Galactic chemical evolution in hierarchical formation models

Arrigoni, Matias

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2010

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 03-10-2019
The evolution of metals through cosmic time.

Abstract

We use the cosmological semi-analytic model (SAM) presented in Chapters 2 and 3 to study the evolution of the mass–metallicity relation (MZR) over cosmic time within the hierarchical galaxy formation paradigm. The model is able to reproduce abundance ratios and supernova rates of early-type galaxies in the local Universe, as well as the elemental abundance ratios and overall metal content in the ICM. At intermediate redshifts ($z = 0.75–2.5$) the models show a fair agreement with the data. However, the predicted evolutionary trend is opposite to that observed. Our simulations show little to no evolution for galaxies with $M_\star < 10^{10} M_\odot$ and a strong change in metallicity for the more massive galaxies. At all redshifts, the oxygen abundance of simulated massive galaxies is consistent with the observations, but for low-mass galaxies it is overpredicted at very high redshift ($z = 3–3.5$) and underpredicted locally ($z \sim 0$). The discrepancy in the abundances of low-mass galaxies at high redshift reflects the fact that, in the SAMs, these galaxies are too efficient at forming stars early in the Universe. This calls for a revision of the feedback and/or star formation schemes adopted in the models.

4.1 Introduction

Metallicities and abundance ratios contain valuable clues on the evolutionary history of galaxies. The chemical enrichment is a record of a galaxy’s star formation history, modulated by the presence of infalls and outflows as well as mergers and interaction between galaxies. Thus the study of the chemical properties of galaxies, in simulations and observations, can be a critical tool to set constraints on galaxy formation models.

The existence of a correlation between mass and metallicity has been known for several decades since the seminal works of Faber (1973) and Lequeux et al. (1979), followed by several studies of local galaxies that showed a relation between the blue luminosity (used as a proxy for the stellar mass) and the metallicity, such that more-luminous (and massive) galaxies are also more metal-rich (Faber 1977; Garnett & Shields 1987; Zaritsky et al. 1994). With the development of more sophisticated stellar population models and the large statistical power provided by the Sloan Digital Sky Survey (SDSS), Tremonti et al. (2004) have determined a clear and well-defined stellar mass–gas metallicity relation (see also Kewley & Ellison 2008). Likewise, Gallazzi et al. (2005) have found a similar relation for stellar metallicity, also using the SDSS survey. Since then, many authors have obtained constraints on the mass–metallicity (MZR: Savaglio et al. 2005; Shapley et al. 2005; Erb et al. 2006; Maiolino et al. 2008; Mannucci et al. 2009) or luminosity–metallicity (LZR) relations (Kobulnicky & Kewley 2004; Maier et al. 2005; 2006; Förster Schreiber et al. 2006) at progressively higher redshifts. The general observational result is that the MZR and the LZR evolve in time with higher redshift galaxies characterized by lower metallicities at given mass (or luminosity). This evolution is not constant in time or with mass (luminosity). The rate of change in metallicity is stronger at high redshift, and less massive galaxies show a larger increment in their abundances than the more massive ones. All the high-z studies mentioned here refer to the gas-phase metallicity, given the difficulties in obtaining the high-S/N spectra required to determine stellar metallicities at such redshifts.

Several physical processes have been proposed as the origin of the MZR. One explanation is that the metal-rich outflows generated by the supernova-driven winds are more prominent in low-mass galaxies, given their shallow potential wells, effectively reducing their enrichment compared to more massive systems (Vader 1986; Tremonti et al. 2004; De Lucia et al. 2004; Kobayashi et al. 2007; Finlator & Davé 2008; Somerville et al. 2008). An alternative scenario in shaping the MZR is that of “galaxy downsizing”, where lower-mass galaxies form their stars later and on longer timescales than higher-mass galaxies. In this sense, at any given time, lower-mass galaxies have formed a smaller fraction of stars and, consequently have lower metallicities. This scenario is supported by both observations (Franceschini et al. 2006; Asari et al. 2007; Pérez-González...
et al. 2008) and simulations (De Lucia et al. 2006; de Rossi et al. 2007; Fontanot et al. 2009). Other possibilities could be variations of the IMF high-mass cut-off in different star forming environments (Köppen et al. 2007) or the accretion of pristine gas having longer infall times in low mass galaxies (Dalcanton et al. 2004). Models of galaxy formation, like ours, are calibrated with the MZR observed locally. However, different models that ascribe the MZR to different processes will have different implications for its evolution with redshift, and the observational data provides a powerful benchmark to test the models.

In this chapter we use the model presented in Arrigoni et al. (2010) and Arrigoni et al. (submitted; hereafter Chapters 2 and 3, respectively) to probe the evolution of metals over cosmic time and confront our simulations against the latest observations. The outline of the chapter is as follows. In Section 2 we briefly describe the semi-analytic model and its ingredients. In Sections 3 and 4 we present our predictions and compare them with observations. In Section 5 we discuss our results and in Section 6 we summarise our findings and present our conclusions.

### 4.2 The semi-analytic model

The adopted model is that described in Chapters 2 and 3, which extends the semi-analytic galaxy formation model of Somerville et al. (2008, hereafter S08) to include detailed metal enrichment by type Ia and type II supernovae and long-lived stars. The model also includes hierarchical clustering of dark matter haloes, radiative cooling of gas, star formation, supernova (SN) feedback, AGN feedback (in two distinct modes, quasars and radio jets), galaxy mergers and the starbursts triggered by them, the evolution of stellar populations, and the effects of dust obscuration. We refer the reader to the two aforementioned studies for a detailed description of the different prescriptions used to account for these physical processes.

This model has been successful in reproducing a variety of observations in the local Universe and at high redshift, for example, the luminosity and stellar mass function of galaxies, the colour–magnitude relation, galaxy star formation rates as a function of their stellar masses, the relative numbers of early and late-type galaxies, the gas fractions and size distributions of spiral galaxies, and the global star formation history (S08). With the addition of detailed metal enrichment in Chapter 2, the model is able to match the MZR for galaxies and the trend of [$\alpha$/Fe] with stellar mass, as well as the supernova rates as a function of specific star formation rate (SSFR). To achieve these goals, it was necessary to adopt a Chabrier IMF (Chabrier 2003) with a slightly flatter slope above 1 $M_\odot$ ($x = 1.15$ instead of $x = 1.3$), a relatively low fraction of binaries that yield a type Ia SN event (0.04 in the $M = 3$–$16M_\odot$ range), and a bimodal delay-time-
distribution (DTD) with a prompt peak and a later plateau for type Ia supernovae explosions (SNe Ia), as proposed by Mannucci et al. (2006). In Chapter 3 we introduced metal-enhanced outflows in order to match the iron abundance and overall metal content of the ICM in galaxy clusters. In this scenario, 80% of the metals produced and ejected by the stars are deposited directly into the ICM (the hot gas phase associated with the dark matter halo) rather than the ISM (the cold gas phase associated with the individual galaxies).

In this chapter, we adopt a flat $\Lambda$CDM cosmology with $\Omega_0 = 0.28$, $\Omega_\Lambda = 0.72$, $h \equiv H_0/(100 \text{ km s}^{-1}\text{Mpc}^{-1}) = 0.701$, $\sigma_8 = 0.812$, and a cosmic baryon fraction of $f_b = 0.1658$, following the updated values of the cosmological parameters from Komatsu et al. (2009). The stellar yields used come from, as in Chapter 3 Karakas & Lattanzio (2007) for AGB stars, Woosley & Weaver (1995) for type II supernovae and Iwamoto et al. (1999, model WDD3) for type Ia supernovae. The abundances are normalized to the solar values of Grevesse et al. (1996). We also leave the values of the free parameters associated with the galaxy formation model fixed at the fiducial values given in Chapter 2.

4.3 The evolution of the the chemical compositions of galaxies in a hierarchical galaxy formation model

In this section we present our model results for the abundance ratio and metallicity of the ISM and stellar component of galaxies at several different redshifts and test them against a variety of observations (mainly gas phase oxygen abundance). The simulations were run on a grid of haloes with virial mass ranging from $10^{11.1} \text{M}_\odot$ to $10^{14.3} \text{M}_\odot$. For each individual output redshift, an independent grid of merger trees was generated. In this sense, the simulated galaxies at high redshift are not necessarily the progenitors of the low-redshift ones. This is consistent with surveys, since the observed evolution of the MZR should not be considered the evolutionary pattern of individual galaxies, but rather as the evolution of the MZR of the dominant population of star forming galaxies at each epoch (Maiolino et al. 2008).

In the figures presented in the following sections, we show all the simulated galaxies from every halo, distinguishing between satellite (grey scale histogram) and central galaxies (red dots). Because the grid of halos has the same number of realizations for the different halo masses, an unrealistically large number of galaxies belonging to massive halos are produced. For this reason, the mean value shown in the figures is not a straight average of all the galaxies, but weighted by the halo mass function of the dark matter halo in which each galaxy resides. Therefore the mean abundance values follow a realistic distribution of galaxies.
4.3: The evolution of the chemical compositions of galaxies in a hierarchical galaxy formation model

4.3.1 The mass-metallicity relation

At intermediate and high redshift, metallicities are derived by a simultaneous fit of all available strong emission-line ratios. Strictly speaking, the measured quantity is the gas-phase oxygen abundance. We used an ensemble of observations at different redshifts to test our models. The data sets used for comparison are Tremonti et al. (2004) at $z \sim 0.1$, Savaglio et al. (2005) and Zahid et al. (2010) at $z \sim 0.7$, Shapley et al. (2005) and Liu et al. (2008) at $z \sim 1.0–1.5$, Shapley et al. (2004) and Erb et al. (2006) at $z \sim 2.2$, and Maiolino et al. (2008) and Mannucci et al. (2009) at $z \sim 3.0–3.5$. It should be noted that the variety of strong emission line diagnostics used for high-redshift objects are calibrated with local sources. Should the line excitation conditions change with redshift, the mismatch between the different calibration scales would introduce artificial evolutionary effects on the mass-metallicity relation. However studies have shown that, at least up to $z \sim 2–2.5$, these calibrations deviate by only 0.1 dex (or less) with respect to local galaxies (Liu et al. 2008; Maiolino et al. 2008). Such small deviations will not affect the analysis that follows. Another issue is that the different line diagnostics used at different redshifts are not calibrated the same way and may introduce artificial evolutionary effects (Kewley & Ellison 2008). Taking this into account, Maiolino et al. (2008) cross-calibrated the surveys at lower redshifts and corrected the inferred abundances to match a single metallicity scale. The recalibrated abundances were available for all the surveys used for comparison, with the exception of Shapley et al. (2005) and Liu et al. (2008). The metallicity calibrator used in the latter studies ($N_2$) produces abundances that are systematically lower with respect to the other surveys (which have been corrected to the $R_{23}$ calibrator). The difference goes from $-0.15$ dex at low masses to $-0.3$ dex for high masses (Savaglio et al. 2005). Using the cross-calibration procedure described in Maiolino et al. (2008), we correct the data shown at $z \sim 1–1.5$ (Liu et al. 2008, Shapley et al. 2005) to match the same metallicity scale.

Figure 4.1 shows the gas phase oxygen abundance as a function of stellar mass for model galaxies at different redshifts, with the observational data sets overplotted. The simulations show reasonable agreement with the data, especially at intermediate redshifts ($z = 0.75 - 2.5$). However, the evolutionary trend is opposite to that observed. The data show a clear evolution of the MZR at all masses, being more pronounced for the lower mass systems. Our simulations, on the other hand, show little to no evolution for galaxies with $M_* < 10^{10}$ $M_\odot$ and a moderate change in metallicity for the more massive galaxies. The high-mass end of the MZR evolves at the highest redshifts (an increase of 0.2 dex between $z \sim 2 – 3.5$) and stays in place below $z = 1.5$. The predicted metallicities should increase by $\sim 0.35$ dex at all masses between $z \sim 2–3.5$ to match the observations. The underprediction at $z = 0$ might not be so strong. At all but the highest
Figure 4.1: Gas-phase oxygen abundance vs. stellar mass at various redshifts. The grey scale shows the conditional probability distribution for satellite galaxies and the red dots, the central galaxy of each simulated halo. The green lines shows the mean for all the simulated galaxies (both central and satellites, weighted by the halo mass function; thick lines) and the 1σ dispersion (thin lines). The pink line is the mean at $z = 0$ shown at all other redshifts for comparison. Blue symbols show the observational data sets. In each panel, these are taken from Tremonti et al. (2004) for $z = 0$ (the lines mark the 2.5, 16, 50, 84 and 97.5 percentiles, respectively); Savaglio et al. (2005) blue, and Zahid et al. (2010) cyan for $z = 0.75$; Shapley et al. (2005) upward triangles and Liu et al. (2008) downward triangles for $z = 1$ and $z = 1.5$; Erb et al. (2006) upward triangles and Shapley et al. (2004) downward triangles) for $z = 2$ and $z = 2.5$; Mannucci et al. (2009 upward triangles) and Maiolino et al. (2008 downward triangles) for $z = 3$ and $z = 3.5$. 
4.3: The evolution of the chemical compositions of galaxies in a hierarchical galaxy formation model

Figure 4.2: Stellar metallicity vs. stellar mass at various redshifts. The grey scale shows the conditional probability distribution for satellite galaxies and the red dots, the central galaxy of each simulated halo. The green lines shows the mean for all the simulated galaxies (both central and satellites, weighted by the halo mass function; thick lines) and the $1\sigma$ dispersion (thin lines). The pink line is the mean at $z = 0$ shown at all other redshifts for comparison. The blue lines in the $z = 0$ panel indicate the 16, 50 and 84 percentiles from Gallazzi et al. (2005); the blue triangles at $z = 0.75$ and $z = 1$ are taken from Schiavon et al. (2006, processed as described in the text).
redshifts, the oxygen abundance of the simulated massive galaxies is in overall agreement with the observations, but for low-mass galaxies it is overpredicted at very high redshift \((z = 3–3.5)\) and underpredicted locally \((z \sim 0.1)\). As the observations go from low metallicity at high redshift to high metallicity at low redshift, they sweep across the locus of the simulated galaxies giving a remarkable agreement between the data and the model predictions at intermediate redshifts.

The fact that we overpredict the metallicity of low-mass galaxies at high redshift and that the MZR shows no evolution over cosmic time for these mass ranges is related to a problem already known to SAMs within the \(\Lambda CDM\) paradigm. In these models low-mass galaxies form too large a fraction of their stars very early while they are the central galaxy in DM halos with \(V_c \sim 200\) km/s. Moreover, once the galaxies become satellites, they remain passive up to the present epoch because of an overquenching of satellite galaxies. This is caused by the assumption that the hot halo is instantly stripped from satellites as they enter a larger host halo, thus shutting down any further cooling onto satellite galaxies (Fontanot et al. 2009). This calls for a revision of the feedback and/or star formation schemes implemented in the models, especially in low-mass systems, since it appears that either star formation is less efficient or the metals are removed more efficiently from these galaxies than previously assumed.

As a counterpart to the gas phase metallicity, in Figure 4.2, we show the stellar mass–stellar metallicity relation at the same output redshifts as before. In this case, we only have observational constraints locally (i.e. at \(z \sim 0\) Gallazzi et al. 2005), since the high S/N spectra required for absorption line diagnostics to determine the stellar metallicity are not readily available for high redshift galaxies. There are, however, estimates of stellar metallicities at \(z \sim 0.8–1\) based on absorption-line indices measured by Schiavon et al. (2006) on stacked spectra. At redshift zero, unlike for the gas metallicity, the simulated galaxies are in very good agreement with the data at all mass ranges. In any case, the models are well within the \(16^{th}\) and \(84^{th}\) percentiles of the observations across the full mass range. At \(z \sim 0.8–1\) the agreement with the data is still remarkably good. It is interesting to note that, in the model, satellite galaxies (especially at high stellar masses) are more metal-rich than central ones. This is probably related to the overquenching of satellite galaxies mentioned before since, in this scenario, the metal-poor ICM gas only cools onto the central galaxy. This is effect is seen also in the gas phase metallicity, and at all redshifts. Regarding the evolution of the stellar MZR, it follows qualitatively the same trends as the gas-phase MZR: a clear increase in metallicity for massive galaxies \((M_\star > 10^{10} M_\odot)\) with decreasing redshift, while low-mass galaxies show little evolution over cosmic time.

* The absorption-line indices \(H\delta_F\) and \(Fe4383\) were converted into single-stellar-population equivalent stellar metallicities and ages using the procedure described in Trager et al. (2008), assuming a typical \([\alpha/Fe] = +0.2\) for the high-mass galaxies observed by Schiavon et al. (2006).
4.3.2 Abundance Ratios

We now present our predictions for the evolution of the \([\alpha/Fe]\)-stellar mass relation, both in the gas-phase and the stellar component (by \(\alpha\) we mean the composite abundance of Ne, Mg, Na, Si and S). At the moment we only possess data for the stellar abundance ratio of local galaxies (Trager et al. 2000a, Paper I), so we simply present our predictions to be challenged by future observations (see Appendix B for an alternative approach).

The predicted gas-phase \([\alpha/Fe]\) ratios at various redshifts are shown as a function of stellar mass in Figure 4.3. At high redshift (\(z \sim 3.5\)) all galaxies lie on a very flat and extremely tight relation and have approximately the same \([\alpha/Fe]\). The value is essentially set by the abundance ratio of SN II products, slightly polluted by prompt type Ia supernovae. As time progresses, more and more (delayed) SN Ia products are deposited into the ISM, lowering the mean value of the abundance ratio and significantly increasing the scatter. The differential inflows and outflows of gas introduce a very mild slope at intermediate redshifts. It is remarkable, however, that the gas-phase \([\alpha/Fe]\) shows a rather flat behaviour with stellar mass at all redshifts. One possible explanation for this trend could be the high level of mixing the gas experiences. In the models, the metals ejected by the stars are deposited mostly into the ICM and are later accreted by the galaxies, which themselves experience outflows (either SN-driven, for low-mass galaxies, or AGN-driven, for high-mass galaxies). In this sense, the cold gas in galaxies is being constantly recycled through the intracluster medium in our models. Considering that the abundance ratios in the ICM are fairly constant for all halo masses (Chapter 3), it seems reasonable that in the ISM the abundance ratios show little correlation with galactic stellar mass.

Unlike the MZR, which shows the same qualitative evolution in both the gas-phase and stellar component, the evolution of the \([\alpha/Fe]\)-stellar mass relation is quite different from that of the gas, as can be seen from Figure 4.4. Even though at very high redshift the trend is rather flat, the scatter in the stars is substantially larger and the mean value is higher by 0.1 dex, due to, perhaps, less pollution by prompt SN Ia. The uniform abundance ratio at high redshift is a consequence that galaxies of all masses have similar timescales for star formation, further evidence that low-mass galaxies form too fast at high redshift in SAMs (including our model). As we move to the present epoch, low- and intermediate-mass galaxies, with more extended star formation histories and delayed onset of the star formation, progressively populate themselves with stars enriched by SN Ia, significantly decreasing their abundance ratios and steepening the slope of the relation. On the other hand, the more massive galaxies show a much milder decrease in their abundance ratios, caused by the accretion of smaller systems and some residual star formation. Note that by \(z = 0\) the agreement with the observations is remarkable. Unlike the gas-phase \([\alpha/Fe]\), the scatter in the stellar
Figure 4.3: Gas-phase [α/Fe] vs. stellar mass at various redshifts. The grey scale shows the conditional probability distribution for satellite galaxies and the red dots represent the central galaxy of each simulated halo. The green lines shows the mean for all the simulated galaxies (both central and satellites, weighted by the halo mass function; thick lines) and the 1σ dispersion (thin lines). The pink line is the mean at z = 0 shown at all other redshifts for comparison.
4.3: The evolution of the chemical compositions of galaxies in a hierarchical galaxy formation model

Figure 4.4: Stellar $[\alpha/Fe]$ vs. stellar mass at various redshifts. The blue triangles at $z = 0$ are data from Trager et al. (2000a), as revised in Chapter 2; all other points and lines as in Fig. 4.3
component remains almost constant. The picture of low-mass galaxies at low redshifts having subsolar \([\alpha/Fe]\) due to having more extended star formation histories is consistent with low-mass galaxies at high redshift forming too fast because the latter are not the progenitors of the former but rather of higher-mass, lower-redshift objects. Finally, it is interesting to note that evolution of the abundance ratio is \textit{opposite} to that of the stellar metallicity, meaning that change with redshift in \([\alpha/Fe]\) is stronger for low-mass galaxies while that of \([Z/H]\) is more prominent for high-mass galaxies.

### 4.4 Evolution of Supernovae Rates

The evolution of chemical composition of galaxies is dominated by the interplay of star formation and supernovae. Our model must therefore track supernova rates as a function of cosmic time in order to properly track the evolution of galaxy abundances. In recent years, many surveys have probed the evolution of supernova rates up to fairly high redshifts. These observations provide independent constraints on our adopted model for the rate of explosions of SNe Ia. We tested our model against a compilation of studies: \cite{Mannucci:2005}, \cite{Madgwick:2003}, \cite{Neill:2006}, \cite{Pain:2002}, \cite{Barris:2006}, \cite{Poznanski:2007}, \cite{Kuznetsova:2008}, \cite{Dahlen:2008}.
4.5: Discussion

(2007, \( z \sim 0.75–1.75 \)), Kuznetsova et al. (2008, \( z \sim 0.4–1.55 \)) and Dahlen et al. (2008, \( z \sim 0.47–1.61 \)).

In Figure 4.5 we show our results for the SNIa rate density as a function of redshift. The models agree qualitatively with the observations, showing a rapid increase in the SN rate up to \( z \sim 1.5 \) and slowly declining beyond \( z \sim 2 \) (although there is no data to compare with at these high redshifts). Our models however overpredict the rate by a factor two at \( z = 0 \) and a factor 3–4 by \( z \sim 2 \). There are, nonetheless, several issues that alleviate these discrepancies. First of all, we are only showing the statistical errors from the surveys; systematic errors due to misclassification of the SN event, uncertainties in the type Ia SN luminosity function, and \( k \)-corrections can be as large as the statistical ones (Dahlen et al. 2008). Furthermore, SNe Ia associated with the prompt population go off in highly dust obscured regions, especially at high redshift, and a large fraction of them can go undetected by the observations. Mannucci et al. (2007) computed that the missing fraction is about 35% at \( z = 2 \) and progressively smaller at lower redshifts (15% at \( z = 1 \) and only 2% at \( z = 0 \)).

The observational uncertainties just mentioned account for some of the difference between the data and the models but not all of it. The most straightforward way to modify the model to better match the observations would be to reduce the fraction of binaries that yield a SN event (parameter A in Chapter 2) since the SNR depends linearly on it. In fact, some SN Ia models suggest that the white-dwarf explosion efficiency decreases at high redshift due to the lower metallicities (Dahlen et al. 2008 and references therein). However, in our models, this parameter has a strong lower limit constraint given by the iron abundance in the ICM and cannot be reduced much below our fiducial value (Chapter 3). Overall, given that large uncertainties in the measured rates, our models are quite consistent with the observations, in particular regarding the rise and decrease of the SNR with redshift.

4.5 Discussion

The lack of evolution in the MZR for low-mass galaxies is due to the fact that, in the SAMs, small galaxies form too large a fraction of their stars at a very early time (Fontanot et al. 2009), and therefore galaxies are assembled once they are already evolved. On the other hand, observations show that at \( z > 3 \) LBGs are massive, with high gas fractions, but still metal-poor which suggest that galaxies at high redshift are assembled from relatively unevolved small systems, implying that most of the merging occurs before most of the star formation (Maiolino et al. 2008; Mannucci et al. 2009).

It is clear that the treatment of the feedback processes in the models needs to be improved, so that metals are removed more efficiently from low-mass galaxies,
Figure 4.6: Effective yields (A), gas fractions (B), gas mass (C) and mass of metals in the gas phase (D) as a function of stellar mass at various redshifts (coded by colour: $z \sim 0$, 0.8, 2.2, 3.1 as black, red, green and blue, respectively). The lines are the average properties from the models. The dots are the observational estimates from Tremonti et al. (2004, $z \sim 0$), Zahid et al. (2010, $z \sim 0.8$), Erb et al. (2006, $z \sim 2.2$) and Mannucci et al. (2009, $z \sim 3.1$).

or star formation is less efficient. One plausible solution could be the inclusion of type Ia supernova energetics. In our models, SNIa only contribute to the chemical enrichment but the SN energy feedback is driven only by type II SN. The prompt population of the DTD keeps the SNIa rate high at high redshifts and the composite contribution of both types of SN might produce the necessary effect. However, the ratio between type II and type Ia supernovae is about 10 at $z \sim 3.5$. Since both types are roughly equally energetic, the overall correction would be small and probably insufficient to blow out enough cold gas to bring the gas surface density below the star formation threshold – especially if we take into account that, at high redshift, galaxies are quite compact. Moreover, the “hot enrichment” scheme implemented in our models already puts the bulk of the metals produced by the stars directly into the ICM, to be later reaccreted by the galaxies. It is therefore unlikely that stronger SN feedback would help decrease the gas-phase metallicities.

The scenario that arises is, then, one where star formation is too efficient at
high redshift. To probe whether this is indeed the case, it is useful to look at
the effective yields, since they relate to both metallicity and gas fractions. In a
closed box model with instantaneous recycling, the gas-phase metallicity is given
by $Z = y_T \ln(\mu^{-1}_{\text{gas}})$, where $y_T$ is the true yield and $\mu_{\text{gas}} = M_{\text{gas}}/(M_{\text{gas}} + M_{\text{star}})$
is the gas mass fraction. This equation can be turned around and define the
effective yield as $y_{\text{eff}} = Z/\ln(\mu^{-1}_{\text{gas}})$, which is valid for any star formation and
outflow/inflow history. Real galaxies do not evolve as closed boxes and their
effective yields are lower than the true yield, given the contributions of feedback
and inflow (Edmunds 1990; Dalcanton 2007).

In Figure 4.6 we show the effective yield, the gas fraction, the gas mass and the
mass of metals in the cold gas as a function stellar mass at various redshifts. For
all four properties, the agreement at the present epoch is remarkable. However,
at higher redshifts, the models are in clear contradiction with the data, especially
at the low mass end. It has been proposed that the positive trend of the effective
yield at $z \sim 0$ is a consequence of galactic winds being more prominent in low-mass
galaxies (Tremonti et al. 2004). Moreover, metal-enhanced winds (such as those
adopted in our models) will produce low effective yields in galaxies with high
gas fractions (i.e. low stellar masses; Dalcanton 2007). This explains why our
models show low effective yields for low-mass galaxies, even at high redshift, in
stark disagreement with the observations. The negative trend observed at high
redshift could be due to the star formation efficiency decreasing with increasing
stellar mass (Erb et al. 2006; Zahid et al. 2010).

Turning to the gas fractions, we see that model low-mass galaxies are quite
gas-poor when compared with the data (hence the lower $y_{\text{eff}}$) at high redshift.
High-mass galaxies, on the contrary, are too gas rich. This is also reflected in
the gas and metal mass. This suggests that the overprediction of the oxygen
abundance at high redshift is likely to be caused by too-efficient star formation
in low-mass galaxies and inefficient outflows for high-mass galaxies. Finally, it
is interesting to note that, although one would expect the mass of metals to
increase as the metallicity increases (at lower $z$), the observed metal enrichment
is a consequence of fractional rise in metals with respect to the gas, although both
are depleted (Zahid et al. 2010). In this sense, the models agree qualitatively with
the data.

To summarize, the scenario that stands is one in which the MZR and its
evolution is driven by combination of metal-enhanced outflows coupled to star
formation efficiencies varying with galactic stellar mass, in the sense that the
outflows are more efficient and the star formation less efficient at low stellar
masses. Low mass galaxies in the SAM are known to be overly-efficient at forming
stars at high redshift, leading to an excessive metal abundance.

Our findings are in broad agreement with other studies of the evolution of the
MZR within the framework of hierarchical galaxy formation models that make
use of cosmological hydrodynamical simulations (Kobayashi et al. 2007; de Rossi
chapter 4: The evolution of metals through cosmic time.

et al. 2007; Brooks et al. 2007; Finlator & Davé 2008). All of these models successfully reproduce the the MZR between $z = 2$ and 0, but none explain the observed relation at $z \sim 3$ satisfactorily, which is commonly overpredicted. Amongst these models, de Rossi et al. (2007) show the largest discrepancy with the observations which is due to the lack of significant SN feedback in their simulations. When feedback is taken into account, the models perform better, as in the case of Kobayashi et al. (2007) and Finlator & Davé (2008) that include the effects of hypernovae and momentum-driven winds, respectively. For these authors the MZR is governed by primarily by outflows that are more efficient at low stellar masses, which remove metal-enriched gas and, furthermore, reduce the gas densities and, hence, the star formation efficiency. On the other hand, Brooks et al. (2007) conclude that the low metallicities observed in low mass galaxies are mainly due to their low star formation efficiencies rather than direct blowouts. The general conclusion from these studies and ours is that the shape of the MZR and its evolution result from the combination of galactic winds being more efficient and star formation being less efficient at low stellar masses.

4.6 Conclusions

We use a cosmological semi-analytic model of galaxy formation within the framework of hierarchical assembly to study the evolution of metals over cosmic time, especially the evolution of the mass–metallicity (MZR) and mass–[α/Fe] relations, both in the cold gas and stellar component. The model is able to reproduce abundance ratios and supernova rates of early-type galaxies in the local Universe as well as the elemental abundance ratios and overall metal content in the ICM (Chapters 2 and 3) by assuming a slightly flat IMF ($x = 1.15$), a bimodal Delay-Time-Distribution for type Ia supernovae and a “hot recycling” mode, in which 80% of the metal-rich material ejected by the stars is deposited directly into the ICM rather than the ISM. Our main findings can be summarized as follows.

(i) Much like the observations, we find a clear MZR at all epochs, even at $z \sim 3.5$, both in the gas phase and the stellar component. The agreement in the ISM oxygen abundance for massive galaxies ($M_* > 10^{10} M_\odot$) is quite good at all but the highest redshift ($z = 3.5$). On the other hand, the metallicity of small galaxies is underpredicted at low redshifts and overpredicted at high redshifts. At intermediate redshift ($z \sim 2-2.5$) the agreement between the simulated MZR and the observed one is remarkable. Due to the uncertainties in the observed abundances, the discrepancy between the model and the data in the absolute value of the metallicity at a given redshift is not a major concern. The real problem with the models is that they predict the opposite trend in evolution: our simulations show a moderate change in metallicity for massive galaxies and no evolution for the low-mass ones, whereas the data shows a clear evolution of
4.A: Data sets: sample selection, mass and metallicity determinations.

the MZR at all masses, being more pronounced for the lower mass systems.

(ii) Gas-phase [$\alpha$/Fe] abundance ratios present a rather flat behaviour with stellar mass at all redshifts, with the mean value decreasing (and the scatter increasing) with lower redshift as SN Ia products are deposited into the ISM. This flat trend in [$\alpha$/Fe] with mass in the simulations is likely due to the constant recycling of the ISM through the ICM, which also shows flat abundance ratios as a function of halo virial mass (Chapter 3). The stellar mass–stellar abundance ratio relation evolves with an increasing slope as redshift decreases. This is because low-redshift low-mass galaxies have a longer timescale for star formation than high-redshift low-mass systems, while high-mass galaxies have roughly the same timescale at all redshifts (at high-$z$ the relation is rather flat due to galaxies of all masses having similar star formation histories).

(iii) Our predictions for the redshift evolution of the type Ia supernova rate are consistent with the observations showing a steep rise from $z = 0$ to $z \sim 1.5 - 2$ and a slow decline towards higher redshifts. Our modelled rates are, however, about a factor 2 too high. This discrepancy is alleviated by the fact that a considerable fraction of SN may be undetected in the surveys, especially at high redshifts.

Summarizing, we have found the MZR is already in place at high redshift. This relation arises from a combination of metal-enhanced outflows coupled to star formation efficiencies varying with galactic stellar mass, with the latter being perhaps the dominant factor. The evolution of the high-mass end is consistent with the observations, but the low-mass end shows no evolution, confirming that small galaxies form too early and too fast. Star formation in model galaxies is too efficient while they are central galaxies in dark matter halos with $V_c \sim 200\,\text{km}\,\text{s}^{-1}$ (Fontanot et al. 2009). The problem is aggravated by the assumption that cool gas infall stops once they become satellites in a larger halo. A better implementation of the feedback processes would be ideal, yet at the moment it is not clear which mechanism would provide a solution. Furthermore, the evidence suggests that stronger feedback in not enough – it is quite likely that the star formation prescriptions in SAMs need also to be revised in such a way that star formation becomes less efficient for low-mass galaxies at high redshift.

Appendix 4.A Data sets: sample selection, mass and metallicity determinations.

The different data sets used in this paper to test the models are drawn from a variety of surveys. In this appendix we briefly describe the criteria for sample selection as well as the methods used by the different authors to determine the stellar mass and gas phase metallicity of the sampled galaxies.
Tremonti et al. (2004) select a subsample of star-forming galaxies from the Sloan Digital Sky Survey (SDSS) by imposing a redshift cut of $0.005 < z < 0.25$ and that more than 10% of the total galaxy light is observed by the fiber. Furthermore, they require that the galaxies included in the sample have emission lines of H$\beta$, H$\alpha$, and [N II] $\lambda$6548 detected at greater than 5 $\sigma$. They also impose that the parameters needed for mass determination have small errors; these criteria are $\sigma(m_z) < 0.15$ mag, $\sigma(H\delta_A) < 2.5$ Å, and $\sigma(D_n(4000)) < 0.1$. To determine the stellar masses they assign stellar M/L ratios to the galaxies by using a Bayesian analysis to associate the observed $D_n(4000)$ and $H\delta_A$ values with a model drawn from a large library of Monte Carlo realizations of galaxies with different star formation histories and metallicities and use the $z$-band magnitude to characterize the galaxy luminosity. They estimate metallicities statistically, based on simultaneous fits of all the most prominent emission lines ([O II], H$\beta$, [O III], H$\alpha$, [N II], [S II]) with a model designed for the interpretation of integrated galaxy spectra (Charlot & Longhetti 2001).

Savaglio et al. (2005) extract their galaxies from the Gemini Deep Deep Survey (GDDS) which targeted galaxies with photometric redshifts $0.8 < z < 2$ and $K < 20.6$. The GDDS sample selection was based on the requirement that the spectrum of the galaxies (with secure redshift) covers the spectral interval of the [O II] $\lambda$3727, [O III] $\lambda\lambda$4959,5007, and H$\beta$ lines. The stellar masses were determined by SED-fitting of the optical/NIR photometry using the PEGASE.2 stellar population synthesis model. Estimates of the metallicity are provided by emission-line fluxes of [O II] $\lambda$3727, [O III] $\lambda\lambda$4959,5007, and H$\beta$ through the $R_{23} \equiv \log([\text{O III}]/[\text{O II}])$ calibrator.

Zahid et al. (2010) make use of the DEEP2 (Deep Extragalactic Evolutionary Probe 2) survey (Davis et al. 2003). The relatively high-resolution ($R > 5000$) spectra cover the nominal spectral range 6500–9100 Å. This spectral range corresponds to a redshift window of $0.75 < z < 0.82$ in which they observe the requisite lines for calculating the emission line ratios used in determining metallicity. In selecting galaxies from this sample for analysis, they require that the S/N for H$\beta$ be greater than 3. They estimate galaxy stellar masses by comparing BRI and $K_s$ photometry with stellar population synthesis models in order to determine the mass-to-light ratio. The stellar templates of Bruzual & Charlot (2003) and an IMF described by Chabrier (2003) are used to synthesize magnitudes. They use the strong line diagnostics of Kobulnicky & Kewley (2004), which uses the $R_{23}$ and $O_{32} \equiv \log([\text{OIII}]/[\text{OII}])$ emission-line ratios, in order to obtain an estimate of galaxy gas-phase metallicities.

Shapley et al. (2005) and Liu et al. (2008) also draw their sample from the DEEP2 survey, but in different redshift windows: $0.96 < z < 1.05$ and $1.36 < z < 1.5$. Galaxies were selected to span the full range of absolute B luminosities in the DEEP2 survey, from $M_B \sim -20$ to $-23$. All targets have rest-frame $(U - B)_0$ colors blueward of the minimum in the observed color bimodality in the
DEEP2 survey, and, in order to maximize the long-slit observing efficiency, they mostly targeted pairs of galaxies in each redshift window, with separations of up to 25 arcsec. Stellar masses were inferred by SED-fitting of $K_s$-band photometry using Bruzual & Charlot (2003) population synthesis models. The metallicity was determined using two strong-line ratios indicators: $\text{N2} \equiv \log([\text{N II}]/\text{H}\alpha)$ and $\text{O3N2} \equiv \log(([\text{O III}]/\text{H}\beta)/([\text{N II}]/\text{H}\alpha])$.

Shapley et al. (2004) and Erb et al. (2006) draw their galaxies from the rest-frame UV-selected $z \sim 2$ spectroscopic sample described by Steidel et al. (2004). The candidate galaxies were selected by their $U_nGR$ colors, with redshifts for most of the objects in the sample confirmed in the rest-frame UV using the LRIS-B spectrograph on the Keck I telescope. Criteria for selection included (1) galaxies near the line-of-sight to a QSO, for studies of correlations between galaxies and metal systems seen in absorption in the QSO spectra; (2) morphologies: elongated in most cases, with a few more compact objects for comparison; (3) galaxies with red or bright near-IR colors or magnitudes, or occasionally those whose photometry suggested an unusual spectral energy distribution; (4) galaxies that have excellent deep rest-frame UV spectra, or are bright in the rest-frame UV; or (6) members of close pairs with redshifts known to be favorable relative to night-sky lines. Stellar masses were determined from SED fitting to the observed $U_nGRJK$ ($0.3 - 2.2 \mu m$) photometry using Bruzual & Charlot (2003) stellar population synthesis. Gas phase metallicities were determined using the N2 emission line ratio calibrator.

The AMAZE program (Maiolino et al. 2008) target sample consists of Lyman Break Galaxies (LBGs) at $z > 3$ drawn from the Steidel et al. (2003) and the Chandra Deep Field South (CDFS) surveys. For selection, they required that the redshift was such that the emission lines of interest for the metallicity determination ([O III], Hα, [O II], [Ne III]) are out of strong sky emission lines and out of deep atmospheric absorption features. Additionally, they required that the source has been observed with at least two of the Spitzer-IRAC bands, which at these redshifts sample the rest-frame near-IR light. Stellar masses were determined by the broad-band spectral fitting technique. Broad-band photometric data for the sources in the CDFS were collected from the GOODS-MUSIC multiwavelength catalog (from UV to the Spitzer-IRAC bands). For the LBGs in Steidel et al. (2003), optical photometric data were extracted from publicly available images, while Spitzer IRAC and MIPS data were obtained from the Spitzer archive. To determine the metallicities they used three independent emission-line diagnostics: [O III]/H$\beta$, [O III]/[O II] and (when available) [Ne III]/[O II].

Mannucci et al. (2009) also extract their galaxy sample from the Steidel et al. (2003) LBG catalogue. However, in this case, the only criteria for selection was the presence of a bright foreground star needed to drive the adaptive optics module and obtain a resolution comparable with the diffraction limit of an 8-m class telescope, about 0.1 arcsec in the near-IR. Stellar masses were derived by fitting
Figure 4.B1: $[\alpha/\text{Fe}]$ vs. $[\alpha/\text{H}]$ and $[\text{Zn/Fe}]$ vs. $[\text{Zn/H}]$ at two different output redshifts: $z = 2.0$ and $z = 3.0$ (upper and lower panels, respectively). Symbols – black dots: SAM satellite galaxies, red dots: SAM central galaxies, blue triangles: QSO-DLAs (Prochaska et al. 2003), blue squares: GBR-DLAs (Prochaska et al. 2007).

the SED of IRAC photometry (rest-frame J band) using the Bruzual & Charlot (2003) spectrophotometric models of galaxy evolution and smooth exponentially decreasing SF histories, constraining the age to be smaller than the Hubble time at the galaxy redshift. Metallicities were estimated by a simultaneous fit of all available line ratios as in Maiolino et al. (2008).

Appendix 4.B  Gas-phase abundance ratios from DLAs

In Section 4.3.2 we mentioned that we do not have data on abundance ratios, which is true for emission line studies. However it is possible to estimate gas-phase elemental abundances in Damped Lyman Alpha systems (DLAs). These absorption systems arise when the ISM intersects the line of sight to a bright object such as a Gamma-ray burst (GBR-DLA) or a quasar (QSO-DLA) (for a review, see Wolfe et al. 2005). But even in this case most elements cannot usually be measured directly and therefore proxies are used, such as Si and S for the $\alpha$
group or Zn for Fe, and a combination of those three (Si, S and Zn for the total metallicity). Bearing this in mind we compare our models with observations from Prochaska et al. (2003, QSO-DLAs) and Prochaska et al. (2007, GRB-DLAs) and show it in Figure 4.B1. We use simulations with an output redshift of 2 and 3 since DLAs are observed at a wide range of redshifts with a median of \( z \sim 2.5 \).

We can see that the models are substantially more metal-rich, in terms of \([\alpha/H]\), but at the same time have much lower abundance ratios. There are, however, some caveats that make DLA abundances very hard to interpret: they are line-of-sight-weighted abundances through the far outer parts of galaxies (hence the low observed metallicities) and do not represent any sort of galaxy “average” abundances (which is what the models predict), and the abundances themselves are problematic — Fe severely depleted into dust (Prochaska et al. 2007), a reason why Zn is used as a tracer of Fe, but that too is probably at least partly locked up in dust. So [alpha/Fe] vs [Fe/H] is difficult to compare to our models. Furthermore, simulations suggest that lines-of-sight pass through more than one disc (Maller et al. 2001), making the comparison with the individual model galaxies even more complicated.