.7 Clusters vs. Field at $z = 0$ and the Overall Metallicity of the Universe

To what extent are clusters fair samples of the $z \sim 0$ Universe as a whole? In many respects clusters look much different from the field, for example in the morphological mix of galaxies, or in the star formation activity, which in clusters has almost completely ceased while it is still going on in the field. Yet, when we restrict ourselves to some global properties clusters and field are not so different. For example, the baryon fraction of the Universe is $\Omega_{\rm b}/\Omega_{\rm m} \simeq 0.16 \pm 0.02$ (Bennett et al. 2003), which compares to ~ 0.15 as estimated for clusters (White et al. 1993), adopting $h_{70} = 1$. This tells us that no appreciable baryon vs. dark matter segregation has taken place at a cluster scale (White et al. 1993).

Even more interesting may be the case of the stellar mass over baryon mass in clusters and in the field. For the field in the local Universe, Fukugita, Hogan, & Peebles (1998) estimate $\Omega_* = 0.0035h_{70}^{-1}$ for the stellar contribution to Ω. From the 2dF K-band luminosity function, Cole et al. (2001) estimate $\Omega_* = 0.0041h_{70}^{-1}$, with a $\sim 15\%$ uncertainty (adopting a Salpeter IMF). The total baryon density is $\Omega_{\rm b} = 0.039h_{70}^{-2}$, as derived from standard Big Bang nucleosynthesis (and confirmed by *WMAP*; Bennett et al. 2003). This gives a global baryon to star conversion efficiency $\Omega_*/\Omega_{\rm b} \simeq 0.10h_{70}$—that is, over the whole cosmic time $\sim 10\%$ of the baryons have been converted and locked into stars. At the galaxy cluster level, the same efficiency can be measured directly, and following White et al. (1993) one gets

$$\frac{M_*}{M_{\rm ICM}+M_*} \simeq \frac{1}{9.3h_{70}^{-3/2}+1} \simeq 0.1. \tag{1.8}$$

For clusters Fukugita et al. (1998) obtain a $\sim 30\%$ larger value, which, however, is well within the uncertainty affecting these estimates. One can safely conclude that *the efficiency of baryon to galaxies/stars conversion has been* $\sim 10\%$, *quite the same in the "field" as well as within rich clusters of galaxies.* The environment seems to be irrelevant!

Two interesting inferences can be drawn from this intriguing cluster-field similarity:

(1) *The metallicity of the present Universe is ∼1/3 solar.* The metallicity of the local Universe has to be virtually identical to that measured in clusters (∼1/3 solar), since star formation, and hence the ensuing metal enrichment, have proceeded at the same level. In analogy to clusters, a majority share of the metals now reside outside galaxies in a warm intergalactic medium (IGM) containing the majority of the baryons. Most baryons as well as most metals in the local Universe remain unaccounted.

(2) *The thermal energy (temperature) of the local Universe is about the same as the preheating energy of clusters.* Similar overall star formation activities most likely result not only in similar metal productions but also in similar energy deposition by galactic winds. Hence, the temperature in the local IGM is likely to be $kT \approx 0.1-1$ keV, whatever the cluster preheating

will turn out to be. Attempts are currently under way to detect this warm, metal-rich IGM. The detection of O VI-absorbing clouds physically located within the Local Group is a first important step in this direction (Nicastro et al. 2003).

1.8 The Major Epoch of Metal Production

Most stars are either in spheroids or in disks. According to Fukugita et al. (1998) $\sim$3/4 of the total mass in stars in the local Universe is now in spheroids, $\sim$1/4 in disks, and less than 1% in irregular galaxies. Other authors give less extreme estimates; Dressler & Gunn (1990) estimate that the stellar mass in spheroids and disks is about the same (see also Benson, Frenk, & Sharples 2002). In clusters the dominance of spheroids is likely to be even stronger than in the general field. The prevalence of spheroids offers an opportunity to estimate the epoch (redshift) at which (most) metals were produced and disseminated, since we now know quite well when most stars in spheroids were formed.

1.8.1 In Clusters

Following the first step in this direction (Bower, Lucey, & Ellis 1992), I believe that the most precise estimates of the age (redshift of formation) of stellar populations in cluster elliptical galaxies come from the tightness of several correlations, such as the color-magnitude, fundamental plane, and the $\mathrm{Mg}_2-\sigma$ relations, and especially by such relations remaining tight all the way to $z \approx 1$ (Stanford, Eisenhardt, & Dickinson 1998; van Dokkum & Franx 2001; see also Renzini 1999 for an extensive review and reference list). This has taught us that the best way of breaking the age-metallicity degeneracy is to look back at high-redshift galaxies. All evidence converges to indicate that most stars in cluster ellipticals formed at $z \gtrsim 3$, while only minor episodes of star formation may have occurred later.

With most of star formation having taken place at such high redshift, most cluster metals should also have been produced and disseminated at $z \gtrsim 3$. Little evolution of the ICM composition is then expected all the way to high redshifts, with the possible exception of iron from SNe Ia, whose rate of release does not follow the star formation rate, but is modulated by the distribution of the delays between formation of the precursor and explosion time. Still, one expects that the SN Ia rate peaks shortly after a burst of star formation and then rapidly declines, with most events taking place within 1–2 Gyr after formation (e.g., Greggio & Renzini 1983). If so, no appreciable evolution of the iron abundance in clusters should be detectable from $z = 0$ to $z \approx 1$. Note, however, that *late winds* will keep enriching the ICM at a decreasing rate approximately $\propto t^{-1.4}$ (Ciotti et al. 1991).

1.8.2 In the Global Universe

As already noted, at $z \approx 0$ field early-type galaxies show very little differences with respect to their cluster analogs. Moreover, bulges appear very similar to ellipticals in integrated properties, such as the $\mathrm{Mg}_2-\sigma$ and fundamental plane relations (Jablonka, Martin, & Arimoto 1996; Falcón-Baroso, Peletier, & Balcells 2002). In the well studied case of the Milky Way bulge, no trace of stars younger than halo-bulge globular clusters could be found (Zoccali et al. 2003). At $z \approx 1$ old early-type galaxies are also found in sizable numbers in the general field, although it appears that star formation may have been a little more extended than in clusters (Cimatti et al. 2002; Treu et al. 2002; Bell et al. 2004).

Therefore, spheroids in the general field appear almost as old as cluster ellipticals, with the bulk of their stellar populations having formed at $z \gtrsim 2-3$. In this spirit, Hogg et al.

(2002) estimate that at least 65% of the stellar mass is at least 8 Gyr old, or formed at $z > 1$. With $\sim$ 50% of the stellar mass in spheroids that formed $\gtrsim$80% of their mass at $z \gtrsim 2-3$, one can conclude that $\gtrsim$30% of the stellar mass we see today was already in place by $z \approx 3$ (Renzini 1998a). This *indirect* estimate is $\sim$ 3 times higher than *directly* measured in the HDF-N (Dickinson et al. 2003). However, this latter result may be subject to cosmic variance, given the small size of the explored field, and indeed HDF-S appears to be much richer in massive galaxies, hence in stellar mass, at high redshift (Franx et al. 2003).

1.8.3 The Metallicity of the Universe at $z = 3$

With $\sim$ 30% of all stars having formed by $z = 3$, $\sim$ 30% of the metals should also have been formed before such an early epoch. I have argued that the global metallicity of the present-day Universe is $\sim$1/3 solar; hence, the metallicity of the $z = 3$ Universe should be $\sim$1/10 solar (Renzini 1998a). This simple argument supports the notion of a *prompt initial enrichment* of the early Universe. While $\sim$ 10% solar at $z = 3$ is a very straightforward estimate, observational tests are not so easy.

Figure 1.4 (adapted from Pettini 2004) shows that at $z = 3$ the Universe had developed extremely inhomogeneously in chemical composition, with the metallicity ranging from supersolar in the central regions of young/forming spheroids and in QSOs likely hosted by them, down to $\sim 10^{-3}$ solar in the Lyα forest. Making the proper (mass-) average abundance of the heavy elements requires one to know the fractional mass of each baryonic component at $z = 3$, not an easy task. While the Lyα forest may fill most of the volume at $z = 3$ and perhaps contain most of the baryons, it may contain as little as just a few percent of the metals produced by $z = 3$. At this early time most metals are likely to be locked into stars, in metal-rich winds, and in shocked IGM which has already diluted wind materials. This latter medium may have been detected, thanks to its O VI absorption (Simcoe, Sargent, & Rauch 2002).

1.9 The Early Chemical Evolution of the Milky Way

In the K band the Galactic bulge luminosity is $\sim 10^{10}\ L_{\mathrm{K},\odot}$ (Kent, Dame, & Fazio 1991), and in the B band the bulge luminosity is $L_{\mathrm{B}}^{\mathrm{bulge}} \simeq 6 \times 10^9 L_{\mathrm{B},\odot}$. From the empirical yield of metals in clusters ($\sim 0.2 \times L_{\mathrm{B}}\ M_\odot$), it follows that the Galactic bulge has produced $M_{\mathrm{Z}} \simeq 0.2 L_{\mathrm{B}}^{\mathrm{bulge}} = 0.2 \times 6 \times 10^9 \simeq 10^9 M_\odot$ of metals. Where are all these metals? One billion solar masses of metals should not be easy to hide: part of it must be in the stars of the bulge itself; part of it must have been ejected by winds. The stellar mass of the bulge follows from its K-band mass to light ratio, $M_*^{\mathrm{bulge}}/L_{\mathrm{K}} = 1$ (Kent 1992; Zoccali et al. 2003), and its luminosity; hence, $M_*^{\mathrm{bulge}} \simeq 10^{10} M_\odot$. Its average metallicity is about solar or slightly lower (McWilliam & Rich 1994; Zoccali et al. 2003), i.e. $Z = 0.02$, and therefore the bulge stars altogether contain $\sim 2 \times 10^8 M_\odot$ of metals. Only $\sim$1/5 of the metals produced when the bulge was actively star forming some 11–13 Gyr ago are still in the bulge! Hence, $\sim$ 80%, or still $\sim 10^9 M_\odot$, wad ejected into the surrounding space by an early wind.

At the time of bulge formation, such $\sim 10^9 M_\odot$ of metals ran into largely pristine ($Z = 0$) material, experienced Rayleigh-Taylor instabilities leading to chaotic mixing, and established a distribution of metallicities in a largely inhomogeneous IGM surrounding the young Milky Way bulge. For example, this enormous amount of metals was able to bring to a metallicity 1/10 solar (i.e., $Z = 0.002$) about $5 \times 10^{11} M_\odot$ of pristine material, several times the mass of the yet-to-be-formed Galactic disk. Therefore, it is likely that the Galactic disk

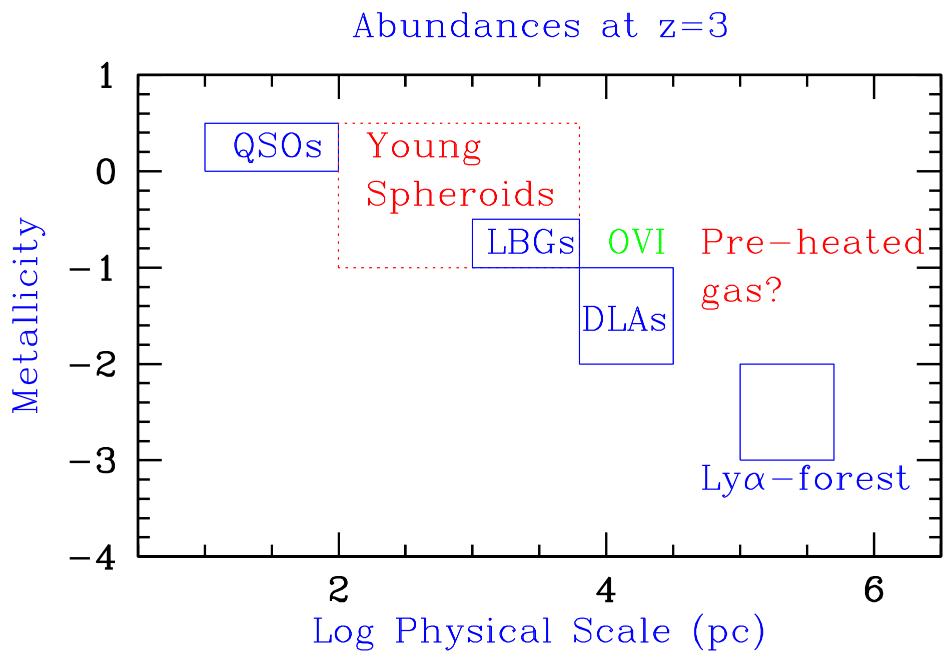

Fig. 1.4. Summary of current knowledge of metal abundances at $z \approx 3$. On the vertical axis the logarithmic abundance relative to solar is reported. The horizontal axis gives the typical linear dimensions of the structures for which direct abundance measurements are available. This figure has been adapted from Pettini (2004) by the inclusion of the box for "young spheroidals," for which the estimate is indirect, as based on the present-day observed metallicity range and on the estimated redshift of formation. The figure also includes the approximate location of the O VI absorbers (Simcoe et al. 2002), and the hypothetical location of the intergalactic medium enriched and preheated by early galactic winds.

formed and grew out of such pre-enriched material, which provides a quite natural solution to the classical "G dwarf problem" (Renzini 2002).

1.10 Summary

A number of interesting inferences are derived starting from a few empirical facts, namely the iron and metal content of the ICM and cluster galaxies, the fraction of the baryons locked into stars in clusters and in the field, and the age and baryon fraction of stellar populations of galactic spheroids. Such inferences include:

- In clusters and in the general field alike there are more metals in the diffused gas (ICM and IGM) than there are locked into stars inside galaxies. The loss of metals to the surrounding media is therefore a major process in the chemical evolution of galaxies.
- In clusters and in the general field alike $\sim 10\%$ of the baryons are now locked into stars inside galaxies. At this global level, the outcome of star formation through cosmic time is largely independent of environment, most likely just because a major fraction of all stars formed before cluster formation.

- Various arguments support the notion that the metals now in the ICM/IGM were ejected by galactic winds, rather then being extracted from galaxies by ram pressure.
- Having processed the same fraction of baryons into stars, the global metallicity of the local Universe has to be nearly the same one can measure in clusters, namely $\sim$1/3 solar.
- For the same reason, one expects the IGM to have experienced nearly the same amount of preheating as the ICM, and therefore to be at a temperature of $\sim 0.1-1$ keV, whatever is the amount of preheating that is required for clusters.
- Given the predominance and formation redshift of galactic spheroids, both in clusters as well as globally in the Universe, it is likely that the Universe experienced a prompt metal enrichment, with the global metallicity possibly reaching $\sim$1/10 solar already at $z \approx 3$. However, most metals remain unaccounted both at low as well as high redshift, and may reside in a warm IGM, the existence of which we have only preliminary observational hints.
- This same scenario may well hold down to the scale of our own Milky Way galaxy, with early winds from the forming Galactic bulge having pre-enriched to $\sim$1/10 solar a much greater mass of gas, out of which the Galactic disk started to form and grew.

References

Aguirre, A., Hernquist, L., Schaye, J., Katz, N., Weinberg, D. H., & Gardner, J. 2001, ApJ, 561, 521

Anders, E., & Grevesse, N. 1989, Geochimica et Cosmochimica Acta, 53, 197

Arimoto, N., Matsushita, K., Ishimaru, Y., Ohashi, T., & Renzini, A. 1997, ApJ, 477, 128

Arnaboldi, M., et al. 2003, AJ, 125, 514

Arnaud, M., & Evrard, A. E. 1999, MNRAS, 305, 631

Arnaud, M., Rothenflug, R., Boulade, O., Vigroux, R., & Vangioni-Flam, E. 1992, A&A, 254, 49

Bell, E. F., Wolf, C., Meisenheimer, K., Rix, H.-W., Borch, A., Dye, S., Kleinheinrich, M., & McIntosh, D. H. 2004, ApJ, submitted (astro-ph/0303394)

Bennett, C. L., et al. 2003, ApJS, 148, 1

Benson, A. J., Frenk, C. S., & Sharples, R. M. 2002, ApJ, 574, 104

Bernardi, M., et al. 2003, AJ, 125, 1882

Bernardi, M., Renzini, A., da Costa, L. N., Wegner, G., Alonso, M. V., Pellegrini, P. S., Rité, C., & Willmer, C. N. A. 1998, ApJ, 508, L143

Borgani, S., Governato, F., Wadsley, J., Menci, N., Tozzi, P., Lake, G., Quinn, T., & Stadel, J. 2001, ApJ, 559, L71

Borgani, S., Governato, F., Wadsley, J., Menci, N., Tozzi, P., Quinn, T., Stadel, J., & Lake, G. 2002, MNRAS, 336, 424

Bower, R. G., Lucey, J. R., & Ellis, R. S. 1992, MNRAS, 254, 613

Buote, D. A. 2000, MNRAS, 311, 176

Cappellaro, E., Evans, R., & Turatto, M. 1999, A&A, 351, 459

Cavaliere, A., Colafrancesco, S., & Menci, N. 1993, ApJ, 415, 50

Chiosi, C. 2000, A&A, 364, 423

Cimatti, A., et al. 2002, A&A, 381, L68

Ciotti, L., D'Ercole, A., Pellegrini, S., & Renzini, A. 1991, ApJ, 376, 380

Ciotti, L., & Ostriker, J.P. 2001, ApJ, 551, 131

Cole, S., et al. 2001, MNRAS, 326, 255

David, L. P., Jones, C., Forman, W., & Daines, S. 1994, ApJ, 428, 544

Davis, D. S., Mulchaey, J. S., & Mushotzky, R. F. 1999, ApJ, 511, 34

De Grandi, S., & Molendi, S. 2001, ApJ, 551, 153

——. 2002, in Chemical Enrichment of Intracluster and Intergalactic Medium, ed. R. Fusco-Femiano & F. Matteucci (San Francisco: ASP), 3

Dickinson, M., Papovich, C., Ferguson, H. C., & Budavari, T. 2003, ApJ, 587, 25

Dressler, A., & Gunn, J. E. 1990, in Evolution of the Universe of Galaxies, Proceedings of the Edwin Hubble Centennial Symposium, ed. R. G. Kron (San Francisco: ASP), 200

Dupke, R. A., & White, R. E., III 2000, ApJ, 537, 123

Evrard, A. E. 2004, in Carnegie Observatories Astrophysics Series, Vol. 3: Clusters of Galaxies: Probes of

Cosmological Structure and Galaxy Evolution, ed. J. S. Mulchaey, A. Dressler, & A. Oemler (Cambridge: Cambridge Univ. Press), in press
Falcón-Barroso, J., Peletier, R. F., & Balcells, M. 2002, MNRAS, 335, 741
Ferguson, H. C., Tanvir, N. R., & von Hippel, T. 1998, Nature, 391, 461
Finoguenov, A., Arnaud, M., & David, L. P. 2001, ApJ, 555, 191
Finoguenov, A., Borgani, S., Tornatore, L., & Böhringer, H. 2003, A&A, 398, L35
Finoguenov, A., David, L. P., & Ponman, T. J. 2000, ApJ, 544, 188
Finoguenov, A., Jones, C., Böhringer, H., & Ponman, T.J. 2002, ApJ, 578, 74
Franx, M., et al. 2003, ApJ, 587, L79
Fukazawa, Y, Ohashi, T., Fabian, A. C., Canizares, C. R., Ikebe, Y., Makishima, K., Mushotzky, R. F., & Yamashita, K. 1994, PASJ, 46, L55
Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, ApJ, 503, 518
Gibson, B., & Matteucci, F. 1997, MNRAS, 291, L8
Greggio. L. 1996, in The Interplay between Massive Star Formation, the ISM and Galaxy Evolution, ed. D. Kunth et al. (Gif-sur-Yvettes: Edition Frontières), 89
Greggio. L., & Renzini, A. 1983, A&A, 118, 217
Hogg, D. W., et al. 2002, AJ, 124, 646
Hamuy, M. 2004, in Core Collapse of Massive Stars, ed. C. L. Fryer (Dordrecht: Kluwer), in press (astro-ph/0301006)
Heckman, T. M. 2002, in Extragalactic Gas at Low Redshift, ed. J. S. Mulchaey & J. Stocke (San Francisco: ASP), 292
Heckman, T. M., Lehnert, M. D., Strickland, D. K., & Armus, L. 2000, ApJS, 129, 493
Ishimaru, Y., & Arimoto, N. 1997, PASJ, 49, 1
Jablonka, P., Martin, P., & Arimoto, N. 1996, AJ, 112, 1415
Kaiser, N. 1991, ApJ, 383, 104
Kent, S. M. 1992, ApJ, 387, 181
Kent, S. M., Dame, T. M., & Fazio, G. 1991, ApJ, 378, 131
Larson, R. B., & Dinerstein, H. L. 1975, PASP, 87, 511
Loewenstein, M. 2001, ApJ, 557, 573
Loewenstein, M., & Mushotzky, R. F. 1996, ApJ, 466, 695
Maraston, C., Greggio, L., Renzini, A., Ortolani, S., Saglia, R. P., Puzia, T. H., & Kissler-Patig, M. 2003, A&A, 400, 823
Matteucci, F., & Vettolani, G. 1988, A&A, 202, 21
McWilliam, A., & Rich, R. M. 1994, ApJS, 91, 794
Mitchell, R. J., Culhane, J. L., Davison, P. J., & Ives, J. C. 1976, MNRAS, 175, 29P
Mohr, J. J., Mathiesen, B., & Evrard, A. E. 1999, ApJ, 627, 649
Mulchaey, J. S., Davis, D. S., Mushotsky, R. F., Burstein, D. 1993, ApJ, 404, L9
——. 1996, ApJ, 456, 80
Mushotzky, R. F. 1994, in Clusters of Galaxies, ed. F. Durret, A. Mazure, & J. T. Thanh Van (Gyf-sur-Yvette: Editions Frontières), 167
——. 2002, Phil. Trans. R. Soc. Lond. A, 360, 2019
Mushotzky, R. F., Loewenstein, M., Arnaud, K. A., Tamura, T., Fukazawa, Y., Matsushita, K., Kikuchi, K., & Hatsukade, I. 1996, ApJ, 466, 686
Nicastro, F., et al. 2003, Nature, 421, 719
Patat, F., Barbon, R., Cappellaro, E., & Turatto, M. 1994, A&A, 282, 731
Pettini, M. 2004, in Cosmochemistry: The Melting Pot of Elements (Cambridge: Cambridge Univ. Press), in press (astro-ph/0303272)
Pettini, M., Shapley, A. E., Steidel, C. C., Cuby, J.-G., Dickinson, M., Moorwood, A. F. M., Adelberger, K. L., & Giavalisco, M. 2001, ApJ, 554, 981
Pipino, A., Matteucci, F., Borgani, S., & Biviano, A. 2002, NewA, 7, 227
Ponman, T. J., Allan, D. J., Jones, L. R., Merrifield, M., McHardy, I. M., Lehto, H. J., & Luppino, G. A. 1994, Nature, 369, 462
Ponman, T. J., Cannon, D. G., & Navarro, J. F. 1999, Nature, 397, 135
Ponman, T. J., Sanderson, A. J. R., & Finoguenov, A. 2003, MNRAS, 343, 331
Pratt, G. W., & Arnaud, M. 2003, A&A, 408, 1
Renzini, A. 1994, in Clusters of Galaxies, ed. F. Durret, A. Mazure, & J. T. Thanh Van (Gyf-sur-Yvette: Editions Frontières), 221

——. 1997, ApJ, 488, 35
——. 1998a, in The Young Universe: Galaxy Formation and Evolution at Intermediate and High Redshift, ed. S. D'Odorico, A. Fontana, & E. Giallongo (San Francisco: ASP), 298
——. 1998b, AJ, 115, 2459
——. 1999, in The Formation of Galactic Bulges, ed. C. M. Carollo, H. C. Ferguson, & R. F. G. Wyse (Cambridge: Cambridge Univ. Press), 9
——. 2000, in Large Scale Structure in the X-ray Universe, ed. M. Plionis & I. Georgantopoulos (Gif-sur-Yvette: Editions Frontiéres), 103
——. 2002, in Chemical Enrichment of Intracluster and Intergalactic Medium, ed. R. Fusco-Femiano & F. Matteucci (San Francisco: ASP), 331
Renzini, A., Ciotti, L., D'Ercole, A., & Pellegrini, S. 1993, ApJ, 419, 52
Scalo, J. M. 1986, Fund. Cosmic Phys. 11, 1
Simcoe, R. A., Sargent, W. L. W., & Rauch M. 2002, ApJ, 578, 737
Songaila, A., Cowie, L. L., & Lilly, S. J. 1990, ApJ, 348, 371
Stanford, S. A., Eisenhardt, P. R., & Dickinson, M. 1998, ApJ, 492, 461
Thomas, D. 1999, in Chemical Evolution from Zero to High Redshift, ed. J. R. Walsh & M. R. Rosa (Berlin: Springer), 197
Tozzi, P., & Norman, C. 2001, ApJ, 546, 63
Treu, T., Stiavelli, M., Casertano, S., Møller, P., Bertin, G. 2002, Apj, 564, L13
Tsuru, T. 1992, Ph.D. Thesis, Univ. Tokyo
Turatto, M. 2003, in Supernovae and Gamma-Ray Bursters, ed. K. W. Weiler (Berlin: Springer), 21
Valageas, P., & Silk, J. 1999, A&A, 350, 725
van Dokkum, P. G., & Franx, M. 2001, ApJ, 553, 90
Vigroux, L. 1977, A&A, 56, 473
White, D. A. 2000, MNRAS, 312, 663
White, S. D. M., Navarro, J. F., Evrard, A. E., & Frenk, C. S. 1993, Nature, 366, 429
Wu, K. K. S., Fabian, A. C., & Nulsen, P. E. J. 2000, MNRAS, 318, 889
Zoccali, M., et al. 2003, A&A, 399, 931