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Metallicity Distributions In and Around Galaxies

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Abstract: Metals are found in all baryonic phases and environments, and our knowledge of their distribution 'in and around galaxies' has significantly improved over the past few years. Theoretical work has shown that the fraction of metals in different baryonic components can vary significantly when different feedback schemes are adopted. Therefore, studies of element abundances provide important information about all gas-dynamical processes which determine the cosmic evolution of baryons. I give here a brief review of recent observational progress, describe the implications of recent theoretical studies, and discuss briefly future prospects.

Keywords: stars: abundances — ISM: abundances — galaxies: abundances — galaxies: evolution — galaxies: high-redshift

1 Introduction

During the last decade, significant progress has been made in the study of element abundances. Accurate measurements of metallicities have been collected for a large number of individual stars for our own Galaxy, and for a number of the brightest members of the Local Group. Large scale surveys such as the 2dF Galaxy Redshift Survey and the Sloan Digital Sky Survey (SDSS) have allowed abundance determinations in hundreds of nearby galaxies. The new generation of large telescopes and sensitive detectors have allowed us to measure a range of chemical elements in stars, HII regions, cold interstellar gas, and hot intergalactic medium, up to an epoch when the Universe was only about one tenth of its current age.

As I will show later, the distribution and amount of heavy elements in the different baryonic components of the Universe are sensitive to physical mechanisms that regulate the evolution of bayons as a function of cosmic time. Therefore, the main motivation of chemical abundance studies is the possibility to use this information as a tool to reconstruct the past history of star formation, and the relative role of feedback processes and various gas-dynamical processes in determining the observed cosmic evolution of baryons (for a classical review on chemical evolution, see Tinsley 1980; for a more recent review focused on the Milky Way and its satellites, see Matteucci 2008).

As mentioned above, metals are present in all baryonic phases and 'environments'. Even in rather low density regions, the inter-galactic medium appears to be polluted to $\gtrsim$1 per cent solar metallicity, as measured by metal lines in the Lyman α absorption systems (see Section 5). How and when this chemical enrichment occurred exactly, is still a matter of debate. From the theoretical point of view, various physical processes can provide viable explanations for the transfer of metals from the stars in galaxies to the inter-galactic and intra-cluster medium, for example ejection of enriched material during mergers, tidal/ram-pressure stripping, galactic outflows (e.g. supernova-driven outflows). The relative importance of these various channels, and the details of how metals are transferred from the stellar to the gaseous (cold and/or hot) phase remain to be understood.

Various techniques have to be used to measure the metal abundances in different baryonic components. Stellar population synthesis models have been extensively used for nearby galaxies (in particular for elliptical galaxies and, in a few cases where the contamination of stellar absorption features by nebular emission can be removed, for late-type galaxies). Optical nebular emission lines have been used to measure the gas phase metallicity of star forming galaxies up to $z \sim 1$. The same method has been used for Lyman break and UV-selected galaxies up to $z \sim 3$. X-ray spectroscopy is necessary to measure the metal content of the intra-cluster medium (ICM). As I will mention in the following, each of these techniques has its own problems and limits, and at least some of them are far from being firmly calibrated.

Chemical enrichment studies have a quite long history that cannot be summarised in a few pages. Given the vastity of the subject, I have deliberately decided to focus mainly on recent observational results and theoretical developments, rather than providing an historical review. In the following sections, in particular, I will provide a brief overview of what is known, observationally, about the metallicity distributions in our own Galaxy (focusing on the stellar halo), in the local Universe and in the ICM and IGM. I will then briefly touch upon the evolution of the mass-metallicity relation and metallicity measurements at higher redshift. In each section, I will

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mention recent theoretical progress, and I will conclude with a few remarks and considerations about future prospects.

2 Metallicity Distributions in Galaxies: the Stellar Halo and Satellites of our Milky Way

Our own galaxy — the Milky Way — is a fairly large spiral galaxy consisting of four main stellar components. Most of the stars are distributed in a thin disk, exhibit a wide range of ages, and are on high angular momentum orbits. A much smaller mass of stars (about 10–20% of that in the thin disk) reside in a distinct component which is referred to as the 'thick disk'. The stars in the thick disk are old, have on average lower metallicity than those of similar age in the thin disk, and are on orbits of lower angular momentum. The Galactic bulge is dominated by an old and relatively metal-rich stellar population, with a tail to low abundances. The fourth component — the stellar halo — represents only a tiny fraction of the total stellar mass ($\sim 2 \times 10^9$ $M_\odot$) and is dominated by old and metal poor stars which reside on low angular momentum orbits (Freeman & Bland-Hawthorn 2002).

Accurate measurements of metallicity, age, and kinematics have been collected for a large number of individual stars in our own Galaxy. Historically, chemical and kinematic information provided the basis for the first galaxy formation models. Eggen, Lynden-Bell & Sandage (1962) studied a sample of 221 dwarf stars and found that those with lowest metal abundance were moving on highly elliptical orbits and had small angular momenta. The data were interpreted as evidence that the oldest stars in the galaxy were formed out of gas collapsing from the halo onto the plane of the galaxy, on a relatively short time-scales (a few times 10^8 yr). About one decade later, Searle & Zinn (1978) found no radial abundance gradient in a sample of 177 red giants and 19 globular clusters. These observations led Searle & Zinn to formulate the hypothesis that the stellar halo (in particular the outer region of the halo) formed through the agglomeration of many subgalactic fragments, that may be similar to the surviving dwarf spheroidal satellites (dSphs) of the Milky Way.

Although the Searle & Zinn scenario appears to be in qualitative agreement with expectations from the hierarchical cold dark matter scenario, the debate between a rapid collapse and a sequence of accretion events is not closed. One problem with the Searle & Zinn scenario was pointed out by Shetrone, Cote & Sargent (2001) who obtained high resolution spectra for 17 stars in three dSph galaxies and noted that stars in the Local Group dSphs tend to have lower α abundances than stars in the stellar halo. These results have been later confirmed with larger samples of stars: e.g. Figure 1 shows the abundance of magnesium and calcium in four nearby dwarf spheroidal galaxies, compared with a compilation of Milky Way and halo star abundances. These observations suggest that the Galactic stellar halo cannot result from the disruption of satellite galaxies similar to those studied by Shetrone and collaborators or Tolstoy and collaborators. It is, however,

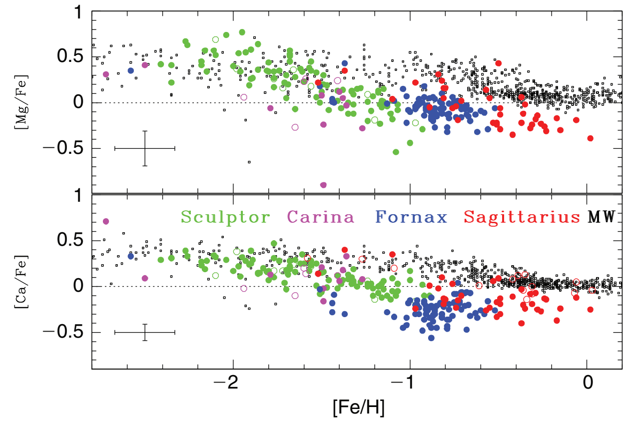

Figure 1 From Tolstoy, Hill & Tosi (2009). α elements (Mg and Ca) in four nearby dwarf spheroidal galaxies (coloured symbols). The small black symbols are a compilation of Milky Way disk and halo star abundances (see original paper for details).

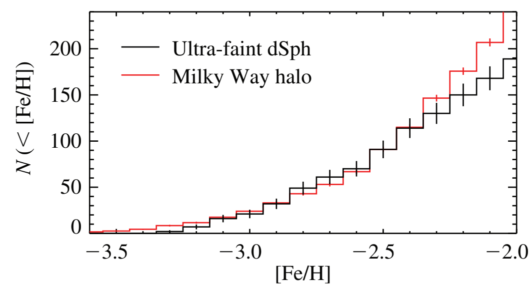

Figure 2 From Kirby et al. (2008). Cumulative metallicity distribution function for the metal-poor tails of the eight ultra-faint dSphs (black) and the Milky Way halo (red). See original paper for more details.

not entirely surprising that the *surviving* satellites might be intrinsically different from the main contributors to the stellar halo. The argument has been put forward in a recent study by Font et al. (2006) who reproduced the observed chemical abundance pattern by combining mass accretion histories of galaxy-size haloes with a chemical evolution model for individual satellites. In the model proposed by Font and collaborators, the main contributors to the stellar halo were accreted early on and were enriched in α elements by Type II supernovae, while the surviving satellites were accreted later, have more extended star formation histories, and stellar populations enriched to solar level by both Type II and Type Ia supernovae (see also De Lucia & Helmi 2008).

A potentially more serious problem with the Searle & Zinn scenario was pointed out by Helmi et al. (2006) who found a significant difference between the metal-poor tail of the dSph metallicity distribution and that of the Galactic halo. In a more recent study, however, Kirby et al. (2008) presented metallicity measurements for 298 individual red giant branch stars in eight of the least luminous dSphs of the Milky Way, and showed that the metallicity distribution of their stars is similar to that of the stellar halo at the metal-poor end (see Figure 2).

Detailed abundance data for many elements are now being collected for larger samples of stars in the

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Milky Way and in several dSph galaxies. It is important to note that each galaxy shows a wide spread in metallicity and that, in some cases, there are clear abundance gradients. It remains to be understood if more luminous dSphs (like those studied by Helmi and collaborators) also host extremely metal-poor stars. Ongoing spectroscopic surveys and detailed comparisons with cosmologically motivated models including star formation and chemical enrichment, will provide in the next future crucial information on the role of dSphs in building the stellar halo of our own Milky Way.

3 Metallicity Distributions in Galaxies — the Local Universe

For galaxies outside our Local Group, metallicity measurements of individual stars are unfeasible, and only integrated values can be derived. Estimates of the ages and metallicities of the stellar population of nearby galaxies can be inferred from their integrated spectra, using stellar population synthesis models. These studies are, however, limited by the difficulty of deriving independent constraints on the age, star formation history, metallicity and dust content of a galaxy. These degeneracies can be broken, at some level, using spectral diagnostics that are not sensitive to dust and have different sensitivities to age and metallicity. Studies in this area have focused, in particular, on a set of absorption features defined and calibrated using the spectra of nearby stars observed at the Lick Observatory: the so called Lick Indexes (Faber 1973; Worthey et al. 1994). These studies are generally limited to early type galaxies because of the lack of hot stars in the Lick library. It is important to note, however, that the age-metallicity degeneracy can be broken only in a relative way, and that the absolute values of the ages and metallicities derived depend strongly on the specific choice of metal indices.

In a recent study, Gallazzi et al. (2005) have combined modern population synthesis techniques with a Bayesian statistical approach to derive likelihood distributions of ages and metallicities for a sample of $\sim 2 \times 10^5$ galaxies from the SDSS. The spectral features used in this study have been selected to depend only weakly on the α/Fe ratio, and estimates of ages and metallicities have been determined also for star forming galaxies, by removing the contamination of stellar absorption features by nebular emission. Figure 3 shows the derived distribution of metallicity as a function of the galaxy stellar mass, obtained by co-adding the two-dimensional likelihood distributions for all galaxies. The figure shows that metallicity increases with stellar mass. The 68 per cent confidence levels, however, show a quite broad distribution, with a large (larger than the intrinsic uncertainties) scatter for a given stellar mass.

A similar relation was observed between the gas-phase metallicity and stellar mass by Tremonti et al. (2004), and is reproduced in Figure 4. Gas phase metallicities are usually estimated using strong nebular emission lines, and calibrations that are based on metallicity sensitive

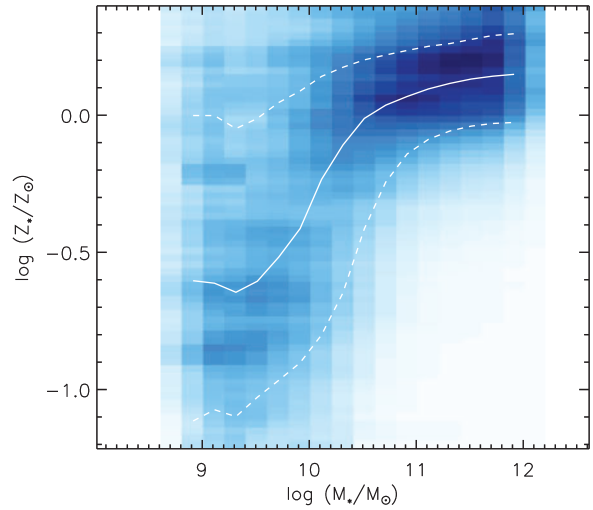

Figure 3 From Gallazzi et al. (2005). Conditional distribution of stellar metallicity as a function of the galaxy mass. The solid line indicates the median of the distribution and the dashed lines the 16th and 84th percentiles. See original paper for details.

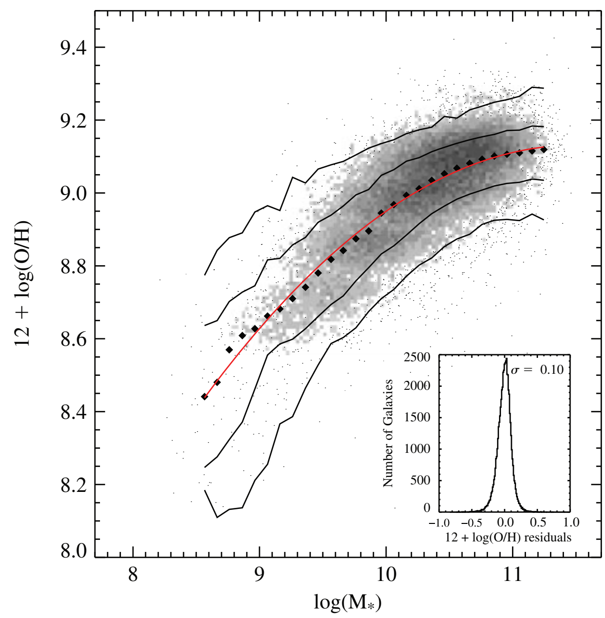

Figure 4 From Tremonti et al. (2004). Relation between stellar mass and gas-phase oxygen abundance for $\sim 5 \times 10^4$ star forming galaxies in the SDSS. The large black symbols represent the median in bins of 0.1 dex in mass that include at least 100 data points. The solid lines mark the contours that enclose 68 and 95 per cent of the data. The red line is a polynomial fit to the data. The inset plot shows the residuals to the fit. See original paper for details.

emission line ratios. Figure 4 shows the vast majority of galaxies having super-solar metallicity[1]. It should be noted, however, that strong-line methods (as used in Tremonti et al.) may systematically overestimate oxygen abundances by as much as 0.2–0.5 dex (Kennicutt, Bresolin & Garnett 2003). Different calibrations have been

[1] Tremonti et al. (2004) adopt $12 + \log[O/H] = 8.69$ as solar value.

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adopted in the literature: methods based on photoionization models, empirical methods based on measurements of the electron temperature of the gas, or a combination of these. Unfortunately, estimates obtained using different calibrations manifest large discrepancies, and can produce mass-metallicity relations with different shapes, y-axis offsets, and scatter (see Kewley & Ellison 2008). This complicates comparisons between different samples and between samples at different redshifts, for which different suites of emission lines are available.

Figure 4 shows a rather linear correlation up to $\sim 10^{10.5}$ $M_{\odot}$, after which a gradual flattening occurs. The correlation is very tight, tighter than the one between stellar mass and stellar metallicity, and extends over three decades in stellar mass. Tremonti and collaborators interpret the shape of the mass-metallicity relation in terms of efficient galactic outflows that remove metals from galaxies with shallow potential wells, an idea that was originally introduced by Larson (1974). Alternative explanations have been proposed: e.g. a lower star formation efficiency in low-mass galaxies (Calura et al. 2009), or a variable integrated initial mass function (Köeppen, Weidner & Kroupa 2007).

There is a striking similarity between the two relations shown in Figures 3 and 4. Gallazzi and collaborators have compared their stellar metallicity measurements with measurements of gas-phase metallicity, for those galaxies for which both measurements are available. They have shown that there is a clear correlation between these quantities, with approximately unit slope, but there is a large scatter in stellar metallicity at fixed gas-phase metallicity. In a closed box model, these two quantities should be tightly related. Therefore, these findings indicate that gas ejection and/or accretion play an important role in galaxy chemical evolution, and that their influence likely varies with stellar mass.

Important constraints on the star formation history of galaxies can be obtained from measurements of α-element abundances. These elements are mainly produced by supernovae Type II that explode on relatively short time-scales (of the order of a few Myrs), whereas the iron-peak elements are mainly produced by supernovae Type Ia, on much longer time-scales. Therefore, the [α/Fe] ratio can be used as an indicator of the star formation time-scale. Since the early 1990s, it has been known that brighter elliptical galaxies host stellar populations that are α enhanced with respect to their lower mass counterparts (Worthey, Faber & Gonzalez 1992). Figure 5 shows stellar population parameters for early-type galaxies in different environments, as a function of the galaxy velocity dispersion and stellar mass. There is a clear trend for increasing [α/Fe] ratios with increasing stellar mass, both in low and high density regions. This trend suggests that the time-scale of star formation correlates with the galaxy stellar mass, and appears to be in contrast with naive expectations based on the growth of dark matter haloes in hierarchical CDM cosmologies. Recent models that take into account the suppression of late gas cooling

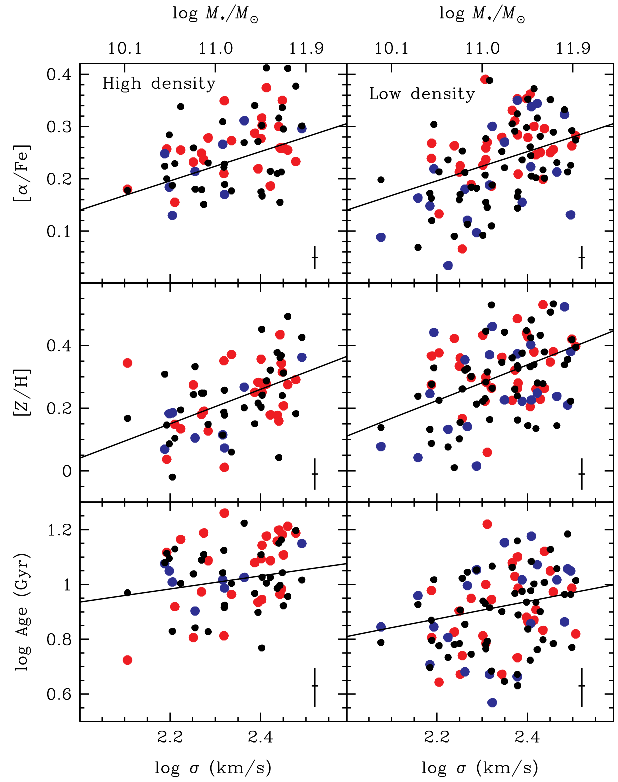

Figure 5 From Thomas et al. (2005). Stellar population parameters as a function of velocity dispersion and stellar mass for early type galaxies (red symbols are ellipticals, and blue symbols for lenticular). See original paper for details.

(and hence star formation) by radio-mode AGN feedback, however, have shown that the observed behaviour is *not in contradiction* with the hierarchical paradigm of structure formation (e.g. De Lucia et al. 2006). In these models, the shape of the mass metallicity relation appears to be particularly sensitive to the adopted feedback model (De Lucia, Kauffmann & White 2004; Bertone, De Lucia & Thomas 2007), confirming that these observations provide strong constraints on how and when baryons and metals were ejected from galaxies.

4 Metallicity Distributions in the Intra-Cluster Medium

Simulations have shown that the baryon fraction in a rich cluster does not evolve appreciably during its evolution. Clusters of galaxies can thus be considered as closed systems, retaining all information about their past star-formation and metal-production histories. This suggests that direct observations of element abundances in the intra-cluster medium (ICM) can constrain the history of star formation in clusters, the efficiency with which gas was converted into stars, the relative importance of different types of supernovae, and the mechanisms responsible for the ejection and the transport of metals. For all elements synthesised in stars after the primordial nucleosynthesis, the energies corresponding to their K- and L-shell transitions are accessible to modern X-ray telescopes. Most

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of the observed emission lines can be converted to elemental abundances under the (reasonable) assumption of collisional equilibrium. Complications due to extinction, non-equilibrium ionization, optical depth effects, etc. are not significant, while the abundance measurements depend crucially on the modelling of the temperature structure (Werner et al. 2008, and references therein).

X-ray observations have shown that the ICM contains a considerable amount of heavy elements, resulting in typical values of the order of one third solar or even higher. Since a large fraction (∼15–20%) of the total mass of a cluster is in the ICM, and galaxies contribute for a much smaller fraction (∼3–5%), assuming that the typical metallicity of cluster galaxies is about solar (Renzini 1997) implies that there is more mass in metals in the ICM than in all the galaxies in a cluster. Recent observations have also shown that the typical metallicity in the ICM appears to decrease by about 50% to $z \sim 1$ (Balestra et al. 2007). Cool core clusters (with peaked X-ray emission at their centres due to condensed regions of cooler gas) usually exhibit centrally peaked metallicity distributions, while flat distributions of metals are usually observed for non cool-core clusters. Observations of element abundances are consistent with the idea that the excess of metals in the central regions of cool core clusters is produced by supernovae Ia associated with the central cD galaxy (Tamura et al. 2001; De Grandi et al. 2004). If metals originated from the stars produced in the central galaxy, the abundance profile would follow the light profile in absence of mixing. The observed metal profiles are, however, shallower than the corresponding light profiles, suggesting that metals are mixed into the ICM and transported towards the outer regions by some physical process(es).

Deep observations of bright clusters with XMM-Newton and Chandra allow the construction of maps of the 2D distribution of metals in the ICM. Used together with maps of thermodynamic properties, these maps can provide important information about the merging history of the cluster. Figure 6 shows the map of Fe abundance in M87. The half light radius of M87 is shown as a black circle while the 90-cm radio-emission contours are shown in white. In addition to a radial gradient, which is usually observed in the central regions of galaxy clusters, the map in Figure 6 suggests the presence of deviations associated with the inner radio lobes. These deviations are interpreted by Simionescu et al. (2008) as a result of the influence of the central AGN on the spatial distribution and transport of metals.

Various additional physical processes can provide viable mechanisms for the transfer of metals from galaxies into the ICM, and several theoretical studies have been carried out in order to quantify their relative importance (for a recent review, see Schindler & Diaferio 2008). One physical process that is expected to be more important in clusters than in average regions of the Universe is *ram-pressure stripping*: galaxies travelling through a dense intra-cluster medium suffer a strong pressure that sweeps cold gas (and the metals in it) out of the stellar disc.

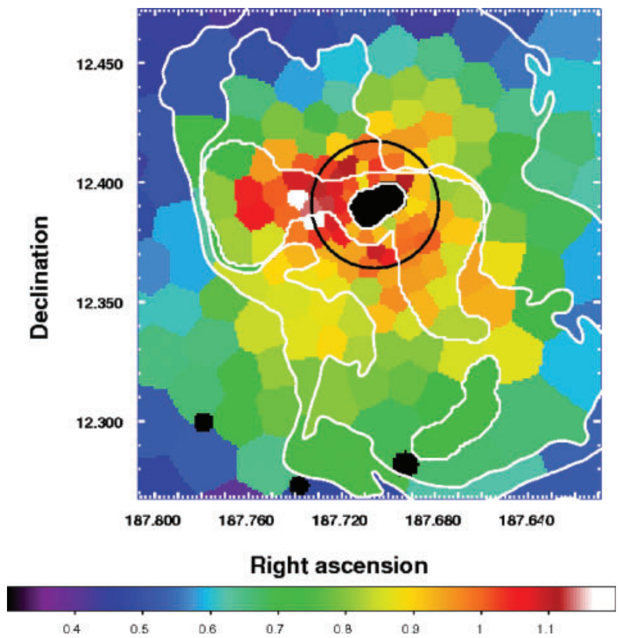

Figure 6 From Simionescu et al. (2008). Map of the iron abundance in M87. See original paper for details.

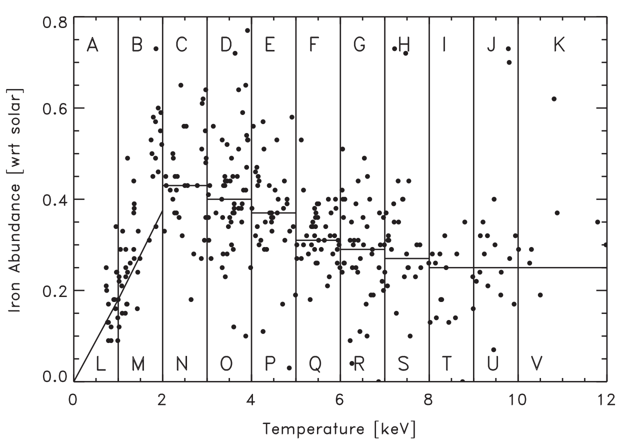

Figure 7 From Baumgartner et al. (2005). Iron abundance (with respect to solar) as a function of the ICM temperature. Each point is a single cluster measurement, while the lines show where the boundaries were placed for stacking individual measurements. See the original paper for details.

Hydrodynamical simulations, however, suggest that this process can account only for ∼10 per cent of the overall observed level of enrichment in the ICM within a radius of 1.3 Mpc (Domainko et al. 2006). As noted by Renzini (1997), there is also a direct observational evidence that ram-pressure cannot play a dominant role in the chemical enrichment of the ICM because this process would operate more efficiently in high velocity dispersion clusters. A positive correlation between the richness of the cluster and its metal content is not supported by observations, as shown in Figure 7.

Another obvious source of chemical enrichment is provided by supernova driven winds, which are expected to play a dominant role in the outer regions of galaxy clusters, where they can travel to larger distances due to the lower ICM pressure. On the observational side, evidence

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in support of the existence of outflows from galaxies has grown rapidly in the last years. Powerful galactic winds appear to be ubiquitous in local starburst galaxies and in high-redshift Lyman Break galaxies (Heckman 2002).

Different methods to estimate the outflow rate suggest that this is of the same order of magnitude of the star formation rate, with outflow speeds varying in the range 400–800 km/s, and approximately independent of the galaxy circular velocity. Observations also indicate, however, that galactic winds are complex and multi-phase outflows of cool, warm, and hot gas, dust, and magnetized relativistic plasma (Veilleux, Cecil & Bland-Hawthorn 2005). In addition, it is important to remember that observational estimates of outflow rates should not be confused with the rates at which mass and metals *escape* from galaxies, because they are derived from material that is still quite deep within the gravitational potential of the galaxy's dark matter halo. Whether the gas reheated by supernova explosions will leave the halo depends on a number of factors like the amount of intervening gas, and the fraction of energy lost by radiative processes. Given these uncertainties and the dynamical complexity of the outflows, an accurate implementation of the feedback process in hydrodynamical simulations is still very difficult, and needs to rely on 'sub-grid' physics (i.e. this physical process is not modelled from first principles, but 'implemented' using theoretically and/or observationally motivated relations, as is done in semi-analytic models).

As noted in a recent review by Borgani et al. (2008), hydrodynamical simulations are in qualitative agreement with most recent observations. Some problems are, however, persistent: e.g. too much gas cools at the centre of massive clusters, leading to abundance profiles that are usually steeper than observed. The problem is alleviated by the inclusion of AGN feedback: Figure 8 shows a comparison between observational data and simulations including supernovae driven winds (dashed green line) and different implementations of AGN feedback (red and cyan lines). In these simulations, profiles from different runs have similar central slopes. This happens because the effect that different feedback mechanisms have in displacing enriched gas and regulating star formation almost balance each other in the central regions. In the outer regions (at cluster-centric distances $\gtrsim 0.2 R_{200}$), the metal abundance profile in runs including AGN feedback (red and cyan lines) becomes flatter with respect to the profile obtained in a run with only galactic winds (green line), resulting in a better agreement with observational measurements. The flattening in the outer regions is due to the fact that AGN feedback displaces large amounts of enriched gas from star forming regions at high redshift and, at the same time, efficiently suppresses cooling at low redshift.

5 Metallicity Distributions in the Inter-Galactic Medium

The existence of metals in the inter-galactic medium (IGM) has been known for about two decades by their

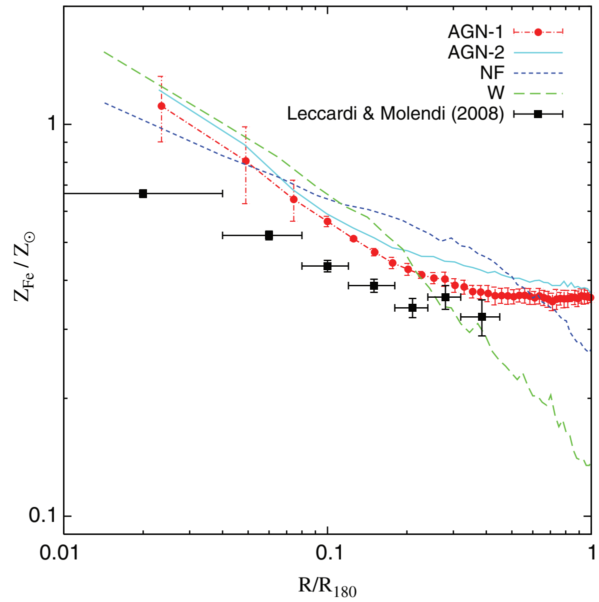

Figure 8 From Fabjan et al. (2010). Comparison between the observed and simulated profiles of emission-weighted Iron metallicity. Black symbols with error bars show observational measurements for galaxy clusters with $T_{500} > 3$ keV. Different lines correspond to different simulation runs: no feedback (blue dashed), galactic winds (green dashed), and different AGN feedback implementations (red dot-dashed and cyan solid). See the original paper for details.

absorption lines in the spectra of high-redshift quasars. First indications by Meyer & York (1987) were later confirmed with the advent of 8m-class telescopes and high-resolution spectra, that clearly showed the presence of measurable amounts of heavy elements (about one per cent solar) in the Lyman α Forest absorbers (e.g. Songaila & Cowie 1996). More recent studies have indicated that heavy elements are present at all densities, down to at least the mean cosmic density (Schaye et al. 2003) and that, on small scales, the distribution of metals in the IGM is highly inhomogeneous.

Among the different types of QSO absorbers, damped Lyman α systems (DLAs) have received particular attention (for a review, see Wolfe, Gawiser & Prochaska 2005). These objects are characterised by H I column densities $N(\text{H I}) \gtrsim 2 \times 10^{20}\,\text{cm}^{-1}$, and hydrogen appears to be mainly neutral in these systems, implying that they represent important neutral gas reservoir for star formation at high redshift. A nice review of recent metallicity measurements in DLAs is provided by Pettini (2006). Data show that the mean metallicity of these systems is relatively low (about one tenth solar or lower), but that individual measurements span a wide range of metallicities, from solar to less than one hundredth solar. A few measurements of element abundance patters are available, and suggest that, at least some DLAs, have [α/Fe] ratios lower than those measured in Milky Way stars of low metallicities. This has been interpreted as an indication of low levels of star formation (e.g. Matteucci & Recchi 2001).

Several recent studies have tried to constrain the cosmic evolution of the metal content of the IGM through

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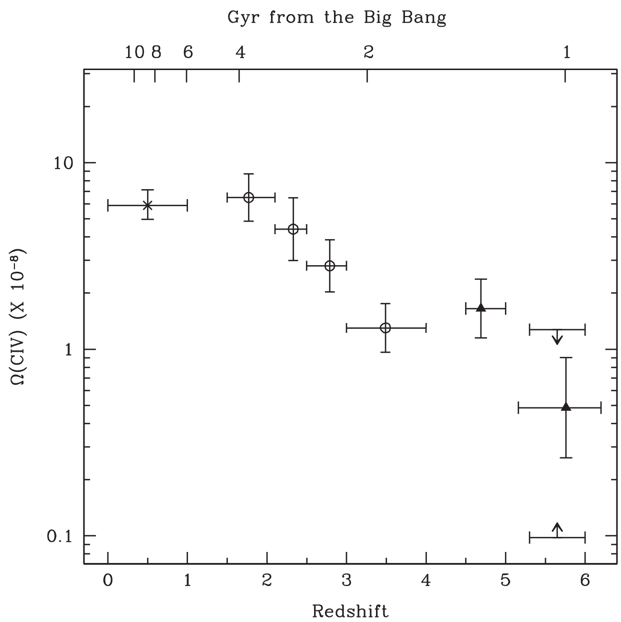

Figure 9 From D'Odorico et al. (2010). Mass density of CIV as a function of redshift. The lowest redshift data point is from Cooksey et al. (2010), solid triangles are from Pettini et al. (2003) and Ryan-Weber et al. (2009). Finally, the 95 per cent confidence interval at the highest redshift considered are from Becker et al. (2009).

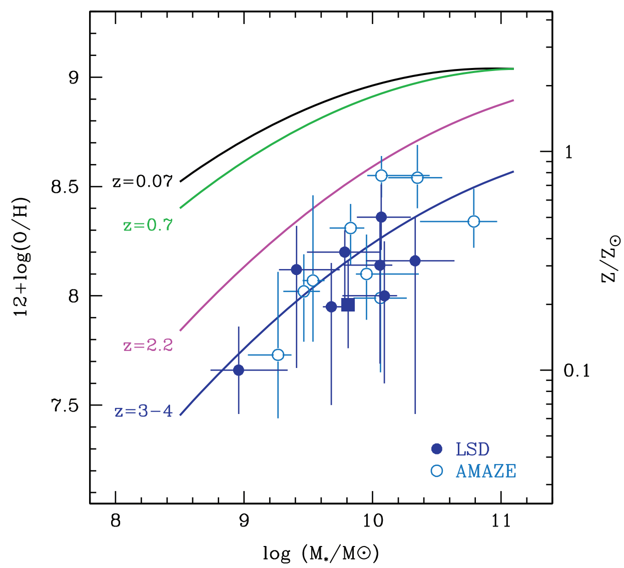

Figure 10 From Mannucci et al. (2009). Evolution of the mass-metallicity relation from $z = 0.07$ (Kewley & Ellison 2008), to $z = 0.7$ (Savaglio et al. 2005), $z = 2.2$ (Erb et al. 2006), and $z = 3$–4 (Maiolino et al. 2008; Mannucci et al. 2009). All data have been calibrated to the same metallicity scale and IMF. The lines show quadratic fits to the data (see original papers for details).

measurements of the CIV mass density, $\Omega_{\rm CIV}$. Figure 9 is from a recent study by D'Odorico et al. (2010) and shows a significant increase of $\Omega_{\rm CIV}$ at $z \lesssim 3$ and a downturn at $z > 5$ (Becker, Rauch & Sargent 2009; Ryan-Weber et al. 2009). A satisfactory theoretical interpretation for the trends shown in Figure 9 is still missing. The most recent theoretical study in this area is that by Oppenheimer & Davé (2008). These authors have used cosmological simulations which include feedback in the form of momentum driven winds, and found an apparent lack of evolution of the CIV mass density from $z \sim 5$ to $z \sim 1.5$. In the simulations, this results from an overall increase in the cosmic abundance of carbon, and a parallel reduction of the fraction of triply ionized carbon. None of the simulations presented in this study predict the recently observed increase of $\Omega_{\rm CIV}$ towards lower redshift.

From the theoretical viewpoint, the details of how large volumes of the IGM could have been seeded by the products of stellar nucleosynthesis at early times, and how these products could reach such low overdensities remain to be understood. Galactic winds might play an important role in polluting the IGM, particularly at high redshift, when star formation rates are more elevated and the energy deposited by supernovae can potentially disrupt the shallow potential wells of proto-galaxies. The observed enhancement of metal abundances in the proximity of Lyman-break galaxies suggests that star forming galaxies might be an important source of later chemical enrichment. A number of recent numerical studies have focused on comparing different feedback schemes with various observational measurements (e.g. Oppenheimer & Davé 2008; Tescari et al. 2009). These studies confirm that galactic winds are indeed able to enrich large comoving volumes of the IGM at high redshift. Numerical results are in qualitatively good agreement with observational measurements, but not without problems. For example, in these simulations the metallicity distributions of DLAs (as traced by the velocity widths) and the observed recent increase of $\Omega_{\rm CIV}$ (as mentioned above) are not well reproduced, suggesting that either the feedback scheme adopted is too simplistic/incorrect, or that there are some physical mechanisms not included in the simulations (e.g. enrichment by Population III stars, turbulence, etc.).

6 Metal Abundances at High Redshift

Several studies have recently focused on the evolution of the mass-metallicity relation as a function of redshift. Results are summarised in Figure 10. As discussed earlier, the shape of the mass-metallicity relation provides important constraints on feedback mechanisms and on their efficiency as a function of the galaxy's potential well. Particular care, however, needs to be taken when interpreting the data shown in Figure 10. At different redshifts, different emission lines are available, so that different calibrations need to be used. The strong effects on the shape and zero-point of the metallicity calibration can lead to incorrect evolutionary interpretations. In addition, samples observed at different epochs do represent different classes of objects that are not necessarily linked from an evolutionary point of view. This also complicates any comparison with galaxy formation models and/or simulation results.

A (now incomplete) summary of our current knowledge about element abundances at $z \sim 2.5$ is provided in

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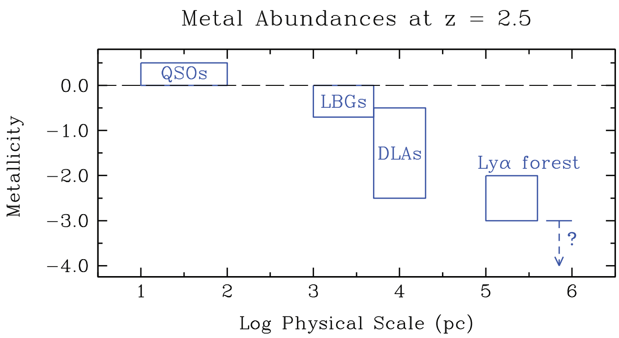

Figure 11 From Pettini (2006). Snapshot of the metallicity of different components of the high redshift universe. The logarithm of the metallicity is plotted relative to solar (indicated by the long-dash line at 0.0) as a function of the typical linear scale of the structure to which it refers.

Figure 11 from Pettini (2006). This figure shows the metallicities measured in different systems at high redshift, as a function of the typical linear scale of the structure to which it refers. The figure shows a clear trend of decreasing abundances with increasing scale. The gas in the inner 10–100 pc of the highest overdensities, where supermassive black holes reside, is enriched to solar or supersolar levels. Actively star-forming galaxies sample physical scales of the order of a few kpc, and are enriched to near solar metallicity. DLAs likely sample more diffuse gas at the outskirts of galaxies in the process of formation and, as mentioned earlier, they represent a quite heterogeneous population with a large scatter in the degree of chemical enrichment. Finally, the Lyman α Forest is believed to trace large scale structures of moderate overdensity relative to the cosmic mean, and it appears to contain only trace amounts of metals. Figure 11 shows that, at any cosmic epoch, the degree of metal enrichment depends strongly on the scale considered.

Integrating the comoving star formation rate deduced from galaxy surveys, it is possible to calculate (adopting some conversion factors) an estimate of the comoving density of metals which should have accumulated by a given redshift. As discussed by Pettini (2006), when adding together the contributions shown in Figure 11, one can account for about 40% of the metal production from the Big Bang to $z = 2.5$. The contribution from sub-DLAs (not included in the calculation by Pettini) amounts to about 6 per cent of the expected metals at $z \sim 2.5$ (Peroux et al. 2007). The *missing metals problem* has been revisited by Bouché et al. (2007) who estimated that currently known galaxy populations at $z \sim 2$ can account for $\gtrsim$30 to $\lesssim$60 per cent of the metals expected, which is approximately what is required to close the metal budget. As noted by Bouché and collaborators, however, it is unclear what the overlap is between the various galaxy populations at this redshift. A conservative estimate provided by these authors, is that we can currently account for $\gtrsim$65 per cent of the metals expected at $z \sim 2.5$, the metals being equally spread between galaxies and IGM.

Still uncertain is the contribution provided by the so-called Warm Hot Intergalactic Medium (WHIM), a tenuous and elusive phase that is predicted by numerical simulations. This baryonic phase is expected to be characterised by relatively high temperatures ($T \sim 10^5$–10^7 K), and is predicted to radiate most of its energy in the ultraviolet and X-ray bands. Current X-ray telescopes do not have enough sensitivity to detect the hotter WHIM, but future space missions (e.g. Constellation X, XEUS) should be able to detect both emission lines and absorption systems from highly ionised atoms. Interestingly, recent numerical simulations show that the metal distribution in this phase depends significantly on the details of feedback (Tornatore et al. 2009), therefore providing an additional tool to study the physical processes responsible for the chemical enrichment of the Universe.

7 Discussion and Conclusions

As discussed above, metals are widespread in our Universe and different techniques have to be used to measure their amounts in different baryonic components (stars, cold inter-stellar medium, hot intra-cluster gas, intergalactic medium). At least for some of these techniques, there are still large uncertainties on the observational calibration, which complicates the comparison between measurements at different redshift and/or in different bands.

Much work is going on to improve the precision of the observational measurements and to push element abundance studies to higher and higher redshift. Stellar population synthesis models have been improved significantly in recent years: many new empirical libraries have been made available with improved spectral resolution and parameter coverage (e.g. Sánchez-Blázquez et al. 2006), and many libraries of theoretical high-resolution stellar spectra for both scaled-solar and α-enhanced chemical mixtures have been published (Coelho et al. 2007, and references therein). Parallel effort is going in the direction of refining photoionization models (such as MAPPINGS, Dopita et al. 2005) which help us correctly diagnose physical properties of star forming galaxies. Accurate measurements of metallicities for much larger samples of individual stars for our Galaxy and its satellites will be available in the coming years from a number of ongoing astrometric and spectroscopic surveys (e.g. the satellite *Gaia*, Perryman et al. 2001; the Sloan Extension for Galactic Understanding and Exploration, Beers et al. 2004). Future X-ray satellites will likely push the study of the distribution of metals in the ICM to larger radii in nearby clusters, and allow metallicity profiles to be measured at higher redshift (see e.g. Giacconi et al. 2009). High-resolution spectroscopy in the X-ray and in the UV (e.g. with the Cosmic Origin Spectrograph onboard the Hubble Space Telescope) will also allow us to make progress in the study of the diffuse warm-hot baryons in the local Universe.

From the theoretical viewpoint, hydrodynamical simulations and semi-analytic models provide the interpretative

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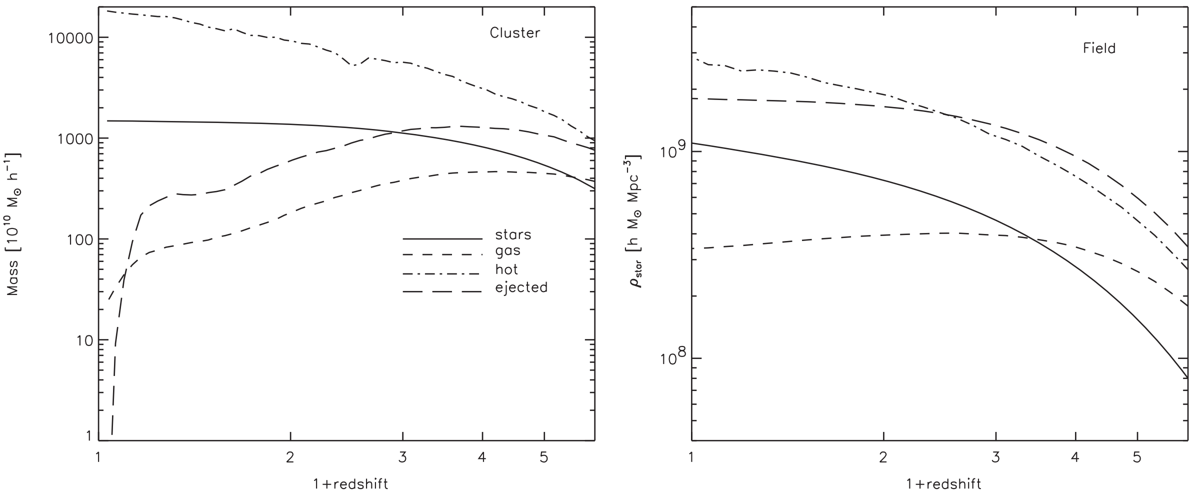

Figure 12 From De Lucia et al. (2004). Evolution of the metal content in different phases. The solid line represents the evolution of the metal content in stars, the dashed line the cold gas, the dashed-dotted line the hot gas, and the long-dashed line the ejected component. The metal content in each phase is normalised to the total mass of metals produced from all galaxies considered. The left panel shows the results for galaxies within the virial radius of a massive ($\sim 10^{15}$ $M_\odot$) cluster, while the right panel shows the results for a typical 'field' region. See original paper for details.

framework for these observational studies. Many theoretical predictions are already available but not always these studies have been able to provide a 'self-consistent' description of the circulation of the baryons in different components. Indeed, cosmological hydrodynamical simulations have mostly focused on the distribution of metals in the IGM and ICM, but the numerical resolution adopted is insufficient to study the metal distribution in galaxies. On the other hand, semi-analytic models can provide detailed predictions on the distribution of metals in the stellar and gaseous components but do not provide details on the spatial distribution of the metals.

Figure 12 shows the evolution of the metal content in different phases for one particular feedback scheme implemented in a semi-analytic code by De Lucia et al. (2004). The left panel corresponds to a cluster simulation while the right panel is for a region with average density. Comparison between the two panels shows that cosmic variance effects are going to play an important role when trying to constrain different feedback schemes using observational metallicity measurements. Nevertheless, the same study pointed out (and many later studies confirmed) that the fraction of metals (as well as their distribution) in different baryonic components varies significantly when different feedback schemes are adopted. It is therefore to be expected that the vast amount of data that will be available in the next future, and detailed comparisons with theoretical models will eventually tell us a great deal about how galaxies ejected their metals over the history of the Universe.

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