Chemical Evolution on the Scale of Clusters of Galaxies, and Beyond

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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 \( \sim 2 \) keV, and the elemental proportions (i.e. the [\( \alpha/\text{Fe} \)] ratio) appear to be solar. From these evidences it is argued that both the IMF as well the relative contributions of SN types are likely to be universal. Constraints on the past SN activity in galaxy clusters are then derived, and support is given to the notion that the average SNIa rate was much higher in the past, i.e. at least 10 times more than currently observed in local elliptical-s.

It is also argued that cluster metallicity (\( \sim 1/3 \) solar) should be taken as representative of the low-z universe as a whole. There is now compelling evidence that the bulk of stars in cluster as well as in field ellipticals and bulges formed at high redshifts (\( z \gtrsim 3 \)). Since such stars account for at least \( \sim 30\% \) of the baryons now locked into stars, it is argued that at least 30\% of stars and metals formed before \( z \gtrsim 3 \). As a consequence, the metallicity of the universe at \( z = 3 \) is predicted to be \( \sim 1/10 \) solar. This requires the cosmic star formation rate to run at least flat from \( z \sim 1 \) to \( z \sim 5 \), which appears to agree with the most recent direct determinations of the star formation rate in Lyman-break galaxies.

1 Introduction

Clusters of galaxies are the largest entities for which we have chemical information, hence for which chemical evolution can be studied. Moreover, there are reasons to believe that low-redshift clusters are reasonably fair samples of the nearby universe, as far as global star formation and ensuing chemical evolution are concerned. Therefore, their study can allow us to address in a semiempirical way chemical evolution on the largest possible scale, that of the universe as a whole. In doing so, several interesting constraints can be set on the lower scales as well, such as individual galaxies.

This paper is organized as follows. Section 2 presents the current evidence for the chemical composition of local clusters of galaxies at low redshift, for both the intracluster medium (ICM) and for cluster galaxies. In Section 3 the production of iron on the scale of clusters is discussed, setting requirements on the number of Type Ia and Type 2 supernovae (SN) that are necessary to account for the observed amount of iron. Current theoretical yields are also checked vis à vis the observational constraints. In Section 4 the current evidence is briefly reviewed for the bulk of stars in galactic spheroid-s (i.e. ellipticals and bulges alike) being
very old, formed at high redshift, no matter whether they reside in rich clusters or in the low density environment we usually refer to as the field. In Section 5 these evidences are used to set constraints on the past history of star formation and metal production, hence on the metallicity of the high-$z$ universe.

2 The Chemistry of Galaxy Clusters

Theoretical simulations predict that the baryon fraction of rich clusters cannot change appreciably in the course of their evolution (White et al. 1993). We can then expect within a cluster to find confined in the same place all the dark matter, all the baryons, all the galaxies, hence all the metals, that have participated in the play. Clusters are then good archives of their past star formation and metal production history.

Metals in clusters are partly spread through their ICM, partly locked into galaxies and stars. The mass of metals in the ISM of galaxies is instead negligible compared to that in the two other components. ICM abundances can be obtained from X-ray observations, while optical observations combined to population synthesis models provide estimates for the metallicity of the stellar component of galaxies.

2.1 The Iron Content of the Intracluster Medium

The existence of large amounts of iron in the ICM was first predicted on purely theoretical grounds (Larson & Dinerstein 1975). Soon iron was actually detected via the iron-K X-ray emission at $\sim 7$ keV (Mitchell et al. 1976). Fig. 1 shows the iron abundance in the ICM of clusters and groups as a function of ICM temperature, from a compilation of existing data (Renzini 1997, hereafter R97). As it will become apparent later in this section, perhaps even more interesting than the ICM abundance of iron is the quantity called the iron-mass-to-light-ratio ($\text{Fe}_\text{M/L}$) of the ICM, which is defined as 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 (cf. Songaila, Cowie, & Lilly 1990; Ciotti et al. 1991; Arnaud et al. 1992; Renzini et al. 1993; R97). The $\text{Fe}_\text{M/L}$ of clusters and groups is shown in Fig. 2.

The drop of the derived $\text{Fe}_\text{M/L}$ in poor clusters and groups (i.e. for $kT<2$ keV) can be traced back to a drop in both factors entering in its definition, i.e., in the iron abundance (cf. Fig. 1) and in the ICM mass to light ratio (R97). We don’t know whether this drop is a real effect. Groups may not behave as closed boxes, and 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, Mulchaey & Mushotzky 1998). In addition, there may be a diagnostic problem, since for $kT<2$ keV iron is derived from iron-L transitions involving iron ions with 3 to 8 bound electrons. The atomic physics of iron-L is therefore far more complex and uncertain than that of the iron-K, which is due to transitions in H-like and He-like iron (Arimoto et al. 1997). For this reason I will not further discuss clusters whose ICM is cooler than $kT<2$ keV.
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Fig. 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 \( z > 0.35 \), represented by small filled circles.

Fig. 1 and 2 show that both the iron abundance and the FeM/L in rich clusters (\( kT \sim 2 \text{ keV} \)) 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 \( H_o = 50 \). The most straightforward interpretation is that clusters did not lose iron (hence baryons), nor selectively acquired pristine baryonic material, and that the conversion of baryonic gas into stars and galaxies has proceeded with the same efficiency and stellar IMF in all clusters (R97). Otherwise, we should observe cluster to cluster variations of the iron abundance and of the FeM/L. The theoretical prediction by White et al. (1993) of the constancy of the baryon fraction in clusters is nicely supported by these evidences.

2.2 The \( \alpha \)-Elements in the Intracluster Medium

X-ray observations have also allowed to measure the abundance of other elements in the ICM, especially that of the \( \alpha \)-elements such as O, Ne, Mg, and Si, with the ASCA X-Ray telescope having superseded all previous attempts. A high \( \alpha \)-element enhancement, \(< [\alpha/\text{Fe}] > \sim +0.4 \), was initially reported (Mushotzky 1994), an estimate that was soon revised down to \(< [\alpha/\text{Fe}] > \sim +0.2 \) (Mushotzky et al. 1996). This may still suggest a modest \( \alpha \)-element enhancement, with the ICM enrichment being dominated by SNII products. However, even this modest \( \alpha \)-element overabundance vanishes when consistently adopting the “meteoritic” iron abundance for the sun, as opposed to the “photospheric” value (Ishimaru & Arimoto 1997). One can then conclude that there is no appreciable \( \alpha \)-element enhancement in the ICM, with a formal average \(< [\alpha/\text{Fe}] > \sim +0.04 \pm \sim 0.2 \) (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. In particular, this implies a similar ratio of the number of Type Ia to Type II SNe, as well as a similar IMF (R97). This result suggests 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. Perhaps this is just telling us that like it is difficult to look into a molecular cloud, it is also difficult for the star forming core of the cloud to have an idea of the galaxy in which it happens to be located.

It is nevertheless worth mentioning that other interpretations have been proposed. For example, bimodal star formation, with most of the metals in the ICM having been produced by a now extinct generation of only massive stars, has been advocated by Elbaz, Arnaud, & Vangioni-Flam (1995), see also Larson (1998). The decoupling of the stellar population having made the cluster metals, from the one now making the cluster light, would require fine tuning to account for the observed constancy of the Fe/M/L which is illustrated in Fig. 2. Such constancy is instead the straightforward consequence of a universal IMF.

2.3 The Iron Content of Galaxies and the Iron Share

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. Hence, the average iron abundance cannot be much different from solar, even when taking into account the presence of radial gradients (Arimoto...
et al. 1997), $\alpha$-element enhancements (Davies, Sadler, & Peletier 1993), and the luminosity bias (Greggio 1997).

The global iron abundance of a whole cluster is therefore given by:

$$Z_{\text{Fe}}^{\text{CL}} = \frac{Z_{\text{Fe}}^{\text{ICM}} M_{\text{ICM}} + Z_{\text{Fe}}^{\star} M_{\star}}{M_{\text{ICM}} + M_{\star}} = \frac{5.5 Z_{\text{Fe}}^{\text{ICM}} h^{-5/2} + Z_{\text{Fe}}^{\star} h^{-1}}{5.5 h^{-5/2} + h^{-1}}, \quad (1)$$

where $Z_{\text{Fe}}^{\star}$ is the average abundance of stars in galaxies and $M_{\star}$ is the mass in stars. For the second equality I have assumed as prototypical the Coma cluster values adopted by White et al. (1993): $M_{\text{ICM}} \simeq 5.5 \times 10^{13} h^{-5/2} M_\odot$ and $M_{\star} \simeq 10^{13} h^{-1} M_\odot$. With $Z_{\text{Fe}}^{\text{ICM}} = 0.3$ solar and $Z_{\text{Fe}}^{\star} = 1$ solar, equation (1) gives a global cluster abundance of 0.34, 0.37, and 0.41 times solar, respectively for $h = 0.5, 0.75,$ and 1. Under the same assumptions, the ratio of the iron mass in the ICM to the iron mass locked into stars is:

$$\frac{Z_{\text{Fe}}^{\text{ICM}} M_{\text{ICM}}}{Z_{\text{Fe}}^{\star} M_{\star}} \simeq 1.65 h^{-3/2}, \quad (2)$$

or 4.6, 2.5, and 1.65, respectively for $h = 0.5, 0.75,$ and 1. 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 $H_\odot$. These estimates could be somewhat decreased if clusters contain a sizable population of stars not bound to cense-d individual galaxies, if the average iron abundance in stars is supersolar (luminosity-weighted determinations underestimate true abundances, e.g. Greggio 1997), or if the galaxy $M_\star/L$ ratio is larger than the value used here, i.e., $<M_\star/L_B> = 6.4 h$ (White et al. 1993). In any event, it is clear that there is at least as much metal mass out of cluster galaxies (in the ICM), as there is inside them (locked into stars). [Note that the contribution of the ISM of galaxies is now negligible.] This must be taken as a strong constraint by models of the chemical evolution of galaxies: clearly galaxies do not evolve as a closed box, and outflows must play a leading role.

With the adopted masses and iron abundances for the two baryonic components one can also evaluate the total cluster Fe$/L$:

$$\frac{M_{\text{Fe}}^{\text{ICM}} + M_{\text{Fe}}^{\star}}{L_B} \simeq 1.3 \times 10^{-2} (1.65 h^{-1/2} + h) (M_\odot/L_\odot), \quad (3)$$

or Fe$/L$=0.037 or 0.034 $M_\odot/L_\odot$, respectively for $h = 0.5$ and 1. The total Fe$/L$ is therefore fairly insensitive to the adopted distance scale.

### 3 Empirical and Theoretical Metal Yields

From the near solar proportions of cluster abundances one obtains the total metal mass to light ratio of a typical cluster as $M_Z/L_B \simeq 10 \times M_{\text{Fe}}/L_B \simeq 0.3 \pm 0.1 (M_\odot/L_\odot)$. It is worth noting that this is an interesting, fully empirical estimate of the metal yield of stellar populations. In Section 4 it will be documented that the bulk of stars in galaxy clusters are very old, say $\sim 15$ Gyr old.
Hence, a single burst approximation may not be too rough for some applications. This empirical yield means that ∼ 15 Gyr after a burst of star formation there are ∼ 0.3 \( M_\odot \) of metals for each \( L_\odot \) of blue light from the surviving (low-mass) stellar population. It therefore connects the prompt release of the metals by stars at the top end of the IMF to the luminosity released ∼ 15 Gyr later by the stars at the lower end of the IMF of this same stellar population. A concrete example may help familiarizing with the concept. Consider a globular cluster, with \( L_B = 10^5 L_\odot \), \( Z = 10^{-4} \), age=15 Gyr and \( M = 10^5 M_\odot \). With this empirical yield the globular cluster stellar population has produced ∼ 3 × 10^4 \( M_\odot \) of metals. Yet such cluster now contains only 10 \( M_\odot \) of metals, which actually pre-existed its formation (as well know the overwhelming majority of globulars are not self-enriched). All these ∼ 3 × 10^4 \( M_\odot \) of metals were promptly ejected through a cluster wind driven by the ∼ 10^4 SNIIs that exploded during the first 30 Myr of the cluster life. Therefore, the cluster was able to rise to its own metallicity ∼ 3 × 10^5 \( M_\odot \) of uncontaminated material, i.e. 3000 times its own present mass. Metal enrichment is a very quick process!

As in Tinsley (1981), the metal yield is usually defined per unit mass of stars, a quantity which theoretical counterpart depends on the poorly known low mass end of the IMF. The estimate above gives instead the yield per unit luminosity of present day cluster galaxies, a quantity that depends on the IMF only for \( M \gtrsim M_\odot \). Theoretical mass-related yields have been recently estimated by Thomas, Greggio, & Bender (1998) based on massive star and supernova explosion models (Woosley & Weaver 1995; Thielemann, Nomoto, & Hashimoto 1996). These yields can be purged of their mass dependence, and transformed into luminosity-related yields. To this end, let us assume an age of 15 Gyr for the bulk of stars in clusters (cf. Section 4), and use the proper luminosity-IMF normalization (Renzini 1998a); i.e. \( \psi(M) = A M^{-(1+x)} \) for the IMF with \( A \simeq 3.0 L_B \), where \( L_B \) is the luminosity of the stellar population at at the age of 15 Gyr. Thus, theoretical yields turn out to be \( M_Z/L_B = 0.08, 0.24 \), and \( 0.33 M_\odot/L_\odot \), respectively for \( x = 1.7, 1.35 \), and \( 1.00 \), which compares to \( M_Z/L_B \simeq 0.3 \pm 0.1 M_\odot/L_\odot \) for the empirical cluster value. One can conclude that current stellar yields do not require a very flat IMF to account for the cluster metals.

### 3.1 The Relative Role of Type Ia and Type II Supernovae

SN rates are measured in SNUs, with 1 SNU corresponding to \( 10^{-12} \) SNs yr\(^{-1}\) \( L_B^{-1} \). As well known, clusters are now dominated by E/S0 galaxies, which produce only Type Ia SNs at a rate of ∼ 0.06 SNU for \( h = 0.5 \) (Cappellaro et al. 1993). Assuming such rate to have been constant through cosmological times (15 Gyr), the number of SNIa’s exploded in a cluster of present-day luminosity \( L_B \) is therefore ∼ \( 6 \times 10^{-14} \times 1.5 \times 10^{10} L_B \simeq 10^{-3} L_B \). With each SNIa producing ∼ 0.7 \( M_\odot \) of iron, the resulting \( \frac{Fe}{L} \) of clusters would be:

\[
\left( \frac{M_{Fe}}{L_B} \right)_{\text{SNIa}} \simeq 7 \times 10^{-4},
\]
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which falls short by a factor $\sim 50$ compared to the observed cluster Fe $M/L$. The straightforward conclusion is that either SNIa’s 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 SNIa rate in E/S0 galaxies and bulges, with the past average being some $10$ to $50$ times higher than the present rate (Ciotti et al. 1991; R97). Observations of SNIa’s at high redshift is now becoming a major area of observational cosmology (e.g. Garnavich et al. 1998), and whether the SNIa rate was indeed much higher in the past could soon be tested directly.

In the case of SNIa’s 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 SNIa 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 $M_{Fe}^{II}(M)$ produced by each SNII event as a function of progenitor’s mass. Renzini et al. (1993) list empirical reasons to believe that this is not a strong function of initial mass, and that assuming $0.07 M_\odot$ of iron per event (as in SN 1987A) cannot be too far from reality. The total number of SNII’s $N_{SNII}$ is obtained integrating the stellar IMF from e.g. 8 to $100 M_\odot$, with the IMF being $\psi(M) = 3.0 L_B M^{-0.7}$.

Clearly, the flatter the IMF slope the larger the number of massive stars per unit present luminosity, the larger the number of SNII’s, and therefore the larger the implied Fe $M/L$. Thus, integrating the IMF one gets:

$$(M_{Fe}/L_B)_{SNII} = M_{Fe}^{II} N_{SNII}/L_B \approx \begin{cases} 0.003 & \text{for } x = 1.7 \\ 0.009 & \text{for } x = 1.35 \\ 0.035 & \text{for } x = 0.9. \end{cases} \tag{5}$$

We conclude that if the Galactic IMF slope ($x = 1.7$, Scalo 1986) applies also to ellipticals in rich clusters, then SNII’s underproduce iron by about a factor of 10 compared to what demanded by equation (3). Instead, making all the observed iron by SNII’s would require a very flat IMF ($x \approx 0.9$).

It is worth noting that for an IMF slope somewhere between Scalo’s and Salpeter’s SNII’s make about 1/4 to 1/3 of the total iron, while the rest has to be made by SNIa’s, just as in the so-called standard chemical model for the chemical evolution of the Milky Way (cf. Renzini et al. 1993, R97).

3.2 Clusters as Fair Samples of the Local Universe

To what extent the cluster global metallicity, and the ICM to galaxies iron share are representative of the low-$z$ universe as a whole? For example, Madau et al. (1996) adopt $H_0 = 50$, a stellar mass density parameter $\Omega_\star = 0.0036$, and a baryon mass density parameter $\Omega_\text{b} = 0.05$. With these values the fraction of baryons that have been locked into stars is $\sim 7\%$. This compares to $\sim 1/(1 + 5.5h^{-3/2})$ in clusters, or $\sim 6\%$ and $\sim 10\%$, respectively for $h = 0.5$ and 0.75.
Fukugita, Hogan & Peebles estimate \((\Omega_*/\Omega_b)_0 = 0.13\) for \(h = 0.5\), which is a factor of 2 higher than the cluster value, but they may have overestimated the stellar mass in spheroids (see Section 4.2). Therefore, it appears that the global, universal efficiency of baryon conversion into galaxies and stars \(- (\Omega_*/\Omega_b)_0 \) is nearly the same as that observed in local clusters, which supports the notion of clusters being representative of the low-\(z\) universe as a whole.

With nearly the same fraction of baryons having been turned into stars in the field as in clusters, one can legitimately entertain also the notion that no major difference in metal enrichment exists between field and clusters. Therefore, the global metallicity of the present-day universe is likely to be \(\sim 1/3\) solar, as that of the only place where we can thoroughly measure it: galaxy clusters. If so, the metal share of the IGM to galaxies should be nearly the same as the cluster ICM to galaxies metal share, as given by equation (2), with most of the metals residing in the IGM rather than within field galaxies (R97).

4 The Prompt Initial Enrichment of the Universe

The cluster abundances as illustrated in the previous section don’t say much about the cosmic epoch when the bulk of the cluster metals were produced and dispersed through the ICM. The only constraint comes from the iron abundance in moderate redshift clusters \((z \simeq 0.5)\) being the same of local clusters (see Fig. 1), hence the bulk of iron had to be manufactured at \(z \gtrsim 0.5\). Future X-ray missions could probably bring this limit to \(z \simeq 1\). A much more stringent constraint comes from current age estimates of the dominant stellar populations in cluster ellipticals, the likely producers of the bulk of the metals, and from other fossil evidences which are concisely reported in this section.

4.1 The Age of Spheroids

An important breakthrough on the formation epoch of stars in cluster ellipticals came from the very tight color-\(\sigma\) relation followed by galaxies in the Virgo and Coma clusters, which demonstrates that the bulk of stars in cluster ellipticals are very old, likely formed at \(z \gtrsim 2\) (Bower, Lucey & Ellis 1992). This result had the merit to cut short inconclusive discussions on the age of ellipticals based on matching synthetic spectra to those of individual galaxies, and showed instead that the homogeneity of elliptical populations sets tight, almost model independent age constraints. Following the same methodological approach, evidence supporting an early formation of the bulk of stars in ellipticals has greatly expanded over the last few years. This came from the tightness of the fundamental plane relation for ellipticals in local clusters (Renzini & Ciotti 1993), from the tightness of the color-magnitude relation for ellipticals in clusters up to \(z \sim 1\), and from the modest shift with increasing redshift in the zero-point of the fundamental plane, \(M_{g2} - \sigma\), and color-magnitude relations of cluster ellipticals (e.g., Aragon-Salamanca et al. 1993; Bender et al. 1997; Dickinson 1995;
Ellis et al. 1997; Kodama et al. 1998; Stanford, Eisenhardt & Dickinson 1998; van Dokkum et al. 1998). All these studies agree in concluding that most stars in cluster ellipticals formed at $z \gtrsim 3$, though the precise value depends on the adopted cosmological parameters.

Fig. 3. The color evolution of early-type galaxies in clusters out to $z \approx 0.9$ (Stanford, Eisenhardt, & Dickinson 1997). The “blue” band is tuned for each cluster to approximately sample the rest frame $U$-band, while the $K$ band is always in the observed frame. Top panel: the redshift evolution of the blue$-K$ color relative to the Coma cluster. A purely passive evolution model is also shown. Middle panel: the intrinsic color scatter, having removed the mean slope of the color-magnitude relation in each cluster and the contribution of photometric errors. The intrinsic scatter of Coma galaxies is shown for reference. Bottom panel: the redshift evolution of the slope of the (blue$-K$) $- K$ color-mag diagram, modulo the slope for galaxies in Coma.

This cogent result has been established for cluster ellipticals, but additional fossil evidence argues for its validity for field ellipticals as well as for most bulges of spirals, i.e. in general for the vast majority of galactic spheroids. Field E/S0 galaxies follow virtually the same $M_{\text{g}_2} - \sigma$ relation of their cluster counterparts, with the age difference being less than $\sim 1$ Gyr (Bernardi et al. 1998).
Most bulges follow the same Mg−σ and color-magnitude relations of ellipticals (Jablonka, Martin & Arimoto 1996). Even more directly, the bulge of our own Galaxy is found to be dominated by stars which age is indistinguishable from that of the Galactic halo, or \( \gtrsim 12 \) Gyr (Ortolani et al. 1995). The case for old spheroidals is more extensively reviewed in Renzini (1999), with an excerpt from Stanford et al. (1998) being shown in Fig. 3.

4.2 Demography of Spheroids

With spheroids containing at least 30% of all stars in the local universe (King & Ellis 1985; Schechter & Dressler 1987; Persic & Salucci 1992), an perhaps as much as \( \sim 75\% \) (Fukugita, Hogan & Peebles 1998), one can rather safely conclude that at least 30% of all stars and metals have formed at \( z \gtrsim 3 \) (Renzini 1998b, 1999; see also Dressler & Gunn 1990). This is several times more than suggested by a conservative interpretation of the early attempt at tracing the cosmic history of star formation, either empirically (Madau et al. 1996) or from theoretical simulations (e.g. Baugh et al. 1998). Nevertheless, it is in good agreement with more recent direct estimates from the spectroscopy of Lyman-break galaxies (Steidel et al. 1998), where the cosmic SFR runs flat from \( z \sim 1 \) all the way to \( z \sim 5 \), as indeed in one of the plausible options offered by Madau et al. (1998).

On the other hand, the standard CDM model of the Durham group predicts that only \( \lesssim 5\% \) of stars have formed by \( z = 3 \) (Cole et al. 1994; Baugh et al. 1998). However, hierarchical models of galaxy formation may be flexible enough to accommodate a major fraction of stars having formed at early times. As well known, star formation and its feedback effects are in fact incorporated in a quite heuristic fashion into CDM models, adopting simple single-parameter algorithms for the rendition of such complex, highly non-linear phenomena.

4.3 The Metallicity of the High Redshift Universe

With \( \sim 30\% \) of all stars having formed at \( z \gtrsim 3 \), and the metallicity of the \( z = 0 \) universe being \( \sim 1/3 \) solar, it is straightforward to conclude that the global metallicity of the \( z = 3 \) universe had to be \( \sim 1/3 \times 1/3 \sim 1/10 \) solar, or more (Renzini 1998b). This opens another area of confrontation, i.e. with direct measures of metallicity at high-z that is obtained from QSO absorbers. The metallicity of DLAs at \( z = 3 \) appears to be \( \sim 1/20 \) solar (Pettini et al. 1997, see their Fig. 4), just a factor of 2 below the predicted value from the fossil evidence. However, the much lower value \( Z \sim 10^{-3}Z_\odot \) at \( z = 3 \) has been estimated for the Ly\(_\alpha\) forest (e.g. Songaila 1997). Ly\(_\alpha\)-forest material is believed to contain a major fraction of cosmic baryons at high \( z \), hence (perhaps) of metals. There is therefore an extremely large discrepancy (by perhaps as much as a factor ~ 300) with the estimated global metallicity at \( z \sim 3 \) being \( \sim 1/10 \) solar. This calls into question the notion of Ly\(_\alpha\) forest metallicity being representative of the the universe metallicity at this redshift. Scaling down from the cluster yield, a metallicity \( 10^{-3}Z_\odot \) was achieved when only \( \sim 0.3\% \) of stars had formed, which
may be largely insufficient to ionize the universe at \( z > 5 \) and keep it ionized up to \( z = 3 \) (Madau 1998; see also Gnedin & Ostriker 1997).

On the other hand, DLA and Ly\( _{\alpha} \)-forest systems may provide a vision of the early universe that is biased in favor of cold, metal-poor gas that has been only marginally affected by star formation and metal pollution. Metal rich objects such as giant starbursts that would be dust obscured, the metal rich passively evolving spheroids, and the hot ICM/IGM obviously do not enlist among QSO absorbers. This suggests that Ly\( _{\alpha} \) forest may not trace the mass-averaged metallicity of high redshift universe, and that the universe was very inhomogeneous at that epoch. Already at \( z \sim 3 \), the bulk of metals may be partly locked into stars in the young spheroidals, partly may reside in a yet undetected hot IGM, a phase hotter than the Ly\( _{\alpha} \) forest phase.

### 4.4 Last Speculations

In conclusion, the fossil evidence on the age of stars in galactic spheroids coupled to an empirical metal yield of stellar populations suggests that the universe was already enriched to \( \sim 1/10 \) solar by \( z \simeq 3 \). This possible prompt initial enrichment (PIE) of the universe may have several interesting ramifications. For example, it may help explaining the origin of the ubiquitous G-dwarf problem, such as in the case of the Galactic disk for which a PIE model was considered very attractive by Tinsley (1981). The idea was that the stars in the old halo pre-enriched the material than later settled to form the disk. This idea can be expanded to say that it was the whole spheroid (of which the bulge is by far the major part) promptly enriched to \( \sim 1/10 \) solar a mass some 150 times its own, and that subsequent cooling and infall of a small fraction of such enriched material gave origin to the galactic disk.

I am grateful to Marc Dickinson for his permission to reproduce Fig. 3 from Stanford et al. (1998).

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