The relation between metallicity, stellar mass and star formation in galaxies: an analysis of observational and model data

Robert M. Yates,1⋆ Guinevere Kauffmann1 and Qi Guo2,3

1Max Planck Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany
2Partner Group of the Max Planck Institut für Astrophysik, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
3Department of Physics, Institute for Computational Cosmology, University of Durham, South Road, Durham DH1 3LE

Accepted 2012 January 19. Received 2011 December 20; in original form 2011 July 15

ABSTRACT
We study relations between stellar mass, star formation and gas-phase metallicity in a sample of 177 071 unique emission line galaxies from the Sloan Digital Sky Survey Data Release 7, as well as in a sample of 43 767 star-forming galaxies at z = 0 from the cosmological semi-analytic model L-GALAXIES. We demonstrate that metallicity is dependent on star formation rate at fixed mass, but that the trend is opposite for low and for high stellar mass galaxies. Low-mass galaxies that are actively forming stars are more metal poor than quiescent low-mass galaxies. High-mass galaxies, on the other hand, have lower gas-phase metallicities if their star formation rates are small. Remarkably, the same trends are found for our sample of model galaxies. By examining the evolution of the stellar component, gas and metals as a function of time in these galaxies, we gain some insight into the physical processes that may be responsible for these trends. We find that massive galaxies with low gas-phase metallicities have undergone a gas-rich merger in the past, inducing a starburst which exhausted their cold gas reservoirs and shutdown star formation. Thereafter, these galaxies were able to accrete metal-poor gas, but this gas remained at too low a density to form stars efficiently. This led to a gradual dilution in the gas-phase metallicities of these systems over time. These model galaxies are predicted to have lower-than-average gas-to-stellar mass ratios and higher-than-average central black hole masses. We use our observational sample to confirm that real massive galaxies with low gas-phase metallicities also have very massive black holes. We propose that accretion may therefore play a significant role in regulating the gas-phase metallicities of present-day massive galaxies.

Key words: ISM: abundances – galaxies: abundances – galaxies: evolution – galaxies: fundamental parameters – galaxies: star formation.

1 INTRODUCTION
Metals are ubiquitous throughout galaxies. They are synthesized in stars and liberated into the interstellar medium (ISM) when stars shed their outer gaseous envelopes towards the end of their lives, and in some cases also into the intergalactic medium (IGM) when the highest mass stars explode as supernovae (SNe). The amount of metals in the diffuse, hot gas around galaxies also determines the rate at which it is able to cool and form stars. Metallicity is, therefore, one of the key physical properties of galaxies, and understanding the processes that regulate the exchange of metals between stars, cold interstellar gas and diffuse surrounding gas can help us understand the physical processes that govern galaxy evolution in general.

The metallicity of stars and gas in galaxies is known to correlate strongly with their luminosities, circular velocities and stellar masses (e.g. Lequeux et al. 1979; Garnett 2002; Tremonti et al. 2004; Gallazzi et al. 2005). However, the physical processes that drive these correlations are not yet fully understood.

Mathews & Baker (1971) and Larson (1974) first suggested that interstellar gas can be driven out of galaxies by SN explosions as galactic outflows. They predicted that galaxies of smaller mass have lower metal abundances because their lower escape velocities allow freshly enriched gas to be more efficiently removed.

The input of energy from SN explosions is now routinely incorporated into hydrodynamical simulations of galaxy formation, either in the form of thermal heating or ‘kinetic feedback’, whereby radial momentum kicks are imparted to particles surrounding sites of star formation in the galaxy. Although these simulations are now able to demonstrate that galactic outflows can yield a good match to the observed mass–metallicity relation (e.g. Kobayashi, Springel...
Another possibility is the presence of a mass-dependent star formation efficiency (SFE). In this scenario, less massive galaxies convert their gas reservoirs into stars over longer time-scales than more massive galaxies. Therefore, less massive galaxies have higher gas-to-stellar mass ratios and are consequently less metal rich. This mechanism has been studied by Brooks et al. (2007) and Filatov & Davé (2008) using smoothed particle hydrodynamics (SPH) simulations. They have suggested that both metal-rich outflows and a variable SFE must play roles in shaping the mass–metallicity relation. Calura et al. (2009) instead claim that an imposed mass-dependent SFE is enough to reproduce the evolution of the mass–metallicity relation without the need for outflows. However, studies of the effective yield\(^1\) in local galaxies strongly suggest that metal-rich outflows are also present, particularly at low masses (Tremonti et al. 2004).

Alternatively, Dalcanton, Yoachim & Bernstein (2004) claim that metal-poor infall can regulate metallicity in disc galaxies. Given that lower mass galaxies tend to have lower star formation rates (SFRs), a net dilution would take place when the time-scale for star formation falls below the time-scale for accretion of metal-poor gas. This would drive down the low-mass end of the mass–metallicity relation.

Finally, variations in the initial mass function (IMF) have also been cited as another factor that might influence the mass–metallicity relation. Köppen, Weidner & Kroupa (2007) propose that a SFR-dependent (and therefore stellar mass-dependent) IMF causes different galaxies to produce different effective oxygen yields. This hypothesis is based on the premise that most stars form in stellar clusters and those smaller, less actively star-forming galaxies are dominated by clusters with lower masses, containing a smaller fraction of massive, oxygen-producing stars. Calura & Menci (2009) also claim that a SFR-dependent IMF is necessary to reproduce the observed relation between velocity dispersion and the stellar alpha enhancement \([\alpha/Fe]\) in local early-type galaxies. However, there are currently conflicting conclusions in the literature as to whether such a variable IMF is present in the real Universe (e.g. Elmegreen 2006; Weidner & Kroupa 2006; Fumagalli, Da Silva & Krumholz 2011; Gunawardhana et al. 2011).

The fact that the interpretation of the mass–metallicity relation is subject to considerable ambiguity has prompted a number of authors to consider alternative ways of quantifying metallicity in galaxies. For example, higher dimensional relations that include additional physical properties could provide better constraints on the processes that regulate metallicity. A study of such relations was first made by Ellison et al. (2008), who found a weak dependence of gas-phase metallicity on specific star formation rate (sSFR) and half-light radius \((r_e)\) at low stellar masses. This dependence was inferred to be due to variations in the SFE. At a given stellar mass, more compact galaxies should have formed stars more rapidly in the past, lowering their present-day sSFR and raising their present-day metallicity.

More recently, Mannucci et al. (2010) have proposed a fundamental metallicity relation (FMR), based on similar findings. In that work, it was shown that the gas-phase metallicities \((Z)\) of both local and high-redshift galaxies were dependent on both stellar mass \((M_*)\) and SFR. The FMR provides a prediction of the metallicity of local galaxies with a 1σ scatter of only ∼0.05 dex. This is a substantial improvement on the mean scatter of ∼0.1 dex reported by Tremonti et al. (2004) for the \(M_*/Z\) relation. Mannucci et al. (2010) found \(Z\) to be strongly dependent on SFR at low stellar masses, but only very weakly dependent on SFR at high stellar masses. A simple model, invoking only mass-dependent outflows and pristine infall, was able to reproduce these trends. The FMR also describes galaxies out to \(z \sim 2.5\). The observed evolution of the \(M_*/Z\) relation was therefore attributed to migration of galaxies along the FMR plane to higher masses and lower SFRs over time.

Finally, Lara-López et al. (2010b) have also carried out an independent study of the relation between \(M_\ast\), SFR and \(Z\). They find a flat Fundamental Plane which provides a prediction of the stellar mass with a 1σ scatter of 0.32 dex, given the SFR and metallicity. The Lara-López plane also extends unchanged out to \(z \sim 3.5\), aligning well with high-redshift data from Maiolino et al. (2008).

Prompted by these findings, in this work we study higher dimensional relations between metallicity and a variety of physical galactic properties. We examine whether the \(M_*/Z\) relation exhibits additional dependences on SFR, sSFR and \(M_{\text{gas}}/M_\ast\). Comparisons are made between the results from observational data and the predictions from semi-analytic models (SAMs) of galaxy formation implemented within a high-resolution simulation of the evolution of dark matter (DM) in a “concordance” Λ cold dark matter (ΛCDM) cosmology.

In Section 2 we present our observational sample, extracted from the latest Sloan Digital Sky Survey (SDSS) spectroscopic data. In Section 3 we explain how we obtain estimates of \(M_\ast\), SFR and \(Z\). In Section 4 we study the dependence of the \(M_*/Z\) relation on SFR, and the dependence of the \(SFR--Z\) and sSFR--Z relations on \(M_\ast\). In Section 5 we discuss the latest version of the semi-analytic galaxy formation code L-GALAXIES (Guo et al. 2011), implemented on the Millennium-II DM N-body simulation (Boylan-Kolchin et al. 2009), and describe how we select samples of simulated galaxies for comparison with the observational data. In Section 6 we present these comparisons and show how trends in the relations between stellar mass, SFR and metallicity can be understood in terms of the prescriptions used for gas accretion, star formation and SN and active galactic nucleus (AGN) feedback. In Section 7 we discuss the viability of different physical mechanisms in regulating the metallicity of galaxies. Finally, in Section 8 we summarize our results.

2 THE OBSERVATIONAL SAMPLE

The sample of galaxies analysed in this paper is drawn from the SDSS MPA-JHU Data Release 7 catalogue (hereafter SDSS-DR7).\(^2\) This catalogue contains ∼900 000 galaxies with available spectra. The sample cuts used here are the same as those adopted by Tremonti et al. (2004), who investigated the \(M_*/Z\) relation using galaxies from the SDSS Data Release 2.

First, we remove all duplicate spectra from the catalogue, reducing it by ∼3.2 per cent and leaving 898 302 galaxies. Then, we take only galaxies with reliable spectroscopic redshifts within the range 0.005 < \(z\) < 0.25. We then remove all galaxies whose fibre-to-total light ratio is less than 0.1. This is defined as the ratio of the flux given

\(^1\) The effective yield is an estimate of the amount of metals liberated into the ISM by stars, via measurements of the gas fraction and gas-phase metallicity. If a galaxy has undergone no outflows or infall of gas (i.e. has evolved as a closed box), then the effective yield is equivalent to the true yield.

\(^2\) Available at http://www.mpa-garching.mpg.de/SDSS/DR7
by the SDSS fibre magnitude to that given by the SDSS model magnitude, in the r band. The 3 arcsec SDSS fibre only probes the inner 1–9 kpc of the galaxies in our samples, and so this cut is needed to eliminate galaxies with metallicity measurements that are heavily biased towards the inner regions. Removing these galaxies raises the median redshift by \(\sim 0.008\). We have checked that increasing the minimum fibre covering fraction to 0.35 (following the recommendations of Kewley & Ellison 2008), or raising the minimum redshift, does not affect any of the main results presented in this paper.

We also make cuts to the signal-to-noise ratio (SNR) of some of the key emission lines required to estimate metallicity, ensuring that \(\text{SNR}(\text{H}\alpha, \text{H}\beta, [\text{N} \text{II}], 6584) > 5\). Again, we have checked that raising this threshold to \(\text{SNR} > 10\) does not change our main results. Following Tremonti et al. (2004), we also make cuts on the accuracy of some additional parameters that were used to estimate stellar masses in their original analysis. All galaxies for which \(\sigma(m) < 0.15 \text{sinh}^{-1}(\text{mag})\), \(\sigma(\text{H}\alpha) < 2.5 \AA\) and \(\sigma(D_{\alpha4000}) < 0.1\) are removed. This is done purely to achieve consistency with their original sample selection criteria. The stellar masses that we use for our current DR7 analysis are derived using \(u, g, r, i, z\) SDSS photometry.

Of those galaxies for which \(\text{SNR}([\text{O} \text{II}], 5007) > 3\), AGN hosts were removed following the prescription given by Kauffmann et al. (2003b) for defining AGN in the Baldwin, Phillips & Terlevich (1981) (BPT) diagram. For galaxies with \(\text{SNR}([\text{O} \text{II}], 5007) < 3\), only those with \(\log([\text{N} \text{II}], 6584/\text{H}\alpha) > -0.4\) were retained, thus removing low-ionization AGN from the sample.

Finally, a cut to the derived values of \(M_\ast\) and \(Z\) was made, based on the ‘confidence’ with which they were estimated from fits to synthetic spectra or H\(\alpha\) region models using CLOUDY (Ferland et al. 1998) (see Section 3). The 1\(\sigma\) spread in the likelihood distribution of the best-fitting model must be less than 0.2 dex in both quantities for the galaxy to remain in the sample.

The application of these cuts leaves a base sample of 177,071 emission line galaxies. The number of objects removed by each of these cuts can be derived from Table 1.

### Table 1. The number of objects remaining after each sample cut is applied (in the order they were applied).

| Sample cut | Remaining objects |
|------------|-------------------|
| Removing duplicates | 898,302 |
| Redshift cut | 761,215 |
| Fibre-to-total light cut | 727,012 |
| SNR cut | 354,574 |
| \(\sigma(m_\ast, \text{H}\alpha, D_{\alpha4000})\) cut | 338,547 |
| AGN cut | 239,912 |
| \(M_\ast, Z\) confidence cut | 177,071 |

---

stellar masses are based on fits to photometric data, rather than to Lick indices as in Kauffmann et al. (2003a). Dust corrected total SFRs are calculated using the technique described by Brinchmann et al. (2004), with improvements to the aperture corrections as detailed by Salim et al. (2007). This method for estimating SFRs is based on fitting to a grid of photoionization models derived from the CLOUDY code (Ferland 1996; Ferland et al. 1998), as detailed by Charlot & Longhetti (2001), and using the stellar population synthesis models of Bruzual & Charlot (2003). It thus accounts for the fact that the H\(\alpha\)-to-SFR conversion factor will depend on metallicity, and it also allows the dust-free value of the Balmer decrement to differ from the ‘standard’ Case B value (see Brinchmann et al. 2004 for a more extensive discussion).

The use of total SFRs rather than fibre SFRs shifts the median SFR up by \(~0.6\) dex. The size of this shift for each galaxy depends on the redshift and stellar mass. For example, when switching from Bayesian total SFRs to H\(\alpha\)-based fibre SFRs, the SFR shifts downwards most dramatically at the lowest redshifts and masses. This is because these galaxies have larger apparent sizes, and are therefore more extended with respect to the fibre aperture than more distant, massive galaxies.

As mentioned above, metallicities are calculated using two different procedures to produce two different data sets. The first procedure uses two of the strong line diagnostics calibrated by Maiolino et al. (2008), producing our Sample T1. These diagnostics were derived using a combination of empirical and theoretical methods (see Kewley & Ellison 2008 for a detailed description of such methods). 259 local galaxies of \(Z < 8.35\), with \(T_e\) derived metallicities compiled by Nagao, Maiolino & Marconi (2006) were used, combined with 22,482 SDSS-DR4 galaxies of \(Z > 8.4\), with metallicities derived using the photoionization model outlined in Kewley & Dopita (2002). The resulting combined calibrations are given by equation (1) and table 4 in the Maiolino et al. (2008) paper.

We then follow Mannucci et al. (2010) by taking the average of the metallicities given by the [\(\text{N} \text{II}], 6584/\text{H}\alpha\) diagnostic and the \(R_{23}\) diagnostic as the final metallicity estimate for each galaxy. We also corrected all line fluxes for dust, following Cardelli, Clayton & Mathis (1989). This lowers the metallicities estimated via \(R_{23}\) by \(~0.03\) dex at the highest masses, but makes very little difference to those estimated via [\(\text{N} \text{II}], 6584/\text{H}\alpha\) because the two lines involved are of very similar wavelengths.

Once removing those galaxies with (a) uncertain estimates of \(M_\ast\), or SFR from the SDSS-DR7 catalogue, (b) emission lines that have too low SNR for accurate \(Z\) estimates and (c) estimates of \(Z\) from the two diagnostics used that differ by more than 0.25 dex, Sample T1 is left with 120,491 galaxies.

The second procedure uses the values of \(Z\) provided by the SDSS-DR7 catalogue to produce our Sample T2. These metallicities are calculated using the same grid of photoionization models used to obtain the SFRs, by finding the model that best matches the observed fluxes of all the most prominent optical emission lines ([\(\text{O} \text{II}], \text{H}\beta, [\text{O} \text{II}], \text{H}\alpha, [\text{N} \text{II}], \text{H}\beta, [\text{N} \text{II}]\) and [\(\text{S} \text{II}]\). We refer the reader to Appendix A for a brief discussion on the merits of using this Bayesian technique over simpler emission line ratios when studying local, high-\(Z\), star-forming samples.

---

© 2012 The Authors, MNRAS 422, 215–231

Monthly Notices of the Royal Astronomical Society © 2012 RAS
Removing galaxies without robust estimates for $M_*$, SFR or $Z$ from the catalogue reduces Sample T2 to 112,797 galaxies.

Details of Samples T1 and T2, when binned by $M_*$ and SFR, are provided in Table 2. We note that oxygen abundance is used as a proxy for global gas-phase metallicity throughout this work. We express metallicity in terms of the number of oxygen atoms to hydrogen atoms in the gas component of a galaxy, normalized to the dimensionless quantity $Z = 12 + \log(O/H)$. The current determination of the solar oxygen abundance in these units is $Z_\odot = 8.69$ (Allende Prieto et al. 2001; Asplund et al. 2009).

## 4 OBSERVATIONAL RESULTS

In this section, we examine whether the $M_*-Z$ relation exhibits additional dependences on SFR. The region of the parameter space of interest for our analysis is $8.6 < \log(M_*) < 11.2$, $-2.0 < \log(SFR) < 1.6$ and $8.5 < Z < 9.2$, as this covers 98 per cent of the galaxies in both our observational samples.

For a presentation of the basic $M_*-Z$ relation obtained for Sample T2, without considering its dependence on SFR, see Appendix B.

### 4.1 The $M_*-Z$ relation, as a function of SFR

In order to study the dependence of the $M_*-Z$ relation on SFR, we follow the same approach as Mannucci et al. (2010), binning galaxies by $M_*$ and SFR, and calculating the median metallicity in each bin. Bins are of width 0.15 dex in both dimensions, and only those which contain $\geq 50$ galaxies are plotted. Fig. 1 shows this $M_*-Z$ relation for Sample T1 (left-hand panel) and Sample T2 (right-hand panel). The data are coloured by SFR, as are fits to the relation at a series of fixed SFRs (solid lines).

The left-hand panel of Fig. 1 shows, qualitatively, the result previously described by Mannucci et al. (2010): there is an increase in metallicity with increasing mass, but also a clear and ordered dependence of metallicity on SFR at fixed mass. Metallicity depends strongly on SFR at low masses, but is virtually independent of SFR at high masses in this sample. A similar result is found when using metallicities based only on the $[\text{N} \text{II}]/[\text{O} \text{II}]$ diagnostic calibrated by Kewley & Dopita (2002), although, the dependence of $Z$ on SFR at high masses becomes a little stronger. $[\text{N} \text{II}]/[\text{O} \text{II}]$ is considered to be more accurate than $[\text{N} \text{II}]/H_\alpha$, due to its lack of sensitivity to the ionization parameter (Kewley & Dopita 2002; Kewley & Ellison 2008). The SFR dependence at high mass could be affected by saturation of the $[\text{N} \text{II}]/H_\alpha$ at high metallicities, allowing only a small range in $Z$ in this regime. However, there could also be issues with the use of nitrogen in general, such as its treatment in the stellar population synthesis models used to form theoretical metallicity calibrations (Liang et al. 2006). This is briefly discussed in Appendix A. In order to more directly compare with previous works, we choose to use the average value from the $R_2$ and $[\text{N} \text{II}]/H_\alpha$ diagnostics for Sample T1. The $1\sigma$ spread about the median $Z$ for Sample T1 is 0.07 dex, compared to 0.08 dex reported by Mannucci et al. (2010).

The similarity between our Sample T1 and the Mannucci et al. (2010) sample holds despite the different methods used to obtain SFRs, with Mannucci et al. (2010) adopting $H_\alpha$-based fibre SFRs, rather than the Bayesian total SFRs preferred here. This suggests that the particular SFR estimation method chosen is not critical for the relationship between $M_*$, SFR and $Z$ observed.

The key difference between the Mannucci et al. (2010) sample and our Sample T1 is the range of SFRs sampled. The higher range of SFRs seen in Sample T1 (and Sample T2) is explained by a combination of factors. First, total SFRs rather than fibre SFRs are used, allowing for a more accurate estimate of the star formation across a whole galaxy (see Section 2). Secondly, the simpler $H_\alpha$-based method yields lower SFR estimates for high-$M_*$ galaxies of given $H_\alpha$ luminosity. This is because the conversion factor used in the $L(H_\alpha)$-to-SFR equation, provided by Kennicutt (1998), is dependent on metallicity, and hence stellar mass. Brinchmann et al. (2004) report that this Kennicutt value is most accurate for galaxies with stellar masses of $\sim 10^{10.5} \, M_\odot$, and will underestimate the SFR in more massive galaxies. Note, however, that the intrinsic Balmer decrement for Case B recombination is also metallicity- and mass dependent. A fixed Case B ratio can overestimate the attenuation due to dust by up to $\sim 0.5$ mag for the most massive, metal-rich galaxies (Brinchmann et al. 2004). This will counteract somewhat the underestimate in SFR from a fixed conversion factor for higher mass galaxies. None the less, the use of total SFRs and a variable conversion factor combine to shift the median value of SFR up by $\sim 0.6$ dex for Samples T1 and T2.

The $M_*-Z$ relation for Sample T2 is somewhat different to that of Sample T1. It extends down to lower stellar masses and metallicities, and exhibits a different SFR dependence. At low stellar masses, both samples show a similar dependence on SFR: low-SFR galaxies are more metal rich. However, at high stellar masses, high-SFR galaxies are more metal rich in Sample T2, whereas there is no dependence on SFR seen in Sample T1. Sample T2, therefore, exhibits a SFR dependence at both low and high mass, with a ‘twist’ in the $M_*-Z$ relation around $M_* \sim 10^{10.2} \, M_\odot$. We note that the same features are obtained when using the sample selection criteria of Mannucci et al. (2010), rather than those outlined in Section 2. This indicates that the choice of sample cuts does not significantly affect our findings.

The extension to lower stellar masses seen for Sample T2 is mainly due to the removal of galaxies from Sample T1 during ‘cleansing’. Low-redshift galaxies ($z < 0.03$) are excluded from Sample T1 because the $[\text{O} \text{II}]\lambda3727$ line (required for estimating metallicity using the $R_2$ ratio) is not measurable. These galaxies can remain in Sample T2, extending the $M_*-Z$ relation down a further $\sim 0.3$ dex in stellar mass.

The difference in the dependence of metallicity on SFR at high stellar masses is mainly attributable to the metallicity derivation method chosen. Fig. 2 shows a comparison of the values of $Z$ obtained from the two methods used. Only the 93,971 galaxies present...
Metallicity and star formation in galaxies

Figure 1. The $M_\ast - Z$ relation for Sample T1 (left-hand panel) and Sample T2 (right-hand panel). Filled circles show the median metallicities of galaxies binned by $M_\ast$ and SFR, as are the fits at fixed SFRs (solid lines), plotted for $\log({\text{SFR}}) = −0.975$ (Sample T2 only), $−0.675$, $−0.375$, $−0.075$, $0.225$, $0.525$, $0.825$ (1.125 Sample T2 only). The dependence of $Z$ on SFR for the two samples is clearly different. For example, Sample T2 exhibits a clear dependence at high mass.

Figure 2. A comparison of the oxygen abundances obtained from the two metallicity diagnostics used in this work. Data are binned by $M_\ast$ and the estimation of SFR described in Section 2. Points are coloured by SFR. The $x$-axis represents the technique outlined by Mannucci et al. (2010), using strong line ratio calibrations from Maiolino et al. (2008). The $y$-axis represents the Bayesian technique outlined by Tremonti et al. (2004). There is a clear and systematic overestimation of $Z$ from the former method relative to the latter. This discrepancy is also more significant for low-SFR galaxies.

It is not straightforward to determine which of the two methods considered here is most accurate at estimating oxygen abundance. The calculation of indirect gas-phase metallicities is fraught with complications, and a full discussion on the merits of different methods is well beyond the scope of this work (however, see Appendix A for a brief discussion). Noting that the qualitative properties of Sample T1 are already well described by Mannucci et al. (2010) using their data, we choose to drop further analysis of Sample T1 and focus on Sample T2 in the rest of this work.

4.2 The SFR–$Z$ and sSFR–$Z$ relations, as a function of $M_\ast$

The SFR–$Z$ relation for Sample T2 is shown in the left-hand panel of Fig. 3. Points are coloured by stellar mass, and fits to the relation at four fixed stellar masses are also shown (solid lines).

This plot shows the same SFR dependences seen in the $M_\ast - Z$ relation, but from another projection on to the $M_\ast - \text{SFR} - Z$ space. Again, in addition to the drop in $Z$ with increasing SFR seen for low-mass galaxies, Sample T2 also clearly exhibits a downturn in metallicity with decreasing SFR at higher stellar masses.

When instead considering the dependence of SFR on $Z$, by re-binning Sample T2 by $M_\ast$ and $Z$, we find that SFR slowly increases with metallicity, and that galaxies at the higher redshift end of our sample have higher SFRs. This is complimentary to the findings of previous works, such as Lara-Lopez et al. (2010a), although in that work, Hα-based fibre SFRs and $R_{23}$-based metallicities were used. At fixed mass, we find again that SFR decreases with increasing $Z$ at low mass, and increases with increasing $Z$ at high mass.

Finally, we note that it is actually more sensible to study the dependence of the $M_\ast - Z$ relation on the sSFR ($\text{SFR}/M_\ast$, hereafter sSFR$\ast$), rather than the SFR. A dwarf galaxy with a SFR of 1 $M_\odot$ yr$^{-1}$ is a much more ‘active’ system than a giant elliptical galaxy forming stars at the same rate. The sSFR, on the other hand, is a normalized quantity, and provides a measure of the present-to-past-averaged SFR of the galaxy. Another related quantity is the 4000-Å break strength. This is characterized by the $D_n4000$ index,

in both samples are included, and these are re-binned by $M_\ast$ and SFR. We can see that for metallicities below $Z \sim 9.1$, the strong line ratio method used for Sample T1 yields systematically higher values of $Z$ compared to the Bayesian method used for Sample T2, and that this difference is larger for galaxies with lower SFRs. A similar effect is seen when binning galaxies by $M_\ast$ and Hα-based fibre SFRs.

© 2012 The Authors, MNRAS 422, 215–231
Monthly Notices of the Royal Astronomical Society © 2012 RAS.
Figure 3. The SFR–Z relation (left-hand panel), (SFR/M*)–Z relation (middle panel) and Dn4000–Z relation (right-hand panel) for Sample T2. Fits to the data for four fixed masses are shown (solid lines). The drop in Z with increasing SFR (decreasing Dn4000) is seen for low-mass galaxies in all three relations. A drop in Z with decreasing SFR (increasing Dn4000) is also seen for high-mass galaxies, representing the same effect seen at high masses in Fig. 1. The sizes of the points are scaled to the 1σ spread in the values of Z in each bin.

The average flux from two narrow bands on either side of the break (3850–3950 and 4000–4100 Å), sSFR estimates using Hα flux are a good measure of the instantaneous SFR in a galaxy, whereas Dn4000 is more sensitive to stars that have formed over time-scales of a few hundred million years to a gigayear.

The sSFR–Z and Dn4000–Z relations for Sample T2 are presented in the middle and right-hand panels of Fig. 3. The data have been binned by M* and the sSFR indicator in question. The reader should note that small values of Dn4000 correspond to high values of sSFR.

It is encouraging that both these relations exhibit similar trends. Metallicity decreases as a function of sSFR for low-mass galaxies and increases as a function of sSFR for high-mass galaxies. When noting that Dn4000 (an absorption feature) and sSFR (computed from emission line fluxes) are independent quantities, the fact that the same trends with metallicity are seen for both indicates that our results are likely to be robust.

4.3 Projection of least scatter

If both M* and SFR are correlated with metallicity, then a linear combination of the two may provide a tighter relation with metallicity than the traditional M*–Z relation. This was explored by Mannucci et al. (2010), who calculated the scatter in median metallicity around their FMR for a series of projections on to the M*–SFR–Z space, fixing Z as a principle axis. We modify this method slightly to find the mean dispersion in Z of our binned data for the same 2D projections. Following Mannucci et al. (2010), the linear combination of M* and SFR used is denoted by μα, where

$$\mu_\alpha = \log(M_\ast) - \alpha \log(\text{SFR}).$$

The free parameter α defines the projection, and can be varied to shift from the M*–Z relation (α = 0) to sSFR–1–Z (α = 1). The corresponding dispersion function for the binned data of Sample T2 can be seen in the top panel of Fig. 4. To obtain this function, the spread in Z was calculated in 0.1 dex bins in μα, and the mean spread for each projection found. These mean dispersions from α = 0 to 1 were then fitted by a third-order polynomial to provide the solid line shown. The 1σ spread in the dispersions calculated for each projection was also found and fit in the same way (dotted lines).

It is clear that the M*–Z relation (α = 0) is not the optimum projection for Sample T2. However, the decrease in scatter obtained when using the optimum projection (α = 0.19) is only slight (∼0.04 dex). The bottom panel of Fig. 4 shows this optimum projection, which can be fit by the following polynomial:

$$Z = 43.448 - 12.193x + 1.373x^2 - 0.050x^3,$$

within the range 8.5 ≤ μ0.19 ≤ 11.0, where Z = 12 + log(O/H) and x = μ0.19 = log(M_\ast) - 0.19 log(\text{SFR}).

The improvement obtained for our Sample T1 is slightly better. A projection of α = 0.36 reduces the dispersion in Z by ∼0.06 dex compared to the M*–Z relation.

The reason for the less significant improvement seen for Sample T2 is the inverse dependence of Z on SFR seen at low and high masses. The ‘u shape’ that the relation therefore forms in the 3D space makes it difficult to find a projection which reduces the overall scatter as much as in Sample T1.

It is also interesting to note that when using fibre SFRs, the projection of least scatter for Sample T2 drops to α = 0.03, very close to the M*–Z relation. This is because the spread in SFRs at low M* is reduced due to the underestimation of SFR for nearby galaxies. For the same reason, when using fibre SFRs for Sample T1, the value of α shifts down to 0.26. Therefore, although some improvement to the scatter can be obtained by combining stellar mass and SFR in this way, the value of α seems quite sensitive to the quantity derivation methods chosen. As the dispersion around the M*–Z relation for Sample T2 is already relatively tight, we suggest that it is still suitable for most purposes.

When fixing stellar mass as the principle axis, and using the optimum projection determined by Lara-López et al. (2010b), we find a mean dispersion of 0.74 dex and a 1σ scatter of 0.24 dex around M* from residuals. This equates to a 1σ scatter of 0.17 dex around the composite axis from residuals, which can be compared to the value of 0.16 dex quoted by Lara-López et al. (2010b). The correspondence between the two values is good, despite differences in the sample selection. This is probably because both samples take values of M*, SFR and Z from the SDSS-DR7 catalogue.

5 MODEL SAMPLE

In this section, we investigate the relationship between M*, SFR and Z in a SAM of galaxy formation. This allows us to analyse the detailed evolution of individual galaxies as well as global relations, and to compare the models to observations. Analytic descriptions of
physical processes can be self-consistently incorporated into SAMs and then easily adapted, making them more flexible than current SPH simulations. The models also provide large samples of galaxies with predicted stellar masses, metallicities and SFRs, enabling detailed statistical comparisons with the observations to be made.

The model used in our study is the most recent version of L-GALAXIES (Guo et al. 2011), which is developed from previous versions of the code (De Lucia, Kauffmann & White 2004; Croton et al. 2006; De Lucia & Blaizot 2007). L-GALAXIES is a SAM grafted on to DM halo data from the Millennium (Springel et al. 2005) and Millennium-II (Boylan-Kolchin et al. 2009) DM N-body simulations. The current model is able to reproduce the observed stellar mass and luminosity functions, as well as the Tully–Fisher and mass–metallicity relations for present-day star-forming galaxies. It also includes updated analytical treatments for gas cooling and stripping, as well as SN and AGN feedback. The processes important in regulating metallicity that are included in the model are SN-driven outflows with a fixed ejecta speed (this means that metals escape more readily from low-mass galaxies), and gas infall both in the form diffusely accreted pristine gas and gas that was enriched and ejected by the galaxy at an earlier stage. This reintegrated material is returned more quickly into galaxies residing in more massive DM haloes. A detailed description of the analytic recipes used in L-GALAXIES can be found in Guo et al. (2011). The model assumes that the stellar IMF is the same everywhere, and at all epochs.

Our $z = 0$ model sample comprises 43 767 central galaxies extracted from the Millennium Database provided by the German Astrophysical Virtual Observatory (GAVO) (Lemson & Virgo Consortium 2006). We use the catalogues generated by running the L-GALAXIES code on the DM halo merger trees from the Millennium-II simulation, which is able to resolve DM haloes down to a halo resolution limit of $1.89 \times 10^8 \ M_{\odot}$. Galaxies were selected by stellar mass ($8.6 \leq \log (M_*) \leq 11.2$) and SFR ($-2.0 \leq \log (\text{SFR}) \leq 1.6$) to span the same region of parameter space as our observational samples. A 1-year Wilkinson Microwave Anisotropy Probe (WMAP) cosmology (Spergel et al. 2003) with the following parameters is assumed: $\Omega_m = 0.25$, $\Omega_b = 0.045$, $\Omega_{\Lambda} = 0.75$, $n_s = 1$, $\sigma_8 = 0.9$ and $H_0 = 73 \ \text{km s}^{-1} \text{Mpc}^{-1}$.

Both type 0 and type 1 central galaxies are included in the model sample. Type 0 galaxies are those lying at the centres of their DM haloes. These galaxies accrete material that cools from the surrounding halo, as well as satellite systems that sink to the centre of the halo as a result of dynamical friction. Type 1 galaxies are satellite systems embedded within a larger halo. In the current implementation of L-GALAXIES, these galaxies still accrete cold gas from their surrounding self-bound `subhalo’. Over time, the DM and gas in the subhalo is tidally stripped and accretion rates decline. The Millennium Database also contains so-called type 2 satellite galaxies, which have lost their surrounding host DM haloes through tidal stripping. These galaxies generally have no ongoing star formation and are therefore not included in our analysis.

6 MODEL RESULTS

6.1 The relation between $M_*$, SFR and $Z$ at $z = 0$

We bin the galaxies in our sample by $M_*$ and SFR in the same way as was done for our observations. Only bins containing $\geq 25$ galaxies are included in the model plots – half the number required in the observational samples. This is done in order to expand the dynamic range in the plots, but none of our results depends on this choice.

The total cold gas-phase metallicity for each bin is calculated. This is given by the ratio of mass in metals to total cold gas mass, normalized to the solar metal abundance: $Z_{\text{cold}} = 9.0 + \log (M_{\text{cold,z}} / M_{\odot,0.02})$.

The $M_* – Z$ relation for our $z = 0$ model sample is shown in Fig. 5. We see a positive correlation between stellar mass and metallicity.

4 Available at http://www.g-vo.org/Millennium

5 A change in the value of $Z_C$ down to that preferred by Asplund et al. (2009) ($Z_C = 8.69$) does not affect the slope of the relation or the distribution as a function of SFR (see also Bertone, De Lucia & Thomas 2007). We therefore choose to stick with the value of $Z_C = 9.0$ used by Guo et al. (2011) for consistency.
as well as a segregation of this relation by SFR. Interestingly, this segregation is similar to that seen in Sample T2, with a reversal in the SFR dependence from low to high masses. Another way of stating this result is that there is a ‘turnover’ at high stellar masses in the $M_\ast - Z$ relation for low-SFR galaxies. Such a feature is hinted at in Sample T2, but we note that the number of real massive galaxies with emission lines that are strong enough to measure metallicity and that are not dominated by AGN emission is quite small. This may explain the relative weakness of the feature in the observations compared to the model. The stellar mass at which the turnover occurs is $\sim 10^{10.4} M_\odot$, again in quite good agreement with what is seen in Sample T2. It should be noted that the same turnover is seen when only type 0 galaxies are included in the model sample, and so is not a consequence of environmental effects.

The SFR–Z and the sSFR–Z relations are shown in the left-hand and middle panels of Fig. 6. The $D_4$,4000 index is not available for our model galaxies, so only sSFR$_e = SFR/M_\ast$ is used. As in our observations, $Z$ depends on star formation at fixed stellar mass. As in Sample T2, there are a significant number of high-mass galaxies that show the opposite trend to that seen at low masses. Although the range of SFRs in our model sample is shifted downwards compared to that of Sample T2, the overall trend is still that the metallicities of galaxies of mass $\gtrsim 10^{10.5} M_\odot$ decrease with decreasing SFR (sSFR).

In the right-hand panel of Fig. 6 we plot the relation between the gas-to-stellar mass ratio ($M_{\text{cold}}/M_\ast$) and gas-phase metallicity for the same model galaxies. Because cool gas is the fuel for ongoing star formation in a galaxy, the gas-to-stellar mass ratio should correlate with the enrichment of the ISM. Indeed, this is what is seen in our model sample. The average $M_{\text{cold}}/M_\ast$ decreases with stellar mass and with $Z_{\text{cold}}$ for galaxies with stellar masses less than $\sim 10^{10.3} M_\odot$. At higher stellar masses, we again see a turnover towards low metallicities at low $M_{\text{cold}}/M_\ast$. We conclude that the low-sSFR galaxies that contribute to the high-mass turnover in the $M_\ast - Z$ relation also tend to have lower $M_{\text{cold}}/M_\ast$ than other galaxies of a similar mass. This is also seen in the sSFR–$(M_{\text{cold}}/M_\ast)$ relation, shown in Fig. 7, where these galaxies are indicated by red circles.

Currently, there is only limited data available on the gas fractions of high-mass galaxies with low SFRs. However, with the ongoing development of the GALEX Arecibo SDSS Survey (GASS; Catinella et al. 2010) and CO Legacy Database for GASS (COLDGASS; Saintonge et al. 2011) programmes, we will soon have a significant number of gas-to-stellar mass ratios for high-mass SDSS galaxies with which to compare. It will be interesting to see if the relationship between $M_{\text{cold}}/M_\ast$, SFR and $Z$ presented in Figs 6 and 7 is also found in these observations.

6.2 Metallicity evolution in model galaxies

In this section, we study the origin of the turnover in the model $M_\ast - Z$ relation seen in Fig. 5. We do this by splitting the high-mass end of the sample into low- and high-metallicity subpopulations and studying differences in their evolutionary histories. We extracted two high-mass ($M_\ast > 10^{10.8} M_\odot$) subsamples: a high-$Z$ ($Z \geq 9.2$) subsample containing 134 galaxies, and a low-$Z$ ($Z \leq 9.0$) subsample containing 136 galaxies. The mass, metallicity and SFR evolution of these two subsamples was then compared.

The 1-GALAXIES model tracks six distinct mass components of galaxies: stellar mass (in the form of a bulge and disc), black hole mass, cold gas mass (ISM), hot gas mass (ICM), ejected gas mass (IGM) and halo stars (producing the intracluster light). Mass and metals can pass between these components along pre-defined routes, depending on the processes taking place. The top three panels of Fig. 8 show the time evolution of these mass components for three representative galaxies from the model with high stellar masses and high metallicities. In the middle panels, we show the time evolution of the stellar and gas-phase metallicities of the same galaxies. The bottom panels show the time evolution of their SFRs.

The left-hand panels display a type 0 galaxy in which the stellar mass (solid orange line) has been steadily increasing since redshift two. In this galaxy, the mass of cold gas (solid blue line) is always higher than the critical value required for star formation, $M_{\text{crit}}$ (dashed blue line). There is a steady, gradual increase in the metallicity of the stellar, cold gas and hot gas components. This is because stars are formed continuously, synthesizing and distributing metals throughout the galaxy at a higher rate than the dilution due to the accretion of metal-poor gas. Around 64 per cent of the galaxies in our high-$Z$ subsample have formation histories similar to this.

The middle panels show a galaxy that first evolves in a similar way to the galaxy shown in the left-hand panels. It is then accreted on to a more massive DM halo at $z \sim 1.0$, becoming a type 1 object, at which point gas and DM begin to be tidally stripped. Some of these type 1 galaxies, like the example shown in the middle panel, then exhibit a sharp increase in gas-phase metallicity. This is because gas accretion on to the galaxy is reduced, but star formation continues, and as a result, metals continue to be dispersed into ever decreasing volumes of hot and cold gas. In other type 1 galaxies in the high-$Z$ subsample, the cold gas mass drops below $M_{\text{crit}}$ after being accreted, causing the cold gas metallicity to remain constant thereafter, due to a shut-down in both star formation and galactic gas accretion. Type
Figure 6. The SFR–Z relation (left-hand panel), (SFR/M_*)–Z relation (middle panel) and (M_{cold}/M_*)–Z relation for the z = 0 model sample. Fits to the data at four fixed stellar masses are shown (solid lines). The change in SFR dependence from low- to high masses evident in Fig. 5 is again seen. At fixed stellar mass, Z is seen to decrease with increasing SFR (sSFR) at low masses, but decrease with decreasing SFR (sSFR) at high masses. Similarly, there is also a clear anticorrelation between gas-to-stellar mass ratio and metallicity at fixed M_*. Above log(M_{cold}/M_*) \sim -1.0, but a direct correlation at lower gas-to-stellar mass ratios. These results are complimentary to those seen for our observational Sample T2 in Fig. 3.

Figure 7. The sSFR–(M_{cold}/M_*) relation for our z = 0 model sample. The relation for type 0 galaxies (blue line) and type 1 galaxies (green line) is shown, as well as the mean (solid black line) and median (dashed black line) relation for the full sample (shown in grey). The 1σ spread around the mean is shown as dotted lines. The low-sSFR galaxies that form the high-mass turnover in the model M_–Z relation are indicated by red circles. These galaxies tend to have lower-than-average gas-to-stellar mass ratios for their sSFR. 1 galaxies with star formation histories of these forms constitute \sim 30 per cent of the high-Z subsample.

The right-hand panels of Fig. 8 show a class of central galaxy that formed a bulge and a supermassive black hole (SMBH) at redshifts greater than two. The black hole (solid black line) then grew steadily through so-called ‘radio mode’ accretion of hot gas from the surrounding halo. Such galaxies are not representative of the high-Z subsample as a whole (they comprise only 6 per cent of the subsample) and are almost certainly classified as AGN and so missing from our observational samples. Nevertheless, we think they are rather interesting. The galaxy makes it into our high-Z model subsample due to the fact that it accretes many, many satellites over time (4141 since redshift two, compared to only 21 and 71 for the galaxies in the left-hand and middle panels, respectively). The satellites bring in fresh gas, leading to the very ‘bursty’ star formation history seen in the bottom right-hand panel of Fig. 8. We note that this galaxy resides in the centre of the ninth most massive DM halo in the whole Millennium-II simulation at z = 0, and so such a high rate of satellite accretion is perhaps unsurprising.

In conclusion, for the majority of galaxies in the high-Z subsample, the dominant process driving metallicity evolution is clearly a gradual enrichment of the gas phase due to continuous satellite accretion. At these high masses, outflows are inefficient at removing cold gas and metals from the galaxy. At these high SFRs, galactic infall...
rates are too low to dilute the ISM. Consequently, these galaxies become increasingly metal rich with time.

Fig. 9 paints a rather different picture for the evolution of galaxies in the low-Z subsample. All three galaxies have undergone dramatic drops in their cold gas masses, coinciding with a merger event at some stage during the past 10 Gyr. Mergers with mass ratio less than 10:1 are marked by black dots on the $M_{\text{cold}}$ evolution line. Note that no such mergers occur for the three high-Z examples in Fig. 8 – only 7.5 per cent of galaxies in the high-Z subsample have undergone a significant merger over the last 10 Gyr. A merger with mass ratio 3:1 or less is considered a major merger in the model, causing the destruction of the stellar and gas discs and the transfer of this material to the bulge of the descendant. We see from Fig. 9 that not only major mergers cause the sudden drop in $M_{\text{cold}}$. Gas-rich minor mergers are also effective at inducing starbursts and the rapid growth of the central SMBH through ‘quasar mode’ accretion. During such events, a black hole can grow by swallowing both cold gas and the smaller black hole of its companion. 92 per cent of the galaxies in the low-Z subsample have present-day black holes with masses greater than $10^{8}$ $M_\odot$, that were formed through this process. The remaining 8 per cent have either grown their black holes gradually through radio-mode accretion, or do not contain a central SMBH.

We note that although large black holes are a feature of almost all the galaxies in the low-Z subsample, they do not cause the low metallicities seen in these galaxies at $z = 0$. These are instead caused by a cessation in star formation due to the sudden drop in cold gas mass below $M_{\text{crit}}$, followed by accretion of metal-poor gas on to the galaxy. This galactic accretion is limited to a low rate by the suppression of cooling from radio mode AGN feedback, allowing it to continue for an extended amount of time without re-igniting star formation. The three galaxies in Fig. 9 therefore show that gradual dilution of the gas phase due to metal-poor infall of gas in the absence of star formation is the main process producing the low-Z subsample.

This effect is also seen in the difference between the gas-phase metallicities and stellar metallicities ($Z_*$) at $z = 0$. Galaxies in the low-Z subsample tend to have values of $Z_{\text{cold}}$ similar to or less than $Z_*$, rather than systematically higher values like in the high-Z subsample. This suggests that metal-poor infall on to an already evolved galaxy is taking place, at a higher rate than the SFR (Köppen & Edmunds 1999).

Such a dilution effect is not seen in hydrodynamic simulations of galaxy evolution such as those carried out by Finlator & Davé (2008) and Davé, Oppenheimer & Finlator (2011a). In those models, galaxies quickly fall back into an equilibrium between their infall, outflow and SFRs after a perturbative event, whereby $M_{\text{infall}} = M_* + M_{\text{outflow}}$. Instead, the inclusion of AGN feedback in our model enables galaxies to slowly accrete metal-poor gas for a number of gigayears without forming stars.

We note that it remains to be seen whether the fraction of massive galaxies in the models with very little ongoing star formation and low-metallicity reservoirs of cold gas is matched in observations. The low gas fractions of massive galaxies mean that the gas is difficult to detect. Obtaining H1 maps of a large sample of such objects remains a significant observational challenge.

### 6.3 Bulge and black hole masses

As discussed in the previous section, aside from a low gas-to-stellar mass ratio and low $Z_{\text{cold}}/Z_*$ ratio, one clear distinguishing feature of massive, low-Z galaxies in the model is the presence of a massive bulge and massive central black hole formed during a merging event. This is illustrated by the $M_{\text{bulge}}$–$M_{\text{BH}}$ relation in Fig. 10, where the galaxies in the low-Z subsample are highlighted by red circles. Interestingly, it is these galaxies that lie closest to the observational relation found by Haring & Rix (2004). It is unclear whether this

Figure 9. The evolution from $z = 2$ to 0 in mass (top panels), metallicity (middle panels) and SFR (bottom panels) for three typical galaxies from the high-mass, low-Z subsample. These galaxies show the gradual dilution of the cold gas phase that is characteristic of the low-Z subsample. The galaxy IDs for these galaxies from the Millennium Database are provided at the top of each panel.

Figure 10. The $M_{\text{bulge}}$–$M_{\text{BH}}$ relation for our $z = 0$ model sample. The full sample is shown in grey, with the mean relation plotted as a solid black line. The 1σ spread around the mean is shown as dotted lines. Galaxies in the low-Z subsample are highlighted by red circles. These galaxies have higher black hole masses that expected from an extrapolation of mean model relation, but lie nicely along the observational relation derived by Haring & Rix (2004).
Metallicity and star formation in galaxies

225

relation extends down to lower bulge masses with the same slope, or
levels-off as seen in the model. A significant fraction of intermediate
to massive galaxies with smaller central black holes have likely had
their bulges grown through secular processes (Shankar et al. 2011,
2012). Although massive central black holes are not the cause of
the low metallicities in the low-Z subsample, they are an associated
feature that we can look for in the currently available observational
data.

In the left-hand panel of Fig. 11, sSFR is plotted against gas-
phase metallicity for all our high-mass model galaxies. Galaxies
are binned by sSFR and $Z_{\text{cold}}$, and the bins are coloured by the
mean black hole mass of the galaxies in each bin. The number of
galaxies in each bin is also indicated on the plot in white text. It is
clear that low-sSFR, low-Z galaxies have the largest central black
holes in the model.

The right-hand panel of Fig. 11 shows the same plot for an
adapted version of our observational Sample T2 (see Appendix C
for details). Black hole masses were estimated via the measured
stellar velocity dispersion using the $M_{\text{BH}} - \sigma$ relation provided by
Tremaine et al. (2002):

$$\log(M_{\text{BH}}) = \alpha + \beta \log(\sigma/\sigma_0),$$

where $\alpha = 8.13$, $\beta = 4.02$, $\sigma_0 = 200 \text{ km s}^{-1}$ and $M_{\text{BH}}$ is in units of
$M_\odot$. We can see that the observational data also contain a low-Z,
high-$M_{\text{BH}}$ population, though the distinction between this popula-
tion and the majority of the sample is less clear than in the model.

The dichotomy in the observations is more clearly seen in Fig. 12,
where the distribution of black hole masses is shown for galaxies
contained within the two red boxes$^7$ marked in Fig. 11. The black
hole population is clearly shifted to higher masses in the low-Z
region (blue histogram), compared to the high-Z region (red his-
togram). 24 per cent of galaxies within the low-Z region have black
holes of mass $\geq 10^{8.0} M_\odot$. This is only true for 2.7 per cent of galax-
ies in the high-Z region. A correlation between low metallicities,
low sSFRs and high black hole masses therefore seems present in
both our model and observational sample.

6.4 Evolution of the $M_\ast - Z$ relation out to $z \sim 3$

In this section, we analyse the evolution of the $M_\ast - Z$ relation out
to $z \sim 3$. Observations have shown a clear evolution in the

$^7$ The boundaries chosen for these boxes are somewhat arbitrary. They are
designed to cover the two regimes of interest, namely, high-Z, low-$M_{\text{BH}}$
galaxies and low-Z, high-$M_{\text{BH}}$ galaxies. Shifting the boundaries of the two
regions does not affect the results found.
The $M_*-Z$ relation (Maiolino et al. 2008) and $M_*-\text{SFR}$ relation (Noeske et al. 2007a,b; Kajisawa et al. 2010) with look-back time, and such evolution is required for the Mannucci FMR to remain fixed out to $z \sim 2.5$.

In order to investigate this in L-GALAXIES, three supplementary, identically selected samples of type 0 and 1 galaxies were extracted from the data base at redshifts $z = 1.0$, 2.0 and 3.1. These samples contain 63 745, 63 017 and 50 558 galaxies, respectively, within the parameter space of interest.

The evolution of the $M_*-Z$ relation from $z = 3.1$ to 0 in the model is plotted in Fig. 13. The mean SFR at each redshift is also given in the top right of each panel. The SFR is seen to evolve strongly with cosmic time, dropping by $\sim 0.9$ dex from $z = 3.1$ to 0 at fixed mass, in line with the drop observed by Noeske et al. (2007a,b) and Kajisawa et al. (2010). However, there appears to be nearly no evolution in metallicity at fixed stellar mass at all in the model, contrary to observations (solid, dashed and dot-dashed black lines in Fig. 13). The present-day $M_*-Z$ relation agrees well with those of Tremonti et al. (2004) and Kewley & Ellison (2008) at $z = 0$, but the discrepancy with observations becomes increasingly pronounced towards higher redshifts. This suggests that chemical enrichment in the model galaxies proceeded too rapidly at early times.

In order to diagnose whether this hypothesis is correct, we plot the enrichment history from $z = 2$ to the present day of four representative galaxies from the $z = 0$ model sample in Fig. 14. The $M_*-Z$ relation for the entire $z = 0$ sample is also plotted in grey. This is a reasonable test, as a large number of galaxies in the $z = 0$ sample have main progenitors present in the higher redshift samples (the percentage of galaxies that lie on the most massive progenitor (MMP) branch of a $z = 0$ galaxy is indicated in the top left corner of each higher redshift panel in Fig. 13).

We can again see in Fig. 14 the two types of behaviour at high stellar masses described in Section 6.2, with both $Z_{\text{cold}}$ and stellar mass gradually increasing with time for the blue (high SFR) galaxy, and metallicity decreasing with time without any associated increase in stellar mass for the red (low SFR) galaxy. At intermediate masses, stellar mass and metallicity increase together, punctuated by episodes of enhanced gas accretion, such as a gas-rich merger with a metal-poor satellite.

At low masses, the metallicity evolution appears much more erratic. Drastic fluctuations in $Z_{\text{cold}}$ may occur when outflows become extreme enough to drive most of the gas out of the galaxy. This is the case for the lowest mass galaxies in the model, as a result of the SN feedback scheme that has been implemented in L-GALAXIES.

We can see from the grey points in Fig. 14 that the scatter in the $M_*-Z$ relation at $z = 0$ increases towards lower masses as a consequence of this stochastic mode of evolution. We note that it is unclear whether this feature is seen observationally. Lee et al. (2006) have used a sample of 27 nearby dwarf galaxies to argue that the scatter in the observed local $M_*-Z$ relation remains roughly constant down to stellar masses of $\sim 10^6 M_\odot$. If confirmed with larger samples, this might suggest that, unlike metals, cold gas is not driven very effectively out of low-mass galaxies by SNe (Mac Low & Ferrara 1999).

![Figure 13. The evolution of the $M_*-Z$ relation in L-GALAXIES from $z = 3.1$ to 0. The average metallicity at each redshift is plotted (horizontal dotted lines), and the mean SFR at each redshift is given in the top right of each panel. The percentage of galaxies in each higher redshift sample that have direct descendants in the $z = 0$ sample is shown in the top left of each higher redshift panel. Fits to observational data at three different redshifts compiled by Maiolino et al. (2008) are also shown. These are taken from Kewley & Ellison (2008) for $\langle z \rangle = 0.07$, Savaglio et al. (2005) for $\langle z \rangle = 0.7$ and Erb et al. (2006) for $\langle z \rangle = 2.3$. A fit to the Tremonti et al. (2004) $\langle z \rangle = 0.1$ relation (red dashed line) is also shown in the $z = 0$ panel.](https://academic.oup.com/mnras/article-abstract/422/1/215/1020516)
argued that low-SFR galaxies produce relatively fewer SNe, disrupting the ISM less and blowing away metals less efficiently than in high-SFR galaxies (e.g. Mac Low & Ferrara 1999). When considering a closed-box model, lower SFRs at fixed mass imply lower cold gas masses, which in turn imply a higher rate star formation in the past. The ISM of these galaxies would therefore be more metal rich today (Ellison et al. 2008). Alternatively, Dib et al. (2011) have suggested that the interdependence between SFR and $Z$ is due to a more fundamental dependence of the pre-stellar core formation efficiency (CFE) on metallicity. In their analytical model, star-forming regions of higher metallicity form more OB stars, whose stellar winds remove the surrounding gas and so truncate star formation more quickly.

The dependence seen at high stellar mass is, however, more difficult to explain. In the absence of effective galactic outflows at high mass, low-SFR galaxies could simply under-enrich the ISM relative to more actively star-forming galaxies, by producing fewer metals. However, the high-mass dependence seen in our model sample is caused by a turnover in the $M_\ast-Z$ relation. Such a feature cannot be explained by mass-dependent processes alone. If the turnover seen in the model $M_\ast-Z$ relation is indeed real, then additional physical mechanisms must be at play.

Our model points to metal-poor galactic infall at high mass as an explanation. Those high-$M_\ast$ galaxies with low gas-phase metallicities are known to have undergone gradual dilution of their gas phases after a merger event which shut off further star formation. The restriction in the amount of infall by AGN feedback allowed these galaxies to slowly dilute their ISM, without accreting enough gas for star formation to resume. The turnover that this causes in the model is not as clearly seen in our observations. However, correlations between these galaxies and the high-$M_\ast$, low-$Z$ galaxies in our observational sample (namely, their large black hole masses) imply that a dilution process could also be involved in shaping the $M_\ast-Z$ relation in the real Universe (see also Appendix C).

There are, however, two factors hampering this interpretation. First, the dependence of $Z$ on SFR is itself strongly dependent on how these properties are measured (see Section 4). Although a high mass dependence is undeniable in our Sample T2, it is not present in Sample T1, at least not within the range of masses studied.

Secondly, the recipes used to model physical processes in L-GALAXIES, although up-to-date with current theory, are still rather crude, and this could be affecting the galaxy evolution seen in our model galaxies. For example, metals are assumed to fully mix with the ISM before galactic outflows are allowed to drive gas out of the galaxy. This means that it is the subsequent cessation of star formation in low-mass galaxies that is causing the relation between $M_\ast$ and $Z$ in the model, rather than explicitly metal-rich outflows. Additionally, and perhaps relatedly, there is a lack of evolution in the model $M_\ast-Z$ relation, contrary to observations.

Despite these two caveats, we believe our interpretation to be viable. On the observational side, the use of many emission line fluxes and SED fitting (as is done for many trusted stellar mass estimations) is likely to be a more robust way of estimating metallicities than using individual emission line ratios (see Appendix A). On the modelling side, the problems outlined above are currently common to models in general. For example, the SPH simulation described by Davé, Finlator & Oppenheimer (2011b), which exhibits the same evolution of galaxies along the present-day $M_\ast-Z$ relation, also has difficulties reproducing the observed metallicity evolution. Their favoured model (which invokes momentum-driven winds and metal-rich outflows at all masses) shows an increase in $Z$ of $\sim 0.15$ dex from $z = 2$ to 0 for galaxies of stellar mass $\sim 10^{10.5} M_\odot$. 

The main point to take away from Fig. 14 is that galaxies evolve along the present-day $M_\ast-Z$ relation in the model, rather than from much lower metallicities, as suggested by observations. This suggests that it is indeed an overly rapid enrichment of the cold gas phase of galaxies before redshift three that is causing the lack of evolution thereafter in the model.

One possible solution to the problem is that accreted gas is ‘hung-up’ in the atomic phase of the ISM for some time, before it is able to reach high enough densities to form the molecular clouds in which stars are formed (Gnedin, Tassis & Kravtsov 2009; Gnedin & Kravtsov 2011). Recently, Fu, Kauffmann & Krumholz (2010) implemented simplified prescriptions for the formation of molecular gas in galaxies in the L-GALAXIES code to study scaling relations between gas and stars in local galaxies. These recipes have, however, not yet been applied to the more recent Guo et al. (2011) version of L-GALAXIES, which contains stronger and more mass-sensitive feedback. Lagos et al. (2011) have recently implemented star formation laws dependent on the surface density of molecular gas into the GALFORM SAM. Their results suggest that such prescriptions do lower the typical SFR of central galaxies at higher redshifts. Such changes could slow the evolution of the $M_\ast-Z$ relation at high redshifts, allowing more evolution below $z \sim 3.5$.

7 DISCUSSION

In Section 4, we have shown that our preferred observational sample, Sample T2, exhibits a reversal in the dependence of metallicity on SFR from low to high stellar mass. At low masses, low star-forming galaxies have higher metallicities than high star-forming galaxies. At high masses, the opposite is true: low star-forming galaxies have lower metallicities than high star-forming galaxies.

There remains a multiplicity of explanations for the dependence seen at low mass. When considering galactic outflows, it can be
Their fixed, low wind velocity $sw$ model shows an evolution of $\sim 0.1$ dex (an amount similar to that seen in 1-GALAXIES). In comparison, observations suggest an evolution of $\sim 0.5$ dex at the same mass from $z = 2.3$ to 0.07 (Maiolino et al. 2008). Further improvements to the observational determination of gas-phase metallicities, and the ongoing improvements in accurate modelling of galactic evolution, are necessary before significant progress can be made in this area.

8 CONCLUSIONS

We have shown that the gas-phase metallicities of galaxies are dependent on their SFR. This is also true at high masses, where highly star-forming galaxies are seen to have higher metallicities – the opposite trend to that seen at low masses. However, despite this dependence, a projection on to the $M_\ast$–SFR–Z space that combines $M_\ast$ and SFR does little to reduce the scatter in Z compared to the $M_\ast$–Z relation, decreasing the mean dispersion by only $\sim 0.04$ dex.

We also demonstrate the significance of metallicity derivation methods when assessing the relation between $M_\ast$, SFR and Z. Strong line ratio diagnostics provide significantly different metallicity estimates to the Bayesian techniques which utilise emission line fluxes. These differences appear to be greater for low star-forming galaxies. Although we believe that the Bayesian technique used for our Sample T2 provides a more robust measurement of the global gas-phase metallicity in local, high-metallicity, star-forming galaxies, it remains unclear to what extent this is so.

In Section 6, we show that a high-mass SFR dependence is also present in our model sample. This is due to a turnover in the mass-metallicity relation, caused by a gradual dilution of the gas phase in some galaxies, triggered by a gas-rich merger which shuts down subsequent star formation without impeding further cooling. We have proposed that similarities between these low-sSFR model galaxies and those observed at $z = 0$, such as their larger-than-average black hole masses, leave open the possibility that such a process is also driving the SFR dependence seen at high masses in real galaxies. If this is the case, then physical processes other than mass-dependent outflows must also be playing a part in regulating metallicity. Our model indicates metal-poor galactic infall as a likely candidate.

ACKNOWLEDGMENTS

RMY would like to thank Jarle Brinchmann, Gabriella De Lucia, Jonny Elliott, Sara Ellison, Silvia Fabello, Qi Guo, Bruno Henriques, Roberto Maiolino, Filippo Mannucci, Roderik Overzier, Francesco Shankar, Freeke van de Voort, Simon White and Rob Wiersma for invaluable discussions during the undertaking of this work, and acknowledges the financial support of the Deutsche Forschungsgesellschaft (DFG). QG acknowledges support from the National Basic Research Program of China (program 973 under grant No. 2009CB24901), the Young Researcher Grant of National Astronomical Observatories, CAS, the NSFC grants program (No. 11143005) and the Partner Group program of the Max Planck Society, as well as the hospitality of the Institute for Computational Cosmology in Durham, UK. We would also like to thank the referee for insightful and constructive comments.

REFERENCES

Allende Prieto C., Lambert D. L., Asplund M., 2001, ApJ, 556, 63
Asplund M., Grevesse N., Sauval A. J., Scott P., 2009, ARA&A, 47, 481
Baldwin J. A., Phillips M. M., Terlevich R., 1981, PASP, 93, 5
Bertone S., De Lucia G., Thomas P. A., 2007, MNRAS, 379, 1143
Boylan-Kolchin M., Springel V., White S. D. M., Jenkins A., Lemson G., 2009, MNRAS, 398, 1150
Bresolin F., Garnett D. R., Kennicutt R. C., 2004, ApJ, 615, 228
Brinchmann J., Charlot S., White S. D. M., Tremonti C. A., Kauffmann G., Heckman T., Brinkmann J., 2004, MNRAS, 351, 1151
Brooks A. M., Governato F., Booth C. M., Willman B., Gardner J. P., Wadsley G., Sinson G., Quinn T., 2007, ApJ, 655, L17
Brualz A. G., Charlot S., 2003, MNRAS, 344, 1000
Calura F., Menci N., 2009, MNRAS, 400, 1347
Calura F., Pipino A., Chiappini C., Matteucci F., Maiolino R., 2009, A&A, 504, 373
Cardelli J. A., Clayton G. C., Mathis J. S., 1989, ApJ, 345, 249
Catinella B. et al., 2010, MNRAS, 403, 683
Chabrier G., 2003, PASP, 115, 763
Charlot S., Longhetti M., 2001, MNRAS, 323, 887
Croton D. J. et al., 2006, MNRAS, 365, 11
Dalcanton J. J., Yoachim P., Bernstein R. A., 2004, ApJ, 608, 189
Davé R., Oppenheimer B. D., Finlator K., 2011a, MNRAS, 415, 1
Davé R., Finlator K., Oppenheimer B. D., 2011b, MNRAS, 416, 1354
De Lucia G., Blaizot J., 2007, MNRAS, 375, 2
De Lucia G., Kauffmann G., White S. D. M., 2004, MNRAS, 349, 1101
Denicoló G., Terlevich R., Terlevich E., 2002, MNRAS, 330, 69
Dib S., Piau L., Mohanty S., Braine J., 2011, MNRAS, 415, 3439
Ellison S. L., Patton D. R., Simard L., McConnachie A. W., 2008, ApJ, 672, L107
Elmegreen B. G., 2006, ApJ, 648, 572
Erb D., Shapley A. E., Pettini M., Steidel C. C., Reddy N. A., Adelberger K. L., 2006, ApJ, 644, 813
Ferland G. J., 1996, Hazy, A Brief Introduction to Cloudy 90, Univ. Kentucky Internal Report, Lexington
Ferland G. J., Korista K. T., Verner D. A., Ferguson J. W., Kingdon J. B., Verner E. M., 1998, PASP, 110, 761
Finlator K., Davé R., 2008, MNRAS, 385, 2181
Fu J., Kauffmann G., Krumholz M. R., 2010, MNRAS, 409, 515
Fumagalli M., da Silva R. L., Krumholz M. R., 2011, MNRAS, 415, 3439
Gallazzi A., Brinchmann J., Charlot S., Bower R. G., Benson A. J., 2010b, A&A, 521, L53
Gallego N., Rix H.-W., 2004, ApJ, 604, L89
Kajisawa M., Ichikawa T., Yamada T., Uchimoto Y. K., Yoshikawa T., Akyma M., Onodera M., 2010, ApJ, 723, 129
Kauffmann G. et al., 2003a, MNRAS, 341, 53
Kauffmann G. et al., 2003b, MNRAS, 346, 1055
Kennicutt R. C., 1998, ARA&A, 36, 189
Kennicutt R. C., Bresolin F., Garnett D. R., 2003, ApJ, 591, 801
Kewley L. J., 2008, MNRAS, 385, 2181
Kewley L. J., Dopita M. A., 2002, ApJS, 142, 25
Kewley L. J., Ellison S. L., 2008, ApJ, 681, 1183
Kobayashi C., Springel V., White S. D. M., 2007, MNRAS, 376, 1465
Kobulnicky H. A., Kewley L. J., 2004, ApJ, 617, 240
Köppen J., Edmunds M. G., 1999, MNRAS, 306, 317
Köppen J., Weidner C., Kroupa P., 2007, MNRAS, 375, 673
Kroupa P., 2001, MNRAS, 322, 231
Lagos C. d. P., Lacey C. G., Baugh C. M., Bower R. G., Benson A. J., 2011, MNRAS, 416, 1566
Lara-López M. A., Bongiovanni A., Cepa J., Pérez Garcia A. M., Sánchez-Portal M., Cañadell H., Fernández Lorenzo M., Pović M., 2010a, A&A, 519, A31
Lara-López M. A. et al., 2010b, A&A, 521, L53
Larson R. B., 1974, MNRAS, 169, 229
Lee H., Skillman E. D., Cannon J. M., Jackson D. C., Gehrz R. D., Polomski E. F., Woodward C. E., 2006, ApJ, 647, 970

© 2012 The Authors, MNRAS 422, 215–231
Monthly Notices of the Royal Astronomical Society © 2012 RAS
APPENDIX A: ESTIMATING GAS-PHASE METALLICITIES

Obtaining accurate estimates of the gas-phase metallicity is not an easy process, as different diagnostics can provide very different results. However, it should be emphasized that the difference seen between our two observational samples (see Fig. 2) is not simply due to the inherent discrepancies between $T_e$, empirical and theoretical metallicity derivation methods. For the range of metallicities covered by our samples, both take their metallicities via theoretical methods. The difference is instead likely due to the use of either emission line ratios or a Bayesian approach with emission line fluxes in the analysis.

On this point, it should be noted that theoretically derived strong line ratios are known to suffer from a number of problems, including degeneracies (Kewley & Dopita 2002; Kewley & Ellison 2008), sensitivity to the ionization parameter (Kewley & Dopita 2002; Erb et al. 2006), saturation at high metallicities (Kewley & Dopita 2002; Kewley & Ellison 2008), and inconsistency with $T_e$ derived metallicities (Kennicutt, Bresolin & Garnett 2003; Bresolin, Garnett & Kennicutt 2004; Garnett, Kennicutt & Bresolin 2004; Stasińska 2005). It is not clear to what extent the technique used for Sample T2 suffers from these effects. There have been some concerns over the treatment of secondary nitrogen in the population synthesis models used to produce the Sample T2 metallicity estimates (Liang et al. 2006; Yin et al. 2007). Early indications show that accounting for this by excluding the $\text{[N II]}$ (and $\text{[S II]}$) lines from the Bayesian analysis does not change the high-mass SFR dependence seen. Removing these lines only seems to have a significant effect at low masses, strengthening the dependence of $Z$ on SFR seen there.\(^8\)

Although the Bayesian estimates seem robust to the form of nitrogen emission modelling, such issues may still affect simpler strong line ratio diagnostics. For example, the twist in the $M_\star$–$Z$ relation for Sample T2 is reproduced when using the diagnostics calibrated by McGaugh (1991) and Kobulnicky & Kewley (2004), which do not rely on nitrogen. However, this is not the case for the Denicolò, Terlevich & Terlevich (2002) diagnostic, which utilizes the $\text{[N II]} 6584/\text{H}$ ratio (Ellison, private communication). This could be an indication of further uncertainty in strong line ratio diagnostics that include nitrogen.

Additionally, there are two particular issues affecting the calibrations used for Sample T1 at high metallicity. First, there is the binning of data by Maiolino et al. (2008) when calibrating the diagnostics used for our Sample T1. A fit to unbinned data would have heavily biased their diagnostics against the lower metallicities crucial for high-redshift studies such as theirs, due to the paucity of low-Z galaxies available in their present-day calibration sample. However, this does mean that their fits are less precise at high metallicities, which is important for their application to local samples such as ours. Their $R_{23}$ diagnostic overpredicts the average metallicity slightly compared to the average values obtained from the Kewley & Dopita (2002) model for $Z \geq 9.0$ (see fig. 5 in the Maiolino et al. 2008 paper). This raises the metallicity estimated in this regime somewhat, despite the use of the $\text{[N II]}/\text{H}$ diagnostic to bring down the final value.

Secondly, Nagao et al. (2006) have already pointed out that their metallicity derivation method – which uses the same calibration sample as Maiolino et al. (2008) – may overestimate the gas metallicity at $Z > 9.0$ by a factor of $\sim 0.1$ dex compared to the Tremonti et al. (2004) method. This is partly due to the bias towards selecting strongly $\text{[O II]}$ and $\text{[O III]}$ emitting galaxies in the sample causing the fit to be steeper at high metallicities. When considering the $R_{23}$ diagnostic, the fact that $\text{H}$ II emission is also weaker in low star formation environments could explain why the discrepancy we see is more significant at low SFR (see Fig. 2).

Taking all this into account, it is perhaps prudent to suggest that such ratios are not ideal for estimating metallicities for high-$Z$, local samples, where the availability of good spectroscopic data, including all optical emission lines, allows alternative techniques to be utilized.

APPENDIX B: THE BASIC $M_\star$–$Z$ RELATION

The $M_\star$–$Z$ relation obtained for Sample T2, without assessing any SFR dependence, is shown in Fig. B1. In this form, the relation can be seen as an ‘update’ to that of Tremonti et al. (2004), who analysed a sample containing half as many galaxies. The galaxy population is shown in grey, with a third-order polynomial fit to the whole population shown as a solid black line, and given by the following equation:

$$Z = 26.686 - 6.640 x + 0.769 x^2 - 0.028 x^3,$$

where $Z = 12 + \log(\text{O/H})$ and $x = \log(M_\star/M_\odot)$. A fit to the Tremonti et al. (2004) mass–metallicity relation (red dashed line)

\(^8\) It should be noted that a larger number of double-peaked likelihood distributions are produced when removing emission lines from the analysis. This can make it more difficult to determine the true metallicity. Further analysis of this new set of metallicity estimates is needed before more concrete statements can be made.
The $M_\ast$–$Z$ relation for Sample T2 is shown in grey, and a fit to this data is given (black solid line). The median metallicity in bins of 0.15 dex in stellar mass is plotted as black diamonds. The 1σ dispersion in $Z$ about the median is shown as dotted lines. Also shown is the Tremonti et al. (2004) fit to data drawn from the SDSS-DR2 (dashed red line).

Figure B1

The distribution of residuals about $Z$ for the $M_\ast$–$Z$ relation shown in Fig. B1. The mean dispersion of $\sim$0.10 dex is the same as that reported by Tremonti et al. (2004) for their SDSS-DR2 sample.

Figure B2

is plotted for comparison. The standard deviation about the best fit from residuals is 0.102 dex, as shown by Fig. B2. This is the same as the dispersion calculated for the original Tremonti et al. (2004) sample.

There is little quantitative difference between our fit and that of Tremonti et al. (2004). However, our new fit indicates a some-

what more linear relation between mass and metallicity below $\sim 10^{10.5} M_\odot$, and there is a hint of a turnover at the very highest masses. High-mass turnovers in fitted $M_\ast$–$Z$ relations are not uncommon in the literature (McGaugh 1991; Zaritsky, Kennicutt & Huchra 1994; Kewley & Dopita 2002; Kobulnicky & Kewley 2004; Pettini & Pagel 2004), however, they have not been widely discussed in terms of their physical significance.

APPENDIX C: AN ADDITIONAL SET OF MASSIVE GALAXIES

The adaptation made to Sample T2 in Section 6.3 is to include an additional set of 9275 high-mass ($\geq 10^{10.5} M_\odot$) galaxies to the sample. These are the galaxies removed from the default Sample T2 due to having 1σ uncertainties in their stellar mass estimates greater than 0.2 dex. The reason for this larger error seems to be due to large errors in the $u$-band magnitude measured, which is included in the estimation of stellar mass. This error has therefore likely propagated through to the confidence in the best-fitting model during SED fitting, causing these galaxies to have a larger uncertainty in their $M_\ast$ estimate.

Fig. C1 shows that, for masses greater than $\sim 10^{10.5} M_\odot$, these additional galaxies have only slightly greater 1σ errors on their mass estimates than the default Sample T2 galaxies, and that their metallicity estimates are actually more than good enough for them to remain in the sample. We therefore choose to include these high-mass galaxies for our analysis of black hole mass. Their addition is not a necessary condition, but does provide more low-sSFR galaxies and makes the dichotomy seen in the right-hand panel of Fig. 11 clearer.

It is interesting to note that when plotting the $M_\ast$–$Z$ relation for Sample T2 including these additional galaxies, a range of SFR-dependent turnovers can be clearly seen at high mass. This is shown

Figure C1

The mean 1σ errors on the values of $M_\ast$ (solid lines) and $Z$ (dashed lines) provided by the best-fitting models for the default Sample T2 (thick lines), and for the additional galaxies described in Appendix C (thin lines). At high masses, the error in $M_\ast$ for the additional galaxies is only slightly greater than for the Sample T2 galaxies. The metallicity errors in the high-mass regime are well below the maximum acceptable error of $\sigma = 0.2$ dex (indicated by the horizontal dotted line).
in Fig. C2. When considering Figs 11, 12 and C2 together, it seems plausible that the low-Z, high-M∗ galaxies with large SMBHs seen in our model sample are also present in the SDSS, and that processes other than outflows are at play in regulating their metallicities.

**Figure C2.** The M∗–Z relation for Sample T2, when including the additional galaxies described in Appendix C. The shape of the overall relation is unchanged, but turnovers in the relation at fixed SFR are now evident for a wide range of SFRs. This lends favour to the conclusion from our model sample, that processes other than outflows are regulating metallicity at high mass.