The Main Epoch of Metal Production in the Universe

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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. It is 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 not only in cluster ellipticals but also 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 $z \simeq 3$, and correspondingly the metallicity of the universe at $z = 3$ is predicted to be $\sim 1/10$ solar.

1. Introduction

My aim with this paper is to use the local, fossil evidence (i.e. the global metallicity and stellar ages at $z \simeq 0$) to get clues and set constraints on the past metal production and star formation rate (SFR) in the universe. This attempt (see also Rich 1997) is therefore complementary to current efforts to add more and more accurate data points to the global SFR vs redshift diagram (the Madau diagram, for short; Madau et al. 1996, 1997; Madau, these proceedings).

The paper is organized as follows. Section 2 presents the current evidence for the chemical composition of local clusters of galaxies, at low redshift. Section 3 discusses to which extent clusters are representative of the low redshift universe as a whole. In Section 4 a plea is presented for the bulk of stars in galactic spheroids (i.e. ellipticals and bulges alike) being very old, formed at high redshift, hence for a fair fraction of the metals we see at $z \simeq 0$ having been produced at high $z$. I will conclude that this scenario favors high SFRs at high-$z$, with the SFR peaking at $z \gtrsim 2$. Some of these topics are expanded upon in Renzini (1997, hereafter R97).

2. Clusters as Archives of the Past Star and Metal Production

Theoretical simulations predict that the baryon fraction of clusters cannot change appreciably in the course of their evolution (White et al. 1993). This is to say that – unlike individual galaxies – clusters are good examples of a closed box. Metals are ejected by galaxies but retained by clusters. Moreover, as the baryon fraction remains nearly constant no extra-dilution of metals takes place, and eventually we find confined in the same place all the dark matter, all the baryons, all the galaxies, and all the metals that have participated in the play. Hence,
clusters are good archives of their past star formation and metal production history (Cavaliere, private communication).

Metals in clusters are partly spread through their intracluster medium (ICM), partly locked into galaxies and stars. By comparison, the mass of metals ISM of galaxies is negligible. 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. Iron and $\alpha$-Elements in the Intracluster Medium

The best known ICM abundance is that of iron. It comes from the so-called iron-K emission complex at $\sim 7$ keV, prominent in the X-ray spectrum of clusters. Fig. 1 shows the iron abundance of clusters and groups as a function of ICM temperature. Still as a function of ICM temperature, Fig. 2 shows instead the iron-mass-to-light-ratio (Fe$M/L$) of the cluster ICM, measured as the ratio $M_{Fe}^{ICM}/L_B$ of the total iron mass in the ICM over the total $B$-band luminosity of the galaxies in the cluster.

The drop of the derived Fe$M/L$ in poor clusters and groups (i.e. for $kT \lesssim 2$ keV) can be traced back to a drop in both factors entering in its definition, i.e., in the iron abundance and in the ICM mass to light ratio. It is not clear whether this is a real effect, signalling that groups are not closed boxes, or that diagnostic problems are present due to iron being derived from the iron-L instead than from the iron-K complex (cf. R97). I will not further discuss of $kT \lesssim 2$ keV objects.

What emerges from Fig. 1 and 2 is that both the iron abundance and the Fe$M/L$ in rich clusters ($kT \gtrsim 2$ keV) are constant, i.e. independent of cluster temperature, hence of cluster richness and optical luminosity that are correlated quantities. In practice, $Z_{ICM}^{Fe} = 0.3 \pm 0.1$ solar, and $M_{Fe}^{ICM}/L_B = (0.02 \pm 0.01)$. 

![Figure 1. The iron abundance in the ICM as a function of ICM temperature for a sample of clusters and groups, including of six clusters at moderately high redshift with $<z> \simeq 0.33$, represented by small filled circles (from R97).](image)
The simplest interpretation of all this is that clusters did not lose iron (hence baryons), nor acquired pristine baryonic material, and that the conversion of baryonic gas to stars and galaxies has proceeded with the same efficiency and stellar IMF in all clusters (cf. R97). The theoretical predictions on the baryon fraction in clusters (cf. Section 1) find a nice support from these evidences.

Besides iron, X-ray observations allow to measure the abundance of other elements in the ICM, especially of the $\alpha$-elements such as O, Ne, Mg, and Si, with ASCA having superceded any previous attempt in this respect. A fairly high $\alpha$-element enhancement, with $<\alpha/Fe> \simeq +0.4$, was initially reported (Mushotzky 1994), but more recently Mushotzky et al. (1996) have revised down to $<\alpha/Fe> \simeq +0.2$ this estimate (taking a global average for O, Ne, Mg, Si, and Fe). This may still suggest a modest $\alpha$-element enhancement, with the ICM enrichment being dominated by SNII products.

However, Ishimaru & Arimoto (1997) have recently pointed out that the small apparent $\alpha$-element enhancement in the ICM comes from Mushotzky et al. (1996) having assumed reference solar abundances from “photospheric” model atmosphere analysis. The result is different if one uses the “meteoritic” iron abundance instead, which is $\sim 0.16$ dex lower than the photospheric value. Since the meteoritic value is now generally adopted for the solar iron abundance, one can conclude that there is virtually no $\alpha$-element enhancement at all in the ICM (formally $<\alpha/Fe> \simeq +0.04 \pm 0.2$). It is eventually quite reassuring to find that clusters of galaxies are solar as far as the elemental ratios are concerned, which argues for stellar nucleosynthesis having proceeded in quite the same way in the solar neighborhood as well as at the galaxy cluster scale. Specifically, this implies a similar ratio of Type Ia to Type II SNs, as well as a similar IMF (R97). If not else, this will help limiting the number of free parameters to play with.

![The ICM Iron Mass to Light Ratio](image.png)

Figure 2. The iron mass to light ratio of the ICM of clusters and groups (for $H_0 = 50$) as a function of the ICM temperature (from R97).
2.2. The ICM-Galaxies Iron Share

In clusters of galaxies part of iron resides in stars, part in the ICM, and the global iron abundance of the whole cluster is then given by:

\[ Z_{Fe}^{CL} = \frac{Z_{Fe}^{ICM} M_{ICM} + Z_{Fe}^{*} M_{*}}{M_{ICM} + M_{*}} = \frac{5.5 Z_{Fe}^{ICM} h^{-5/2} + Z_{Fe}^{*} h^{-1}}{5.5 h^{-5/2} + h^{-1}}, \]  

(1)

where \( Z_{Fe}^{*} \) is the average abundance of stars in galaxies and \( M_{*} \) is the mass in stars. For the second equality I have assumed as prototypical the Coma cluster values adopted by White et al. (1993): \( M_{ICM} \simeq 5.5 \times 10^{13} h^{-5/2} M_{\odot} \) and \( M_{*} \simeq 10^{13} h^{-1} M_{\odot} \). With \( Z_{Fe}^{ICM} = 0.3 \) solar and \( Z_{Fe}^{*} = 1 \) 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:

\[ \frac{Z_{Fe}^{ICM} M_{ICM}}{Z_{Fe}^{*} M_{*}} \simeq 1.65 h^{-3/2}, \]  

(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 iron is in the ICM, rather than now locked into stars, especially for low values of \( H_0 \). These estimates could be somewhat decreased if clusters contain a sizable population of stars not bound to censed individual galaxies, if the average iron abundance in stars is supersolar (luminosity-weighted determinations underestimate true abundances, Greggio 1997), or if the galaxy \( M/L \) ratio is higher than adopted here, i.e., \( < M_{*}/L_B > = 6.4 h \) (White et al. 1993). However, the bottom line is that there are at least as much metals inside cluster galaxies, as there are out of them in the ICM. This must be taken as a strong constraint when modelling the chemical evolution of galaxies: clearly they 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 FeM/L:

\[ \frac{M_{Fe}^{ICM} + M_{Fe}^{*}}{L_B} \simeq 1.3 \times 10^{-2} (1.65 h^{-1/2} + h) (M_\odot/L_\odot), \]  

(3)

or FeM/L=0.037 or 0.034 \( M_\odot/L_\odot \), respectively for \( h = 0.5 \) and 1. The total FeM/L is therefore fairly insensitive to the adopted distance scale. Simple calculations (cf. Renzini et al. 1993) show that to reproduce this value one needs either a fairly flat IMF \( (x \simeq 0.9) \) if all iron is attributed to SNII’s, or a major contribution from SNIa’s, if one adopts a Salpeter IMF \( (x = 1.35) \). The former option dictates a substantial \( \alpha \)-element enhancement, similar to the values observed in the Galactic halo \( ([\alpha/Fe] \simeq +0.5) \). The latter option instead predicts near solar proportions for the cluster as a whole. The evidence presented in Section 2.1 favors of the second option. From the near solar proportions of cluster abundances one obtains the total metal mass to light ratio of a typical cluster as \( M_{Z}/L_B \simeq 10 \times M_{Fe}/L_B \simeq 0.3 \pm 0.1 (M_\odot/L_\odot) \).

It is worth noting that this is an interesting estimate of the metal yield of stellar populations that is fully empirical. Following Tinsley (1980) the metal
yield is usually defined per unit mass of stars, a quantity which theoretical analog
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 $M \geq M_{\odot}$. Theoretical mass-related yields have
been recently estimated by Thomas et al. (1997) based on massive star models
by Woosley & Weaver (1995) and Thielemann et al. (1996). These yields can
be purged from their mass dependence, and transformed into luminosity-related
yields. For this purpose I assume an age of 15 Gyr for the bulk of stars in clusters
(cf. Section 4), and use the luminosity-IMF normalization from (Renzini 1994):
i.e. $\psi(M) = AM^{-(1+x)}$ for the IMF, one has $A \simeq 3.0L_\odot$. Thus, theoretical yields
turn out to be $M_z/L_\odot = 0.08$, 0.24, and 0.33 $M_\odot/L_\odot$, respectively for $x = 1.7$,
1.35, and 1.00, which compares to $M_z/L_\odot \simeq 0.3 \pm 0.1M_\odot/L_\odot$ 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. Clusters vs Field

A critical issue is 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
$\Omega_* = 0.0036$, a baryon mass density parameter $\Omega_\Lambda = 0.05$, an average solar
metallicity for the stars, and a negligible metal content for the intergalactic
medium (IGM), that comprises the vast majority of the baryons. With these
assumptions the metallicity of the present day universe is $\sim 1 \times 0.0036/0.05 = 0.07$ solar, or $\sim 5$ times lower than the measured value in clusters of galaxies.
In the same frame, the fraction of baryons in galaxies (stars) is $\sim 7\%$, which
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. Therefore, it appears that the efficiency of baryon conversion
into galaxies and stars adopted by Madau et al. (1996) is nearly the same as that
observed in clusters, which supports the notion of clusters being representative
of the low-$z$ universe ($\Omega_* / \Omega_\Lambda$). The metallicity of the clusters is however $\sim 5$
times higher than the metallicity of the low-$z$ universe adopted by Madau et al..
The difference comes from having assumed the IGM to be devoid metals, hence
assuming field galaxies losing a negligible amount of metals, contrary to cluster
galaxies which instead appear to have lost a major fraction of the metals they
have produced. Since the average stellar metallicity is assumed to be solar in
both clusters and field, this also implies a factor $\sim 5$ lower efficiency in metal
production per unit mass turned into stars (yield), compared to galaxy clusters.

Assuming to be real, such drastic differences between the behavior of galaxies
and stellar populations in clusters and in the field would require quite con-
trived explanations (R97). More attractive for its simplicity appears to be the
alternative according to which no major difference exists between field and clusters,
and the global metallicity of the present day universe is nearly the same as
that observed in galaxy clusters, i.e., $\sim 1/3$ times solar. If so, there should be a
comparable share of metals in the field IGM, as there is in the cluster ICM, i.e.,
most of the metals should reside in the IGM rather than within field galaxies
(R97).
4. The Main Epoch of Metal Production and Star Formation

In the previous section I have argued that the present metallicity of the universe, hence the global, time-averaged rate of metal production in are likely to be $\sim 5$ times higher than was adopted by Madau et al. (1996). However, contrary to Mushotzky & Loewenstein (1997), this does not necessarily imply that the global, time-averaged SFR was also underestimated by the same factor, because Madau et al. have adopted for the baryon to stars conversion efficiency of the general field precisely the same value found in clusters. Therefore, rather than to an higher average SFR one can appeal to an higher metal yield, actually, just about the same yield empirically determined for the clusters.

Now, what is the main epoch of metal production in the universe? or, equivalently, when the cosmic SFR has reached its peak value? The most straightforward approach to answer these questions is certainly offered by the direct determination of the global SFR as a function of redshift (the Madau diagram). However, as well known, direct determinations of the global SFR at high redshift encounters two major difficulties: 1) dust obscuration, which on average may be higher than in low redshift galaxies since star formation may predominantly take place in major dust enshrouded, bulge-forming starbursts, rather than more quiescently as later in disks and irregulars; and 2) alternatively, a sizable fraction of the global SFR may take place in small entities below detection threshold, as predicted by current hierarchical models (e.g. Kaufmann 1996). Therefore, the complementary approach based on the fossil record at low redshift will provide a vision of the early universe from a different point of view, hence subject to different biases and uncertainties. Ultimately, the two approaches will have to lead to converging results.

It is now well established by several independent lines of evidence that the bulk of stars in cluster ellipticals formed at high redshift, i.e., $z > 3$ (an extensive set of references is not reported here for lack of space, but can be found in R97). This important conclusion comes from the tightness of the color–σ relation of ellipticals in nearby clusters, the tightness of the distributions of cluster ellipticals about their fundamental plane at low and high redshift, the tightness of the Mg$_2$ – σ relation, again at low as well as high redshift, the tightness of the color-magnitude relation of cluster ellipticals at high redshift, and the small color and fundamental plane evolution out to $z \simeq 0.5$.

This old age conclusion can be generalized to include field ellipticals as well as the bulges of spirals, and state that the bulk of stars in galactic spheroids formed at high redshift, i.e., $z \gtrsim 2 - 3$. Indeed, field ellipticals appear to follow the same Mg$_2$ – σ relation of their cluster analogs (Bernardi et al. 1998), while galactic bulges follow the same Mg$_2$-luminosity (and Mg$_2$ – σ) relation of ellipticals (Jablonka et al. 1996). Moreover, stellar photometry shows that the bulk of stars in the Galactic bulge are as old as the Galactic halo, or $\sim 15$ Gyr (Ortolani et al. 1995), and that there is no evidence for an intermediate age population in the bulge of M31 and its elliptical satellites M32 and NGC 147 (Renzini 1998). The Milky Way and M31 reside in a small, spiral dominated group and yet their bulges are $\sim 15$ Gyr old. It seems reasonable to generalize this to virtually all bulges, given also the strong similarity of bulges and ellipticals.

According to Schechter & Dressler (1987), bulges account for nearly the same star mass as disks, while the star mass in E/S0 galaxies is about twice
that in spirals (Persic & Salucci 1992). Hence, it seems legitimate to conclude
that galactic spheroids contain $\sim 30 - 50\%$ of the baryons now locked into stars.
Therefore, if the bulk of stars in spheroids formed at $z \gtrsim 3$, and they account for
$\gtrsim 30\%$ of the stellar mass at $z = 0$, putting two and two together:

- Some $30\%$ of all stars have formed at $z \gtrsim 3$,
- hence, $\sim 30\%$ of all the metals have been produced at $z \gtrsim 3$,
- hence, the metallicity of the universe at $z = 3$ should be $\sim 1/3$ of its present
day value ($\sim 1/3$ solar), i.e., $\sim 1/10$ solar, or $Z(z = 3) \simeq 0.002$.

At first sight these inferences from the local, fossil evidence appear to con-
ict with some model predictions, and with some of the current interpretations
of the direct observations at $z \gtrsim 3$. For example, the standard CDM model of
Cole et al. (1994) and Baugh et al. (1997) predicts that only $\lesssim 5\%$ of stars have
formed by $z = 3$. Tuning the free parameters of this specific CDM model does
not seem to work without violating other observational constraints (Frenk, this
conference). It seems that more drastic changes are required to produce $\sim 30\%$
of the stars by $z = 3$, perhaps appealing to isocurvature models designed to
allow the early assembly of large galaxies (Peebles 1997).

As far as direct observations are concerned, the fossil evidence supports the
interpretation as lower limits of the SFR estimates at $z \gtrsim 3$ (e.g. Madau et al.
1996). Of the two models presented by Madau et al. (1997) the one in which the
SFR slowly increases all the way to $z = 5$ is favored. It remains to be ascertained
whether the undetected star formation activity is obscured by dust, or dispersed
in small fragments below the threshold of the Hubble Deep Field.

Finally, the predicted global metallicity at $z = 3$ ($\sim 1/10$ solar, or more)
is subject to observational test via the damped Ly$_\alpha$ systems (DLA). These sys-
tems may again provide a biased vision of the early universe, as neither giant
starbursts that would be dust obscured, nor the metal rich passively evolving
spheroids or the hot ICM/IGM enlist among DLAs. Nevertheless, the average
metallicity of the absorbers at $z = 3$ appears to be $\sim 1/20$ solar (Pettini et al.
1997, cf. Fig. 4), just a factor of 2 below the expected value from the fossil
evidence. However, this is much higher than the lower limit to $Z$ at $z = 3$ as in-
erred from Ly$_\alpha$ forest observations (Songaila 1997), which suggests the universe
being very inhomogeneous at that epoch.

I would like to make a last point before closing. While there is now com-
pelling evidence for the stellar populations of ellipticals and bulges being very
old, it is fair to say that the evidence for rather old disk is also growing. As
well known, the ratio of present to average past SFR increases along the Hubble
sequence, and is well below unity at least up to Sbc galaxies (Kennicutt et al.
1994). This means that SFRs in such disks were much higher in the past, hence
disks are also dominated by rather old stars. Moreover, all SFR indicators are
found to anticorrelate tightly with the $H$-band luminosity (hence mass) of spiral
galaxies (Gavazzi et al. 1996), i.e., the heavier a galaxy, the lower its current
SFR, and the older its stellar populations. Big disks appear to have burned
most of their gas at early times, while most of the cosmic star formation is now
confined to lesser galaxies. Hierarchical models of galaxy formation do not nat-
urally account for the angular momentum of real spirals (Navarro & Steinmetz
1997). Perhaps adding the additional problem of accounting for the observed
mass-age correlation may help finding the solution.
I would like to thank Mauro Giavalisco and Piero Madau for the entertaining and instructive discussions we had on these matters.

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