HINTS ON GALAXY FORMATION FROM THE METAL CONTENT OF GALAXY CLUSTERS AND OTHER FOSSIL EVIDENCE

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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. This requires the cosmic star formation rate to run at least flat from $z \sim 1$ to $\sim 5$, which appears to agree with the most recent direct determinations of the star formation rate in Lyman-break galaxies.

1 Introduction

The observation of forming galaxies at high redshift is certainly the most direct way to look at the Birth of Galaxies, and a great observational effort is currently being made in this direction. Yet, high redshift galaxies are very faint, and at least for now only few of their global properties can be measured. Nearby and moderate redshift galaxies can instead be studied in far greater detail, and their fossil evidence can provide a view of galaxy formation and evolution that is fully complementary to that given by high redshift observations. By fossil evidence I mean those observables that do not refer to ongoing, active star formation, and which are instead the result of the integrated past star formation history. This evidence includes the global metallicity of the universe, and the distribution of stellar ages in $z \simeq 0$ galaxies as well as in high redshift, but passively evolving galaxies.

The paper is organized as follows. Section 2 presents the current evidence for the chemical composition of local clusters of galaxies at low redshift, separately for the intracluster medium (ICM) and for cluster galaxies. In Section 3 the current evidence is presented for the bulk of stars in galactic spheroids (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 4 these evidences are used to set constraints on the main epoch of star formation, metal production, and on the metallicity of the high-$z$ universe.
2 Clusters as Archives of the Past Star and Metal Production

Individual galaxies are not good examples of the closed box model of chemical evolution: enriched matter certainly flows out of them, and quasi-pristine material may occasionally infall and be accreted by them. Theoretical simulations predict instead that the baryon fraction of rich clusters cannot change appreciably in the course of their evolution [43]. We can then expect within a cluster to 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. Clusters are then good archives of their past star formation and metal production history, an ideal laboratory for the study of the fossil evidence.

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 Iron and \(\alpha\)-Elements in the Intracluster Medium

Among abundant elements, iron has the most accurately measured ICM abundance. The so-called iron-K emission complex at \(\sim 7\) keV is prominent in the X-ray spectrum of clusters, and allows fairly precise measurements. Fig. 1 shows the iron abundance of clusters and groups as a function of ICM temperature, while Fig. 2 shows the iron-mass-to-light-ratio (Fe\(M/L\)) of the ICM [30]. This is defined 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 \(kT<2\) 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 [30]. 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 the feedback effect of star formation in individual galaxies driving galactic winds [34] [9]. In addition, there may be a diagnostic problem, since in groups iron is derived from iron-L

Figure 1: A compilation of the iron abundance in the ICM as a function of ICM temperature for a sample of clusters and groups [30], including several clusters at moderately high redshift with \(<z\> \simeq 0.35\), represented by small filled circles.
transitions, which involve atomic physics which is far more complicated than that of the iron-K complex [2][30]. For this reason I will not further discuss poor clusters, i.e. those cooler than $kT \lesssim 2$ keV.

Fig. 1 and 2 show that both the iron abundance and the FeM/L in rich clusters ($kT \gtrsim 2$ keV) are independent of cluster temperature, hence of cluster richness and optical luminosity. For these clusters one has $Z_{ICM}^{Fe} = 0.3 \pm 0.1$ solar, and $M_{Fe}^{ICM}/L_B = (0.02 \pm 0.01)$ 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 [30]. Otherwise, we should observe cluster to cluster variations of the iron abundance and of the FeM/L. The theoretical prediction of the constancy of the baryon fraction in clusters [43] is nicely supported by these evidences.

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 attempt in this respect. A fairly high $\alpha$-element enhancement, with $<[\alpha/Fe]> \approx +0.4$, was initially reported [23]. Later this estimate has been revised down to $<[\alpha/Fe]> \approx +0.2$ [24], using a global average among observed clusters, and averaging O, Ne, Mg, and Si for the $\alpha$-elements [30]. In this way a more robust estimate of the global $[\alpha/Fe]$ ratio is obtained, given the errors affecting the abundances of individual elements in individual galaxies. This may still suggest a modest $\alpha$-element enhancement, with the ICM enrichment being dominated by SNII products [23].

However, it has been pointed out that this small apparent $\alpha$-element enhancement in the ICM comes from having assumed the reference solar iron abundance from the “photospheric” model atmosphere analysis [15]. The “meteoritic” iron abundance is instead now generally adopted, and since this is $\sim 0.16$ dex lower than the photospheric value, one can conclude that there is virtually no $\alpha$-element enhancement at all in the ICM (formally $<[\alpha/Fe]> \approx +0.04 \pm \sim 0.2$, [15], [30]). Clusters of galaxies are therefore nearly 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. This implies a similar ratio of the
number of Type Ia to Type II SNs, as well as a similar IMF [30]. This result speaks for the universality of the star formation process (IMF, binary fraction, etc.), and may help limiting the number of free parameters to play with.

### 2.2 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 [2], $\alpha$-element enhancements [8], and the luminosity bias [14].

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

$$Z_{Fe}^{CL} = \frac{Z_{Fe}^{ICM}M_{ICM} + Z_{Fe}^*M_*}{M_{ICM} + M_*},$$

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. [43]: $M_{ICM} \approx 5.5 \times 10^{13} h^{-5/2} M_\odot$ and $M_* \approx 10^{13} h^{-1} M_\odot$. 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:

$$\frac{Z_{Fe}^{ICM}M_{ICM}}{Z_{Fe}^*M_*} \approx 1.65 h^{-3/2},$$

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 $H_\circ$. 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 [14], or if the galaxy $M_* / L$ ratio is higher than adopted here, i.e., $< M_* / L_B > = 6.4 h$ [43]. However, the bottom line is that there is at least as much metal mass inside cluster galaxies, as there is out of them in the ICM. 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 $FeM/L$:

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

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 show that to reproduce this value one needs either a fairly flat IMF ($x \approx 0.9$) if all iron is attributed to SNII’s, or a major contribution from SNIa’s, if one adopts a Salpeter IMF ($x = 1.35$) [34]. The former option dictates a substantial $\alpha$-element enhancement, similar to the values observed in the Galactic halo ($[\alpha/Fe] \approx +0.5$). The latter option instead predicts near solar proportions for the cluster as a whole, and requires the SNIa rate to have been much higher in the past [34]. The evidence presented in Section 2.1 favors 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, fully empirical estimate of the metal yield of stellar populations. Following Tinsley [41], 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 $M > M_\odot$. Theoretical mass-related yields have been recently estimated by Thomas, Greggio, & Bender [40] based on massive star models and supernova explosion [39], [44]. 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 proper luminosity-IMF normalization [29] [31]: i.e. $\psi(M) = AM^{-(1+x)}$ for the IMF with $A \simeq 3.0 L_B$. Thus, theoretical yields turn out to be $M_Z/L_B = 0.08, 0.24, \text{ and } 0.33 \ M_\odot/L_\odot$, respectively for $x = 1.7, 1.35, \text{ and } 1.00$, 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.

2.3 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. [21] adopt $H_0 = 50$, a stellar mass density parameter $\Omega_* = 0.0036$, and a baryon mass density parameter $\Omega_b = 0.05$. With these values the fraction of baryons that have been locked into stars is $\sim 7\%$. This compares to $\sim 1/(1 + 5.5 h^{-3/2})$ 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. [21] is nearly the same as that observed in clusters, which supports the notion of clusters being representative of the low-z universe ($\Omega_*/\Omega_b$).

For lack of direct evidence on the metallicity of the local intergalactic medium (IGM), Madau et al. [21] assumed all the metals in the low redshift universe to be locked into stars (galaxies), with a negligible metal content for the IGM, which however comprises the vast majority of all the baryons. With these assumptions, and adopting the average metallicity of all stars to be solar, 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.

Is this difference real, or does it just reflect the assumption of a zero metallicity IGM? There is no obvious reason why the metal yield of stellar populations should be $\sim 5$ times lower in field galaxies compared to cluster galaxies. On the contrary, assuming the difference to be real would force us to accept a drastic difference between the behavior of galaxies and stellar populations in clusters and in the field, which would require quite contrived explanations [30]. Much simpler, hence more attractive, appears to be the option according to which no major difference in metal enrichment exists between field and clusters, and the global metallicity of the present day universe is nearly the same as that of the only place where we can thoroughly measure it, i.e. in galaxy clusters where it is $\sim 1/3$ times solar. If so, there should be a comparable share of metals in the IGM, as there is in the cluster ICM, i.e., just like most of the baryons, most of the metals should reside in the IGM rather than within field galaxies [30].
3 The Age of Spheroids and the Main Epoch of Metal Production

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 virtually identical to that of local clusters (see Fig. 1), hence the bulk of iron had to be manufactured at \(z \gtrsim 0.5\). 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 schematically reported in this section.

A first tight constraint on the formation epoch of stars in cluster ellipticals came from Bower, Lucey, & Ellis [6] who noted that the very tight color-\(\sigma\) relation followed by galaxies in the Virgo and Coma clusters demonstrates that at least cluster ellipticals are made of very old stars, with the bulk of them having formed at \(z \gtrsim 2\). This result had the merit to cut short inconclusive discussions on the age of ellipticals based on matching synthetic spectra to individual galaxies, and showed instead that the homogeneity of elliptical populations sets tight, almost model independent age constraints. Along these lines, evidence supporting an early formation of ellipticals has greatly expanded over the last few years. This came from the tightness of the fundamental plane relation for ellipticals in local clusters [33], from the tightness of the color-magnitude relation for ellipticals in clusters up to \(z \sim 1\) (e.g., [1], [37]), and from the modest shift with increasing redshift in the zero-point of the fundamental plane, \(\text{Mg}_2 - \sigma\), and color-magnitude relations of cluster ellipticals (e.g., [4], [10], [12], [18], [26], [37], [42]). 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 (e.g. in a \(\Lambda\)-dominated universe this constraint would become \(z \gtrsim 2\)).

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. Indeed, as shown in Fig. 3, field early-type galaxies (ellipticals and S0’s) are found to follow virtually the same \(\text{Mg}_2 - \sigma\) relation of their cluster counterparts, with the age difference being less than \(\sim 1\) Gyr [5], while most bulges follow the same \(\text{Mg}_2 - \sigma\) and color-magnitude relations of ellipticals [17]. 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 [25], and similar conclusions have been reached for the bulge of M31 [31], [16]. It is also worth noting that the close resemblance of cluster and field early-type galaxies illustrated in Fig. 3 indicates that metal enrichment is not detectably different in cluster and in field galaxies.

With spheroids containing at least 30% of all stars in the local universe [27], [35], or even more [13], one can conclude that at least 30% of all stars and metals have formed at \(z \gtrsim 3\) (Renzini [32]; see also Dressler & Gunn [11]). 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 [21] or from theoretical simulations, e.g., [3]. Yet, it is is more in line with recent direct estimates from the spectroscopy of Lyman-break galaxies [38], where the cosmic SFR runs flat for \(z \gtrsim 1\), as in one of the options offered by the models of Madau et al. [22].

At first sight these inferences from the local, fossil evidence appear to conflict 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 the Durham group predicts that only \(< 5\%\) of stars have formed by \(z = 3\) [3], [7]. The supernova-feedback free parameter of this specific CDM model was tuned to reproduce a \(z = 0\) galaxy luminosity function that runs flat at the faint end. Tuning instead to the Zucca et al. [45] luminosity function, which is steep at the faint end, allows to make much more stars at early times (Frenk, this conference), in somewhat
Figure 3: The $\text{Mg}_2 - \sigma$ relation for a sample of early-type galaxies (upper panel), as well as for the field, group and cluster subsamples (lower panels). The corresponding number of objects, the slope, and the zero-point (z.p.) are shown in the upper left corner of each panel. The least squares fits to the $\text{Mg}_2 - \sigma$ relation are also shown. Note that for the three subsamples the slope as derived for the total sample was retained, and only the zero-point was determined [5].
better agreement with the constraint sets by the old age of galactic spheroids. 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 [32]. Damped Ly\(_{\alpha}\) systems (DLA) may offer an opportunity to check this prediction, though they 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 DLAs. Yet, in spite of these limitations the average metallicity of the DLAs at \( z = 3 \) appears to be \( \sim 1/20 \) solar (Pettini et al. [28], see their Fig. 4), just a factor of 2 below the expected value from the fossil evidence. This is still much higher than the extreme lower limit \( Z \sim 10^{-3}Z_{\odot} \) at \( z = 3 \) as inferred from Ly\(_{\alpha}\) forest observations [36]. Ly\(_{\alpha}\) forest material is believed to contain a major fraction of cosmic baryons at high \( z \), hence (perhaps) of metals. There is therefore a potential conflict with the estimated global metallicity at \( z \sim 3 \), and the notion of Ly\(_{\alpha}\) forest metallicity being representative of the the universe metallicity at this redshift. Scaling down from the cluster yield, such low metallicity was achieved when only \( \sim 0.3\% \) of stars had formed, which may be largely insufficient to ionize the universe and keep it ionized up to this redshift [20]. 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. The bulk of metals would be partly locked into stars in the young spheroidals, partly would reside in a yet undetected hot IGM, a phase hotter than the Ly\(_{\alpha}\) forest phase.

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