THE chemical properties and abundance ratios of galaxies provide important information about their formation histories. Galactic chemical evolution has been modelled in detail within the monolithic collapse scenario. These models have successfully described the abundance distributions in our Galaxy and other spiral discs, as well as the trends of metallicity and abundance ratios observed in early-type galaxies. In the last three decades, however, the paradigm of hierarchical assembly in a Cold Dark Matter (CDM) cosmology has revised the picture of how structure in the Universe forms and evolves. In this scenario, galaxies form when gas radiatively cools and condenses inside dark matter haloes, which themselves follow dissipationless gravitational collapse. The CDM picture has been successful at predicting many observed properties of galaxies (for example, the luminosity and stellar mass function of galaxies, color-magnitude or star formation rate vs. stellar mass distributions, relative numbers of early and late-type galaxies, gas fractions and size distributions of spiral galaxies, and the global star formation history), though many potential problems and open questions remain. It is therefore interesting to see whether chemical evolution models, when implemented within this modern cosmological context, are able to correctly predict the observed chemical properties of galaxies.

With the advent of more powerful telescopes and detectors, precise observations of chemical abundances and abundance ratios in various phases (stellar, ISM, ICM) offer the opportunity to obtain strong constraints on galaxy formation histories and the physics that shapes them. However, in order to take advantage of these observations, it is necessary to implement detailed modeling of chemical evolution into a modern cosmological model of hierarchical assembly. In this work we use the semi-analytical approach to incorporate detailed chemical evolution into a ΛCDM galaxy formation model, taking into account enrichment by SNe Ia, SNe II and long-lived stars, and abandoning the instantaneous recycling
approximation by considering the finite lifetimes of stars of all masses. The delay in the metal enrichment by SNe Ia is calculated self-consistently according to the Delay-Time-Distribution (DTD) formalism. The base model includes gas inflows due to radiative cooling of gas and outflows due to supernova and AGN-driven winds, as well as triggered star formation and morphological transformation of galaxies via mergers, hierarchical clustering of dark matter halos, the growth of supermassive black holes, the evolution of stellar populations, and the effects of dust obscuration.

5.1 Results of this thesis

5.1.1 Local Early-type galaxies

As a first test of our SAM+GCE, in Chapter 2, we compare our results with the observed trends of metallicity and abundance ratio ([α/Fe]) against stellar mass of local early-type galaxies, as well as the supernova rate (both type Ia and II) as a function of specific star formation rate, allowing the slope of the IMF and the fraction of binaries that produce a SN Ia event to vary from simulation to simulation. Only the models with a shallow IMF ($x = 1.15$) and a low fraction of SN Ia from binaries ($A \sim 0.03$) match all four observations of early-type galaxies simultaneously. A slightly flatter than standard IMF is necessary in order to produce more massive stars, which enrich the interstellar medium more efficiently, making the galaxies in our simulations become more metal rich and improving the agreement with the data. The production of more massive stars, along with the fact that the star formation histories are more extended in time as the galaxy mass decreases, helps to achieve the correct trend of increasing [α/Fe] with increasing galaxy stellar mass. However, it is also necessary to invoke a low fraction of SNe Ia to raise the zero-point of this relation.

From studying the SNe Ia rates, we find evidence supporting a “two-population” distribution for the type Ia explosions. When using a “classical” DTD based on the convolution of the distribution of secondary masses (in binary systems) and the lifetime of the secondary star, galaxies with high specific star formation rates are better matched by models with a high fraction of binaries that explode as SN Ia ($A$) while those with low SSFR require a low value of $A$. We tested whether the use of a more phenomenologically inspired delay-time distribution of type Ia supernovae would, in fact, improve the results. After implementing a bimodal distribution with a prompt peak and an extended plateau, we found very good agreement with the SN rates, while still matching the trends of [Z/H] and [α/Fe] with stellar mass. In this DTD, about half of all SN Ia explosions associated to a single burst of star formation occur within the first 100 Myr.
5.1.2 The Intracluster Medium

Following the success of our model in reproducing the abundance ratios of early-type galaxies in the local Universe, in Chapter 3 we investigated the metal enrichment of the intracluster medium. Our most important finding is the need for some form of metal enriched outflows from galaxies because the ICM iron abundance is too low otherwise. Adopting “hot enrichment”, in which 80% of the metal-rich material ejected by the stars is deposited directly into the ICM rather than the ISM, seems to be a reasonable solution. We also need slightly more type Ia supernovae, both for the iron in the ICM and the $[^{\alpha/Fe}]$ in the galaxies. Although the fit to SNR vs. SSFR is not as good as in Chapter 2, it is still consistent with the observations.

Regarding the elemental abundance ratios in the ICM, the models predict flat behaviour with cluster temperature, in agreement with the observations. For some elements (O, Si, Ca, Ni) the zero-point is reproduced remarkably well, while others agree only marginally (Ar, S), or are significantly underpredicted (Ne, Mg). This occurs irrespective of whether “hot enrichment” is assumed or not. The $[^{Mg/Fe}]$ can be fixed by increasing the Mg yield in SN II (as is commonly done with the WW95 yields). The discrepancy in the other elements may arise from uncertainties in the yields and/or the correction for radial gradients (we assume that elements that have a gradient share the same one as Fe, which might not be strictly correct, although they cannot be too different).

Overall the model simultaneously produces acceptable predictions for the chemical properties of galaxies in the local Universe and the ICM in nearby clusters. It is, to our knowledge, the first time this has been achieved with semi-analytic models.

5.1.3 The evolution of metals in galaxies with redshift.

In Chapters 2 and 3, we assessed our model against observations in of galaxies in the local Universe and nearby clusters, and passed these tests with a moderate degree of success. But in order to set the ultimate benchmark, the model should also make acceptable predictions for the high redshift universe. For this reason, in Chapter 4, we study the evolution of metals over cosmic time, especially the evolution of the mass–metallicity (MZR) and mass–$[^{\alpha/Fe}]$ relations, both in the cold gas and stellar component. 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. On the other hand, the metallicity of small galaxies is underpredicted at low redshift and overpredicted at high redshift. 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 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 \([\alpha/Fe]\) could be due to the constant recycling of the ISM through the ICM, which also shows flat abundance ratios as a function of halo virial mass. 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) We have also computed the evolution of the type Ia supernova rate. Our predictions 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 of two too high. This discrepancy is alleviated by the fact that a considerable fraction of SN may be undetected in the surveys, especially at high redshift.

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, 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.

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, 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
5.2: Future Prospects

Throughout this thesis, we have used a wide variety of observations to test our model. The comparison, however, should be taken with caution. The observed abundances are light-weighted quantities since they are derived from absorption-

"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.

In short, 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 in the models. Star formation in model galaxies is too efficient while they are central galaxies in dark matter halos with $V_c \sim 200 \, \text{km} \, \text{s}^{-1}$. The problem is aggravated by the assumption that cool gas inflow 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.

5.2 Future Prospects

Figure 5.1: Line-strength indexes of simulated early-type galaxies from 25 realizations of a Coma-cluster-sized halo.
Figure 5.2: Observed (black) and mock (red) line strengths of the TFD08 sample. Mock galaxies are randomly selected from all the galaxies in all the halo realizations in order to match the observed Velocity Distribution Function in the Coma cluster.

line indexes (early-type galaxies), X-ray spectroscopy (ICM) or strong emission-line diagnostics (cold gas-phase). On the other hand, the output of the models are mass-weighted abundances. However, it is reassuring that, at least for stellar componenent of early-type galaxies, the SSP-equivalent (absorption-line-weighted) metallicity correlates very well with its mass-weighted and light-weighted counterparts (Trager & Somerville 2009). Nevertheless, ideally, one would like to calculate metallicity and abundance ratios in the models in the same way as it is done in the observations. Thanks to the latest generation of stellar population models, which are sensitive to age, metallicity and abundance ratios (Trager, Faber & Dressler 2008, TDF08), combined with the star formation and abundance histories produced by the SAMs, it is possible to generate synthetic spectra for the model galaxies and compute line strength indexes to be compared with observations directly. The preliminary results on this are encouraging as we can see from Figures 5.1 and 5.2 where we show the results for simulated galaxies in Coma-sized halos and an observational sample of galaxies in the Coma cluster presented in TDF08.

These new stellar population models, coupled to the ongoing refinement of the prescriptions in the SAMs and the ever-increasing quality of the observations, will lead us to a better understanding of how galaxies form and evolve.