Dilution in elliptical galaxies: implications for the relation between metallicity, stellar mass and star formation rate

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ABSTRACT

We investigate whether dilution in some elliptical galaxies is the cause of a positive correlation between specific star formation rate (sSFR) and gas-phase metallicity ($Z_g$) at high stellar mass in the local Universe. In the Munich semi-analytic model of galaxy formation, LGALAXIES, massive, low-sSFR, elliptical galaxies are seen to undergo a gradual dilution of their interstellar medium, via accretion of metal-poor gas in cold-gas clumps and low-mass satellites. This occurs after a merger-induced starburst and the associated supernova feedback have quenched most of the original gas reservoir. Signatures of this evolution are present in these model galaxies at $z = 0$, including low gas fractions, large central black holes, old ages, and importantly, low ($Z_g - Z_e$). Remarkably, all of these properties are also found in massive, low-sSFR, elliptical galaxies in the sloan digital sky survey data release 7 (SDSS-DR7). This provides strong, indirect evidence that gradual dilution is also occurring in nearby ellipticals in the real Universe. This scenario provides an explanation for the positive correlation between SFR and $Z_g$ measured in high-$M_*$ galaxies, and therefore has consequences for the local fundamental metallicity relation, which assumes a weak anticorrelation above $\sim 10^{10.5} M_\odot$.

Key words: astronomical data bases: miscellaneous – ISM: abundances – ISM: evolution – galaxies: elliptical and lenticular, cD.

1 INTRODUCTION

A considerable amount of attention in the recent literature has been devoted to studying the relation between stellar mass ($M_*$), star formation rate (SFR) and gas-phase metallicity ($Z_g$) in galaxies. The $M_* - $SFR-$Z_g$ relation is believed to be a stronger diagnostic of galactic chemical evolution than the simpler $M_* - Z_g$ relation, as it provides constraints on the recent star formation, as well as the integrated star formation (i.e. $M_*$) and current $Z_g$. However, despite this, there remain a number of possible explanations for the trends seen in this relation in the local Universe.

Ellison et al. (2008b) found an anticorrelation between $Z_e$ and both specific star formation rate (sSFR) and half-light radius at low $M_*$. This dependence was attributed to lower present-day star formation efficiencies in more compact galaxies, as rapid star formation at early times is believed to consume most of the cold gas in these systems. A flat Fundamental Plane relating $M_* - $SFR and $Z_g$ was later found by Lara-López et al. (2010b), which extends unchanged out to $z \sim 3.5$. At the same time, a 3D fundamental metallicity relation (FMR) was found by Mannucci et al. (2010). The FMR corrects for the observed anticorrelation between SFR and $Z_g$ at low $M_*$ to provide a prediction of the metallicity of local galaxies with an expected 1σ scatter of only $\sim 0.05$ dex. The SFR-$Z_g$ dependence at low mass was assumed to be due to highly star-forming galaxies driving stronger galactic winds, which can efficiently remove metals from their small gravitational potential wells.

Some theoretical studies have been able to replicate this relation between $M_* - $SFR and $Z_g$ (e.g. Davé, Finlator & Oppenheimer 2012; Dayal, Ferrara & Dunlop 2013; Lilly et al. 2013). These studies utilize analytical, ‘bathtub’ models, which assume a rapid restoration of a system to an equilibrium between the gas accretion rate and SFR after a perturbative event (e.g. Bouché et al. 2010). Consequently, these models do not take account of physical processes which could force galaxies out of such an equilibrium for an extended period of time (see Section 3).

A study of sloan digital sky survey data release 7 (SDSS-DR7) galaxies by Yates, Kauffmann & Guo (2012, hereafter YKG12) also found an anticorrelation between SFR and $Z_g$ at low mass, but additionally a positive correlation between these two properties at high mass. The key difference between the Mannucci et al. (2010) and YKG12 studies was the metallicity diagnostic used – the former took the average metallicity obtained from the $R_{23}$ (i.e. [O iii]$\lambda$5007/Hβ) and [N ii]/Hα ratios, whereas the latter took the Bayesian metallicities provided by the MPA-JHU catalogue, which are based on fitting six strong emission-line fluxes to synthetic spectra (see Tremonti et al. 2004). YKG12 argued that their choice of

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metallicity diagnostic is likely to be more robust for local, high-$Z_g$ galaxies. This is because, (a) the [N II]/H$\alpha$ diagnostic is prone to underestimating the metallicity in this regime, due to saturation as the electron temperature drops below that required to easily excite the [N II]$\lambda$6584 line. And (b) the $R_{23}$ diagnostic, as calibrated by Maiolino et al. (2008), seems to overestimate the metallicity in this regime compared to the Bayesian technique by up to $\sim$0.2 dex, especially for lower SFR galaxies.

Some recent observational studies support the findings of YKG12. For example, Lara-López et al. (in preparation) found a positive correlation between SFR and $Z_g$ at high mass when using either a [N II]/[O II] or ([O II]/H$\beta$)/([N II]/H$\alpha$) diagnostic, demonstrating that it is not just Bayesian metallicities that produce such a trend. Similarly, Andrews & Martini (2012) have found a slight positive correlation at high mass when using a $R_{23}$ or [N II]/H$\alpha$ diagnostic (separately). However, such a correlation is less clear when using the $T_e$ method, as their sample has only very few galaxies above $\log(M_*) = 10.5\,M_\odot$ (see their fig. 11). Additionally, metallicities derived using the $T_e$ method can be unreliable above $Z_g \gtrsim 8.6$ due to local and global temperature gradients across galaxies (Stasińska 1978a, 2005, but see Croxall et al. 2013). Zahid et al. (2013b) have found a correlation between SFR and dust extinction very similar to that found between SFR and $Z_g$ by YKG12. As dust and metals are known to be produced and distributed in similar ways throughout galaxies (e.g. Dwek 1998), these two correlations could share a common cause. Most recently, Kurk et al. (in preparation) have found a strong positive correlation between SFR and $Z_g$ at high mass in a sample of LUCI/SINS galaxies at $z \sim 2$.

A possible explanation for this positive correlation was provided by YKG12, using the Munich semi-analytic model of galaxy formation, L-GALAXIES. In the model, such a correlation is the consequence of gradual dilution of the interstellar medium (ISM) in low-SFR, massive galaxies by the accretion of metal-poor gas over several Gyr. Secular star formation is shutdown in these systems after a gas-rich merger, which produces a starburst, growth of the central black hole (BH), and ejection of gas via supernova (SN) feedback. Thereafter, the remaining gas is of too low density to continue forming stars, and the presence of ‘radio-mode’ active galactic nucleus (AGN) feedback suppresses cooling of hot gas from the circumgalactic medium (CGM). However, the accretion of metal-poor, cold-gas clumps and low-mass satellites can still proceed (see Section 3.2).

There should be a number of signatures at $z = 0$ of this specific evolution. For example, YKG12 noted that they have larger-than-average central BHs for their mass. In this work, we identify a much wider range of properties at $z = 0$ in the model that are indicative of post-merger gradual dilution. We then utilize an array of publicly available observational data to see if these signatures are also present in real low-SFR, low-$Z_g$ galaxies at low redshift. If so, this would provide strong, indirect evidence that gradual dilution is also taking place in the real Universe.

In Section 2, we describe our model sample. In Section 3, we present our model results, including a description of how dilution occurs in some model, elliptical galaxies. In Section 4, we describe our observational sample and the methods used to obtain various galactic properties. In Section 5, we present our observational results, and compare them to those from our model. In Section 6, we discuss our results in the context of other studies. Finally, in Section 7, we provide our conclusions.

2 THE MODEL SAMPLE

We form a sample of star-forming galaxies at $z = 0$ from the Munich semi-analytic model of galaxy formation, L-GALAXIES (Springel et al. 2001; De Lucia, Kauffmann & White 2004; Springel et al. 2005; Croton et al. 2006; De Lucia & Blaizot 2007; Guo et al. 2011, 2013; Henriques et al. 2013). In the semi-analytic model, galaxy evolution is governed by the transfer of mass among the various galaxy components (central BH, stellar bulge, stellar disc, ISM, CGM, halo stars and ejecta reservoir), according to certain physical laws motivated by observations and simulations. In this work, we use outputs from the latest publicly available version of L-GALAXIES (Guo et al. 2011), run on dark matter (DM) subhalo trees built from the Millennium-II N-body simulation (Boylan-Kolchin et al. 2009). Our model sample was extracted from the Millennium Database$^2$ (Lemson and the Virgo Consortium 2006) provided by the German Astrophysical Virtual Observatory. Galaxies were selected at $z = 0$ only by stellar mass ($\log M_* \geq 8.6\,M_\odot$), providing 64,544 model galaxies at $z = 0$.3

Fig. 1 shows the normalized $M_*$, SFR, $Z_{\text{cold}}$ and mass-weighted age distributions of our model sample. The parameter $Z_{\text{cold}}$ represents the mean metallicity of the cold, ISM gas in model galaxies. This is defined here as $9.0 + \log(M_{Z_{\text{cold}}}/M_{\text{cold}}/0.02)$, and can be compared to the metallicity measured in the star-forming regions of real galaxies, $Z_g = 12 + \log(O/H)$. A more precise estimate of $Z_{\text{cold}}$, using the true ratio of oxygen atoms to hydrogen atoms in the

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$^2$ Available at http://www.g-vo.org/Millenium

$^3$ Type 2 galaxies (also known as ‘orphans’), whose DM subhaloes have been stripped to below the DM subhalo resolution limit of $1.89 \times 10^8\,M_\odot$, are not included in our analysis.
3 Model Results

The top panel of Fig. 2 shows the number density distribution for our model sample in the sSFR–$Z_{\text{cold}}$ plane. Lara-López et al. (2013) have also used the sSFR–$Z_{\text{cold}}$ plane to study the relation between $M_*$, sSFR and $M_{BH}$ in local galaxies. In our case, this plane is useful because it clearly separates the two classes of massive galaxy in which we are most interested. The bottom panel of Fig. 2 shows the number density for only galaxies with $\log(M_*) \geq 10.5 \, M_{\odot}$ (see Section 3.1).

Fig. 3 shows ‘maps’ of the full model sample in the same plane, with the colouring in each panel denoting a different physical property. Galaxies are binned by sSFR and $Z_{\text{cold}}$, and only bins containing 10 or more galaxies are shown. There are clear trends in a number of properties for the sample as a whole. For example, $M_*$ and $M_{BH}$ (panels A and H) increase with gas-phase metallicity, age decreases with sSFR (panel G), and both the SFR and $M_{\text{cold}}$ (panels B and C) follow the net cooling rate (panel I). All of these trends are as we would expect from galaxy evolution in a hierarchically merging, Λ cold dark matter universe, where galaxies are typically expected to grow in mass and metallicity with time.

3.1 Two classes of massive galaxy

In order to study the SFR–$Z_{\text{cold}}$ correlation at high mass, we have selected two subsamples of galaxies with $M_* \geq 10^{10.5} \, M_{\odot}$. The first contains 2160 galaxies with $\log(sSFR) \geq -10.7 \, \text{yr}^{-1}$ and $Z_{\text{cold}} \geq 8.85$. The second contains 318 galaxies with $\log(sSFR) \leq -12.0 \, \text{yr}^{-1}$ and $Z_{\text{cold}} \leq 8.85$. For simplicity, we refer to these two subsamples as enriching galaxies and diluting galaxies, respectively. The former population are typically undergoing an increase in $Z_{\text{cold}}$ with time, whereas the latter population are typically undergoing a decrease in $Z_{\text{cold}}$ with time (see YKG12). As we will see, they could equally be referred to as disc-dominated and bulge-dominated galaxies, young and old galaxies, or metal-rich and metal-poor galaxies. However, for the purposes of this work, we will label them by their typical net change in $Z_{\text{cold}}$ at $z = 0$.

We note here that the exact limits of the selection criteria are somewhat arbitrary. We have attempted to select massive galaxies with ‘typical’ or enhanced star formation for our enriching subsample, and the low-SFR, low-$Z_{\text{cold}}$ tail of the distribution for our diluting subsample (see dashed red and black lines in the bottom panel of Fig. 2). Small changes in these selection criteria do not affect any of our results. For example, increasing the upper $Z_{\text{cold}}$ limit for the diluting subsample to 9.0 increases the number of galaxies by more than a factor of two, but does not significantly alter their average properties.

A cleaner sample of diluting galaxies could be selected by only choosing those systems with a negative change in $Z_{\text{cold}}$ over the last few Gyr. 6.6 per cent of the ‘diluting’ sample have undergone a slight net increase in $Z_{\text{cold}}$ since $z = 0.28$, and so can be considered contaminants, or at least early starters in an extended dilution process. Nonetheless, we only select galaxies by their $z = 0$ properties, to provide a fairer comparison with our observational sample. A cleaner selection simply strengthens the dichotomy seen between the enriching and diluting subsamples in the model.

Fig. 4 shows the stellar mass distribution for the model enriching (red) and diluting (black) galaxies. The mean $M_*$ is $\sim 0.25 \, \text{dex}$ higher for the diluting subsample than the enriching subsample. This is because these galaxies tend to live in denser environments and have many more minor mergers (see Section 3.2). However, we note that the local $M_* - Z_g$ relation flattens off above $\log(M_*) \sim 10.5 \, M_{\odot}$ in both observations and our model, so this difference in mean stellar mass does not imply enhanced $Z_{\text{cold}}$ in diluting galaxies.

In fact, these galaxies have been specifically selected to have low sSFR and low-$Z_{\text{cold}}$.

In Fig. 5, we show histograms of the key physical properties of the enriching (red) and diluting (black) galaxies at $z = 0$. We can clearly see that diluting galaxies have lower SFR (panel A), $M_{\text{cold}}/M_*$ (panel B) and $Z_{\text{cold}} - Z_*$ (panel C) than enriching galaxies, as well
Figure 3. Maps of the distribution of a number of properties in the sSFR–$Z_{\text{cold}}$ plane for our full model sample. The property shown is stated at the top of each panel.

As higher $M_{\text{bulge}}/M_*$ (panel D), older ages (panel E) and larger $M_{\text{BH}}$ (panel F). All of these properties reflect the specific evolution that these galaxies have undergone – a gradual dilution of the ISM after a merger-induced starburst that expelled gas via SN feedback and grew the central BH. Secular star formation and subsequent metal enrichment could not be resumed thereafter due to (a) the small amount of remaining cold gas having a density below the threshold required for star formation and (b) the suppression of further cooling by AGN feedback.

In the case of $Z_{\text{cold}} - Z_*$ (panel C), it is more precise to say that enriching galaxies form a tight distribution around $(Z_{\text{cold}} - Z_*) \sim 0.17$, whereas diluting galaxies exhibit a wider distribution, down to low (even negative) values. This parameter is a useful diagnostic for dilution of the ISM after the last bout of star formation, as low values of $Z_{\text{cold}} - Z_*$ indicate a decrease in the gas-phase metallicity without a corresponding decrease in the stellar metallicity (Küppen & Edmunds 1999). Enriching galaxies are undergoing smooth, continuous star formation, and so have reached an equilibrium between their gas and stellar metallicities, whereas diluting galaxies are experiencing dilution of the ISM, at a greater rate than any star formation, for an extended period of time.

We should therefore expect that the value of $Z_{\text{cold}} - Z_*$ in diluting galaxies anticorrelates with the amount of dilution that has taken place. As no secular star formation occurs during dilution in these model galaxies, we can use the mass-weighted age as a weak proxy for the amount of dilution. Fig. 6 demonstrates that older, diluting galaxies have lower $Z_{\text{cold}} - Z_*$ than younger, enriching galaxies, and that those with the lowest $Z_{\text{cold}} - Z_*$ are indeed the oldest. The large spread in $Z_{\text{cold}} - Z_*$ for the oldest ages is due to the majority of the star formation occurring at higher redshifts for all diluting, elliptical galaxies. The mass-weighted age is therefore less sensitive to the amount of low-redshift dilution than $Z_{\text{cold}} - Z_*$. The colour scheme in Fig. 6 shows that, at fixed age, those galaxies with the largest ‘dilution rate’, $R_{\text{dil}}$, tend to have the lowest $Z_{\text{cold}} - Z_*$. We define $R_{\text{dil}}$ as $[Z_{\text{cold}}(t_{\text{dil}}) - Z_{\text{cold}}(0)]/t_{\text{dil}}$, where $t_{\text{dil}}$ is the look back time from $z = 0$ to when the galaxy first started steadily increasing in $M_{\text{cold}}$.

3.2 Dilution in elliptical galaxies

We will now discuss the type of dilution that occurs in our model diluting galaxies. The final panel in Fig. 3 (panel I) shows the net cooling rate of gas, taking into account the suppression from

$\text{dil}$

A similar result is achieved when defining $t_{\text{dil}}$ as the look back time to when a galaxy first started steadily decreasing in $Z_{\text{cold}}$. 

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AGN feedback. The gross cooling rate of hot gas from the CGM is calculated following White & Frenk (1991) as

$$ M_{\text{cool, gross}} = \begin{cases} \frac{r_{\text{cool}}}{r_{\text{vir}}} \frac{M_{\text{hot}}}{t_{\text{dyn}}} & \text{if } r_{\text{cool}} \leq r_{\text{vir}} \\ \frac{M_{\text{hot}}}{t_{\text{dyn}}} & \text{if } r_{\text{cool}} > r_{\text{vir}} \end{cases}, $$

(1)

where $r_{\text{cool}}$ is the radius within which the cooling time-scale is shorter than the dynamical time (which is given by $t_{\text{dyn}} = r_{\text{hot}}/V_{\text{vir}}$)

and $r_{\text{hot}}$ is the radius out to which hot CGM gas extends in the system (this is the virial radius for central galaxies).

The AGN reheating rate is calculated following Croton et al. (2006) as

$$ M_{\text{reheat, AGN}} = \left(0.2 \frac{M_{\text{BH}} c^2}{V_{\text{vir}}^2}\right). $$

(2)
where the rate of accretion on to the central BH, $\dot{M}_{\text{BH}}$, is given by

$$\dot{M}_{\text{BH}} = \kappa \left( \frac{\eta_{\text{cool}}}{0.1} \right) \left( \frac{M_{\text{BH}}}{10^7 M_\odot} \right) \left( \frac{V_{\text{vir}}}{200 \text{ km s}^{-1}} \right)^3$$  \hspace{1cm} (3)

and the hot accretion efficiency is $\kappa = 1.5 \times 10^{-3} M_\odot \text{yr}^{-1}$.

The net accretion rate is therefore

$$\dot{M}_{\text{cool, net}} = \dot{M}_{\text{cool, gross}} - \dot{M}_{\text{heat,BH}}.$$ \hspace{1cm} (4)

For more details, see Guo et al. (2011, Section 3.9).

Panel 1 of Fig. 3 shows us that such ‘diffuse’ cooling is completely shut down in diluting galaxies, due to strong AGN feedback, whereas it is still occurring in enriching galaxies.\(^5\) This indicates that the gradual dilution of diluting galaxies is \textit{not} due to diffuse cooling of CGM gas, contrary to the conclusion made by YKG12. Instead, we have found that this gradual dilution is due to the accretion of low-mass satellites ($\sim$87 per cent by mass) and cold-gas clumps ($\sim$13 per cent by mass), carried-in by merging DM subhaloes. This merger-based accretion is not affected by the radio jets emitting from the central BH, and so can occur despite the presence of AGN feedback.

Cold-gas clumps are loosely defined as the cold gas inside DM subhaloes that \textit{do not} contain stars. These have a mean cold gas mass of $6.8 \times 10^6 M_\odot$ for the environments around our diluting galaxies. All other infalling objects containing gas \textit{and} stars are called merging satellites, which have a mean cold gas mass of $5.4 \times 10^7 M_\odot$. We note that 94 per cent of all the accreted cold gas on to diluting galaxies since $z \sim 0.28$ comes from objects with baryonic masses (i.e. cold gas plus stars) above $1.0 \times 10^7 M_\odot$.

Fig. 7 illustrates the significance of this mode of accretion for diluting galaxies. Panel A shows that diluting galaxies tend to have a larger number of minor progenitors (i.e. mergers) since $z \sim 0.28$ (i.e. over the last $\sim$3.1 Gyr) than enriching galaxies. This means that, although the average cold gas mass of a merging satellite is similar for both classes ($2.4 \times 10^7 M_\odot$ for diluting galaxies and $2.0 \times 10^7 M_\odot$ for enriching galaxies), the total mass of cold gas accreted is greater for diluting galaxies (panel B). Considering that diluting galaxies also have \textit{low} cold gas masses themselves (Fig. 3, panel B), such merger-based accretion can have a significant impact on their cold gas content by $z = 0$. Panel C of Fig. 7 illustrates this by showing the ratio of the total mass in cold gas accreted to the cold gas mass of the main progenitor at $z = 0.28$ (i.e. the gross increase in $M_{\text{cold}}$ due to mergers). For enriching galaxies, the median ratio is $\sim$1.0 per cent, whereas for diluting galaxies, satellites add an additional 113 per cent in cold gas on average. This leads to enriching galaxies undergoing a net \textit{decrease} in $M_{\text{cold}}$ of 11 per cent on average, whereas diluting galaxies undergo a net \textit{increase} in $M_{\text{cold}}$ of 18 per cent on average, over the last 3.1 Gyr.

This accreted gas is more metal poor than the cold gas in the central galaxy (panel D), and therefore causes the significant dilution of the gas phase over time in diluting galaxies. The fact that this gas comes in during many minor merger events means that the dilution is gradual rather than sudden, with a median drop in $Z_{\text{cold}}$ of $\sim$0.045 dex per Gyr since $z = 0.28$ ($\sim$0.052 dex per Gyr for those galaxies that show a consistent decrease in $Z_{\text{cold}}$ since $z = 0.28$). This drop in $Z_{\text{cold}}$ in low-SFR galaxies over time is the cause of the positive correlation between SFR and $Z_{\text{cold}}$ at high mass in the model FMR at $z = 0$.

Another way to illustrate this evolution is to track the change in key galaxy parameters over time (e.g. YKG12, figs 8 and 9). Fig. 8 shows the median $Z_{\text{cold}}$ as a function of look back time (filled circles), for enriching galaxies (red) and diluting galaxies (black). We can see that $Z_{\text{cold}}$ increases with cosmic time for enriching galaxies and decreases with cosmic time for diluting galaxies. Fig. 8 also shows the evolution of the cold gas accretion rate minus SFR. This is a measure of the relative dilution/enrichment of the ISM; positive values indicate a net dilution (from infalling, metal-poor gas) and negative values indicate a net enrichment (from stars). We can see that enriching galaxies always have negative $\Delta M_{\text{cold,prog}} - \text{SFR}_{\text{MP}}$. This is true even when including gas cooled from the CGM in the calculation. Diluting galaxies always have positive $\Delta M_{\text{cold,prog}} - \text{SFR}_{\text{MP}}$. This shows again how these systems are gradually diluting their ISM over time. We note that the increase in $\Delta M_{\text{cold,prog}} - \text{SFR}_{\text{MP}}$ is due to their average decline in SFR over time, reflecting the evolution of the cosmic SFR density (Madau et al. 1996). The low SFRs and fairly constant merger rates...
of diluting galaxies ensure that their $\Delta M_{\text{cold,prog}} - \text{SFR}_{\text{MP}}$ remains fairly constant over time.

It may be surprising that massive, bulge-dominant galaxies are undergoing minor mergers containing cold gas in the model, when the current understanding is that such systems grow in mass and size predominantly through dissipationless, minor mergers (e.g. White 1976; Naab, Johansson & Ostriker 2009). However, both these pictures are consistent with each other, as the median SFR of these diluting galaxies is only $\sim 0.04\, M_\odot\, \text{yr}^{-1}$ since $z \sim 0.28$, with only 0.6 percent of their present-day stellar mass grown from forming new stars since then, on average. The accretion of stars via mergers over the same time is much more significant, contributing an average of 13.6 percent of the total stellar mass at $z = 0$.

Finally, in Fig. 9 we show the ratio between ‘total gas mass cooled’ and ‘total cold mass accreted’ from $z \sim 0.28$ to the present day. Cooling of CGM gas can clearly be a significant mode of obtaining cold gas in enriching galaxies, whereas it is negligible in diluting galaxies due to the presence of AGN feedback. This reflects the fact that accretion of cold gas via satellites and infalling gas clumps is the dominant mechanism for diluting such galaxies in the model.

In conclusion, we can say that there are a number of clear signatures of dilution in some massive galaxies in the semi-analytic model that can be seen at $z = 0$. These include: lower gas-to-stellar mass ratios, older ages, higher bulge-to-total stellar mass ratios, higher central BH masses and lower $Z_{\text{cold}} - Z_\ast$. We have also shown that metal-poor gas is accreted via minor merger events, rather than via diffuse cooling of hot gas from the CGM.

We now turn to the SDSS, to see if such features are also found in massive, low-sSFR, low-$Z_g$ galaxies in the real Universe.

4 THE OBSERVATIONAL SAMPLES

4.1 Main sample

A main sample of local galaxies was selected from the SDSS-DR7, 109 678 of these were obtained following the selection criteria of Tremonti et al. (2004), as outlined in section 2 of YKG12 for their Sample T2. We refer the reader to those works for further details. In brief, galaxies were selected to have r-band fibre-to-total light ratios $> 0.1$ and signal-to-noise ratios (SNR) of SNR([O\,iii]5007) $> 3$. AGN hosts were removed following Kauffmann et al. (2003b) using the Baldwin, Phillips & Terlevich (1981) diagram for galaxies with SNR([O\,iii]5007) $> 3$. For galaxies with SNR([O\,iii]5007) $< 3$, only those with log([N\,ii]6584/H\alpha) $< -0.4$ were retained, in order to remove low-ionization AGN hosts from the sample. Galaxies with a 1r spread $> 0.2$ in the likelihood distribution of the best-fitting value of $M_\ast$ and $Z_g$ from CLOUDY (Ferland et al. 1998) were also removed. Finally, in order to be consistent with the original Tremonti et al. (2004) sample, galaxies were also required to have $\sigma(m_\ast) < 0.15\, \text{sinh}^{-1}(\text{mag})$, $\sigma(H_\beta) < 2.5\, \text{Å}$ and $\sigma(D_{4000}) < 0.1$.

An additional 40 254 galaxies were included for which $\sigma(M_\ast)$ or $\sigma(Z_g) > 0.2$, but that meet all the other requirements described above. The motivation for this is outlined in appendix C of YKG12; these galaxies have a larger uncertainty in their stellar mass, due to errors in the SDSS $u$-band magnitudes which propagate through to the $M_\ast$ estimates. At log($M_\ast$) $\geq 10.5$, these galaxies actually have estimates of $Z_g$ well within the $\sigma(Z_g) < 0.2$ requirement (see fig. C1 of YKG12), and 98 percent also have $\sigma(M_\ast) < 0.3$. We therefore choose to include these galaxies in order to better probe the high-$M_\ast$.  

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6 Available at http://www.mpa-garching.mpg.de/SDSS/DR7
low-$Z$ region of parameter space that we are interested in for this work. This brings our main sample to a total of 149,932 galaxies.

Stellar masses, total SFRs and fibre-based, gas-phase metallicities are provided by the SDSS-DR7 catalogue. $M_*$ was obtained using fits to $ugriz$ SDSS photometry, and have been corrected from a Kroupa (2001) to a Chabrier (2003) IMF. Total SFRs (also corrected to a Chabrier IMF) were corrected for dust using the Cardelli, Clayton & Mathis (1989) extinction law. SFR and $Z_g$ were obtained by fitting galaxy emission-line spectra to a grid of synthetic spectra from CLOUDY photoionization models, as detailed by Charlot & Longhetti (2001), and using the stellar population synthesis models of Bruzual & Charlot (2003). For more information, see Brinchmann et al. (2004) and Tremonti et al. (2004). We note here that all our conclusions also hold when using a simpler, strong-line-ratio-based metallicity diagnostic (see Section 5).

Fig. 10 shows the normalized $M_*$, SFR, $Z_g$ and $z$ distributions of our Main observational sample (grey). There are fewer low-$M_*$ and low-SFR galaxies than in our model sample (Fig. 1). This is because such galaxies can be ‘lost’ due to low luminosity or low SNR on the optical emission lines used for selection. This is not a significant issue in this work, as we focus on galaxies with $\log(M_*) \geq 10.5$ M$_\odot$.

The number density distribution of the whole Main sample is shown in the top panel of Fig. 11. In the bottom panel, the distribution for galaxies with $\log(M_*) \geq 10.5$ is shown (see Section 5.1).

4.2 H\textsubscript{i}-detected sample

In order to assess the significance of gas fraction on the $M_*–$SFR–$Z$ relation, we formed a subsample containing those galaxies with direct detections of H\textsubscript{i} gas. There is an increasing amount of data available on the H\textsubscript{i} and H\textsubscript{2} content of nearby massive galaxies, thanks to surveys such as ALFALFA (Giovanelli et al. 2005), GASS (Catinella et al. 2010) and COLD GASS (Saintonge et al. 2011). Also, scaling relations that provide an estimate of the gas fraction from other observable properties (e.g. Zhang et al. 2009; Catinella et al. 2012; Li et al. 2012) allow an analysis of the expected H\textsubscript{i} content for a much larger sample of galaxies (see Section 4.5).

3123 galaxies were found by cross-matching our main sample with the ALFALFA-$\alpha$.40 sample (Haynes et al. 2011).\footnote{Available at http://egg.astro.cornell.edu/alfalfa} ALFALFA is a blind survey, detecting H\textsubscript{i} via the 21 cm line within the footprint of the SDSS. In order to match to our main sample,
we (a) removed all ALFALFA objects with a heliocentric velocity ($v_{\text{helio}}$) < 3000 km s$^{-1}$. These are either high-velocity clouds within the Milky Way or galaxies for which redshifts cannot be accurately determined, b) removed all other ALFALFA objects which do not have the O/C code = 1 flag. These are H I regions not associated with galaxies and c) cross-matched the right ascension (ra), declination (dec) and redshift (z) of our main sample with the remaining ALFALFA objects, allowing for maximum errors of $\sigma(\text{ra, dec}) = 10$ arcsec and $\sigma(z) = 0.0003$.

The same maximum errors on ra, dec and z were used to obtain 38 cross-matched galaxies from the GASS-DR1/DR2 samples (Catinella et al. 2012b, hereafter C12). GASS is a targeted survey of $\sim$1000 known SDSS galaxies (232 of which have direct H I detections) of $M_r > 10^{10} M_\odot$, so no removal of intragalactic objects is required. Only galaxies with quality $Q = 1$ were retained. Right ascensions and declinations were obtained from the GASS data by decomposing the associated SDSS IDs (see Appendix A for details). Of these 38 galaxies, 9 are also found in our ALFALFA subsample. For these galaxies, we take the $M_{HI}$ measurements obtained by GASS.

After cross-matching with these surveys, a total of 3161 unique galaxies (2.11 per cent of our main sample) with direct $M_{HI}$ measurements were obtained. The normalized $M_*, SFR, Z_*$ and $z$ distributions for the ALFALFA subsample (black) and GASS subsample (green) are shown in Fig. 10, alongside the Main observational sample (grey).

### 4.3 Z_*$ sample

We also draw a subsample of galaxies for which stellar metallicities ($Z_*$) have been measured for the SDSS-DR4 (Gallazzi et al. 2005). These galaxies were obtained using the same cross-matching requirements described in Section 4.2. We use this subsample to obtain values of $Z_g - Z_*$. As mentioned in Section 3, low-$Z_g$ relative to $Z_*$ is indicative of dilution of the ISM by metal-poor infall after the last star formation event.

We convert $Z_g$ from the SDSS-DR4 catalogue into units of 12 + log(O/H) as follows: $Z_g \text{ [}\odot\text{]} = \log(0.0134) + 8.69$, where 0.0134 and 8.69 are the solar metallicity and oxygen abundance as determined by Asplund et al. (2009), respectively. We note that alternative conversions using different solar values would only shift the amplitude of $Z_g - Z_*$, and would not affect the relative values of this parameter for the two classes of massive galaxy considered in this work (see Section 5.1).

Gallazzi et al. (2005) point out that their stellar metallicity estimates are only reliably constrained for galaxies with an SNR per pixel of $\sim 20$ or higher. Introducing such a cut reduces our $Z_*$ sample by 84 per cent (although it also strengthens slightly the dichotomy in $Z_g - Z_*$ for our two high-mass subsamples, see Section 5). Therefore, we instead choose a slightly weaker cut, selecting only those galaxies with an SNR per pixel of 14.8 (the mean value for the whole SDSS-DR4). Doing so reduces the $Z_*$ sample by only 59 per cent, to 24 275 galaxies, and produces very similar results to a sample using SNR per pixel $\geq 20$.

#### 4.4 NUV – r sample

In order to obtain $M_{HI}/M_*$ estimates via the H I scaling relation derived by C12 (see Section 4.5), we select 1529 brightest cluster galaxies (BCGs) for which NUV – r colours have been measured by Wang et al. (2010) (kindly provided by Wang, private communication). An additional 1662 galaxies were obtained by cross-matching our Main sample with the Galaxy Evolution Explorer (GALEX) GR6 catalogue, matching objects by position and allowing for $\sigma(\text{ra, dec}) \leq 1$ arcsec. Further 418 galaxies were obtained in the same way, by cross-matching our Main sample with the GALEX photometric data for objects in the Lockman Hole and Spitzer First Look Survey (FLS). These data were compiled for the Galaxy Multi-wavelength Atlas from Combined Surveys (GMACS) catalogue by Johnson et al. (2007a,b). The total number of galaxies in our NUV – r sample comes to 3609.

#### 4.5 H I scaling relations

As our H I-detected sample is only a small fraction (2.1 per cent) of our Main sample, we also utilize the H I scaling relation formulated by Zhang et al. (2009, hereafter Z09) to get $M_{HI}$ estimates for all our galaxies. Z09 derived a mean relation between $M_{HI}/M_*, sSFR$, and stellar surface brightness ($\mu_*$) for 800 SDSS-DR4 galaxies cross-matched with the HyperLeda H I catalogue (Paturel et al. 2003). Their relation is given by

$$\log(M_{HI}/M_*) = -0.77 \log(\mu_*) + 0.26 \log(sSFR) + 8.53,$$

where $\log(\mu_*) = \log(M_*/2\pi R_{25}^2)$ and $R_{25,i}$ is the Petrosian i-band half-light radius (in arcsec). All the properties required to estimate the gas-to-stellar-mass ratio from equation (5) are drawn from the SDSS-DR7 catalogue. Z09 also discuss the significance of gas fraction on the $M_*/Z_*$ relation, and we compare our results to theirs in Section 6.3.

We first check that the Z09 scaling relation provides reasonable $M_{HI}/M_*$ estimates for galaxies with direct H I detections from ALFALFA or GASS. This comparison is shown in the top panel of Fig. 12. We can see that, in general, the agreement is good, although the scatter is large. However, in detail, the Z09 scaling relation seems to predict larger $M_{HI}/M_*$ than is measured by GASS (squares).

The GASS survey was specifically designed to observe galaxies until either an H I detection is made or a gas fraction limit of 0.015 is determined (see C12). This allows detections down to much lower H I masses than is possible by ALFALFA, which has an exposure time per galaxy of around a factor of 10 smaller than GASS.

We check if the disparity at low $M_{HI}/M_*$ is specific to the Z09 scaling relation by also comparing direct H I measurements to the $M_{HI}/M_*$ estimates obtained from the C12 scaling relation. This relation is calibrated using GASS galaxies and uses NUV – r colour rather than sSFR derived from optical emission lines. Catinella et al. (2010) and C12 found that massive, H I-detected galaxies form a flat, 2D plane in the $(M_{HI}/M_*)-\mu_*(NUV - r)$ parameter space, which can be well described by

$$\log(M_{HI}/M_*) = -0.338 \log(\mu_*) - 0.235 (NUV - r) + 2.908.$$
This comparison is shown in the bottom panel of Fig. 12 for 228 galaxies from our NUV – r sample that also have direct H i measurements. The C12 relation seems to provide a similar range of $M_{\text{HI}}/M_*$ estimates as the Z09 relation (grey points) for high-$Z_g$ galaxies. This suggests that the larger scatter found at low $M_{\text{HI}}/M_*$ is intrinsic to the difficulty in obtaining good 21 cm measurements for galaxies of such low gas fraction. We will show in Section 5 that both the direct $M_{\text{HI}}/M_*$ estimates and the two scaling relations described here indicate larger gas fractions in enriching galaxies than in diluting galaxies.

We also note that the C12 relation seems to underestimate the gas-to-stellar-mass ratio for low-$Z_g$ high-$M_{\text{HI}}/M_*$ galaxies, compared to direct measurements (green and yellow points in the bottom panel of Fig. 12). Li et al. (2012) have shown that estimators which do not take account of colour gradients in galaxies can underestimate $M_{\text{HI}}/M_*$ in such gas-rich systems. They propose a new estimator, which includes the $g - i$ colour gradient ($\Delta_{g-i}$) to account for this effect. However, such a correction is not required in this work, as we choose to focus on galaxies with relatively high-$Z_g$ and low-$M_{\text{HI}}/M_*$.

### 5 OBSERVATIONAL RESULTS

Fig. 13 shows ‘maps’ of the observational samples in the sSFR–$Z_g$ plane, in the same way as done for the model sample in Fig. 3. Galaxies are again binned by sSFR and $Z_g$, and only bins containing 10 or more galaxies are plotted. For this figure, each galaxy is weighted by $1/V_{\text{max}}$, the inverse of the maximum volume within which a galaxy of that r-band magnitude could be observed by the SDSS. This gives a greater weighting to faint, low-mass galaxies, to account for Malmquist bias.

The first thing we note when comparing Figs 3 and 13 is the different regions of parameter space covered. For example, the median sSFR for the model sample (sSFR = $10^{-10.2}$) is lower than that of the observational sample (sSFR = $10^{-9.82}$). This is because galaxies, particularly those with low $M_*$, tend to form stars too efficiently at high-$z$ in the semi-analytic model. This means that lower SFRs are required at low-$z$ in order to fit the $z = 0$ stellar mass function (e.g. Guo et al. 2011). Henriques et al. (2013) have since addressed this problem, by allowing material ejected from model galaxies to return to the ISM over longer periods of time, increasing their SFRs at low-$z$ (see their fig. 9).

Also, there is a greater fraction of low-sSFR galaxies in the model sample than in the observational sample. This is likely due to the difficulty in obtaining SFR, metallicity and gas mass estimates for such galaxies in the real Universe, which will have intrinsically weaker emission-line strengths, with lower SNR. Galaxies in this region of parameter space may also host AGN, as we believe them to be post-merger systems with large BHs (according to their model analogues), and so may have been removed via the AGN cut.

Nonetheless, clear similarities can still be seen between the model and observational samples. Fig. 13 shows that low-mass galaxies have lower SFRs (panel B), lower H i masses (estimated via the 21 cm line measurements of ALFALFA and GASS, panel C), higher gas-to-stellar-mass ratios (using both the Z09 scaling relation, panel D, and direct estimates, panel I), lower metallicity differences (panel E), larger concentration indices (measured as the ratio of radius containing 90 per cent of the Petrosian r-band light to the half-light radius, panel F), younger ages (inferring from the time since the last starburst via $D_\gamma$, panel G) and lower mass central BHs [inferred from velocity dispersions via the Graham et al. (2011) combined $M_{\text{BH}} - \sigma$ relation, panel H]. All of these trends are also found in our semi-analytic model, L-GALAXIES (see Fig. 3).

We have also checked the stability of our results to changes in the selection criteria. When increasing the minimum SNR(Hz, Hβ, [N ii]) to 10, the low-sSFR edge of the galaxy population is ‘trimmed’ slightly, increasing the median SFR of the whole Main sample by $\sim 0.02$ dex. Conversely, decreasing the maximum redshift to 0.1 removes some high-sSFR galaxies, decreasing the median SFR of the whole Main sample by $\sim 0.18$ dex. Finally, increasing the minimum fibre-to-total light ratio to 0.35 mainly removes low-redshift galaxies, as these tend to have larger apparent sizes, and reduces the Main sample to 32 550 objects. Despite these changes to the size and extremities of the galaxy population, the general trends described above are all unaffected by such changes to the selection criteria. The main conclusions for our high-$M_*$ subsamples are also robust to these changes (see Section 5.1).

### 5.1 Two classes of massive galaxy in the SDSS

When focusing on massive galaxies, we have again selected two subsamples of galaxies with $M_*$  $\geq 10^{10.5}M_\odot$. The first contains 28 681 galaxies with log(sSFR)  $\geq -10.7$ yr$^{-1}$ and $Z_{\text{cold}}$ $\geq 8.85$. 
The second contains 136 galaxies with log(sSFR) ≤ −11.0 yr\(^{-1}\) and \(Z_{\text{cold}} \leq 8.85\). These two regions are marked-out by the red and black dashed lines in the bottom panel of Fig. 11, respectively. To mimic the terminology used for the model sample, we also refer to these as enriching and diluting galaxies. However, we emphasize that it is not a foregone conclusion that these galaxies are the direct analogues of those in our model, and that it is the purpose of this paper to determine whether this could be the case.

As with the model subsamples, we have attempted to select massive galaxies with ‘typical’ or enhanced star formation for our enriching subsample (i.e. systems on or above the main sequence of star-forming galaxies; e.g. Elbaz et al. 2011), and the low-SFR, low-metallicity tail of the distribution for our diluting subsample. In the case of the observational sample, this low-SFR, low-\(Z_g\) tail is less extended due to removal of galaxies with low SNR or which host AGN. Therefore, we have chosen a higher upper limit on sSFR for observed diluting galaxies than in the model sample, in order to recover a statistically significant number of galaxies. All the other limits chosen are the same as used in our model, and that it is the purpose of this paper to determine whether this could be the case.

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Fig. 14 shows the stellar mass distribution for the observational enriching (red) and diluting (black) subsamples. There is little difference between the distributions for these two subsamples, meaning that there is no intrinsic mass dependence affecting the results. We have also checked that the diluting galaxies do not exhibit excess star formation in their central regions relative to enriching galaxies from light reprocessed by dust, by comparing their magnitudes around 12 and 22 \(\mu\)m from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010).

The key finding of this work is that all the signatures of post-merger dilution seen in the semi-analytic model at \(z = 0\) are also found in our SDSS sample. Fig. 15 shows that real, ‘diluting’ galaxies have lower SFR (panel A), \(M_{\text{HI}}/M_*\) (panel B) and \(Z_g - Z_*\) (panel C) than enriching galaxies, as well as larger \(R_{90}/R_{50}\) (panel D), older ages (panel E) and larger \(M_{\text{BH}}\) (panel F). A comparison of the statistical properties of diluting and enriching galaxies between the model and observations is also provided in Table 1.

It should be noted here that considering the absolute values of \(Z_g - Z_*\) in the semi-analytic model and observations should be treated with caution, as they are sensitive to the set of solar
abundances assumed and $Z_g$ diagnostic chosen. However, the fact that diluting galaxies typically have lower $Z_g - Z_*$ relative to enriching galaxies in both the model and observations is a significant result. Also, the fact that both enriching and diluting galaxies in the SDSS have similar median $M_*$ and $Z_*$ (see Table 1) supports the dilution scenario interpretation.

The red, purple and maroon histograms in panel B of Fig. 15 represent the $M_{HI}/M_*$ distribution for massive, enriching galaxies from the main sample (using the $Z09$ scaling relation), the $NUV-r$ sample (using the $C12$ scaling relation) and H$\text{I}$-detected sample (using ALFALFA and GASS measurements), respectively. It is encouraging that all three methods for estimating $M_{HI}$ show that enriching galaxies have higher gas fractions than diluting galaxies.

We emphasize here that, although it is not surprising to see low-SFR, massive galaxies with low gas fractions, high concentrations and older ages, it is surprising that such galaxies also have low-$Z_g$ and low ($Z_g - Z_*$). This suggests that these galaxies could be undergoing dilution similar to that seen in some massive galaxies in our semi-analytic model.

Changes to the selection criteria for the whole Main sample do not affect the conclusions drawn for these two classes of massive galaxy. More stringent cuts simply decrease the sample sizes. For example, increasing the minimum SNR for the H$\alpha$, H$\beta$ and [N II] lines to 10 removes low-sSFR galaxies, and therefore decreases the size of the diluting subsample by $\sim 65$ per cent. Lowering the maximum redshift to 0.1 removes some high-SFR galaxies, therefore reducing the enriching subsample size by $\sim 66$ per cent. Increasing the minimum fibre-to-total light ratio to 0.35 also reduces the diluting subsample by $\sim 69$ per cent. However, the dichotomy seen between the two subsamples remains strong despite such changes.

Importantly, all the trends described above also hold when using the strong-line-ratio-based metallicities of Mannucci et al. (2010), even though this method predicts higher metallicities for galaxies below $Z_g \sim 9.1$ than the Bayesian method (see YKG12, Section 4.1). For example, the mean value of the $M_{HI}/M_*$ for diluting galaxies when selecting by this strong-line-ratio-based metallicity is $\log(M_{HI}/M_*)_{Z09} = -1.7$. This is still 0.51 dex lower than the mean value for enriching galaxies using the same selection criteria. Also, the difference in mean $Z_g - Z_*$ between diluting and enriching galaxies when using the strong-line diagnostic to obtain $Z_g$ is still 0.45 dex. We therefore consider the relative properties of enriching and diluting galaxies to be robust to the metallicity diagnostic chosen.

Fig. 16 shows the relation between $D_{n4000}$ and $Z_g - Z_*$ for massive galaxies in our observational $Z_*$ sample, noting that $D_{n4000}$ measures the time since the last bout of star formation (see e.g. Kauffmann et al. 2003a). This relation can be compared to Fig. 6.
for the model. Although the number of observed diluting galaxies (black points) with reliable stellar metallicities is relatively small (43 galaxies), there is still a clear trend present – diluting galaxies are typically older and have lower \(Z_g-Z_e\) than enriching galaxies, and the maximum \(Z_g-Z_e\) decreases with \(D_{4000}\).

It is also interesting to note that many of the diluting galaxies in our observational sample have early-type morphologies. From visual inspection of the SDSS-DR7 optical thumbnail images alone, \(\sim 62\) per cent appear to be elliptical in shape and lack significant blue emission. This is supported by the higher average concentration index in the diluting subsample (Fig. 15, panel D), and reflects the large bulge-to-total stellar mass ratios seen for diluting galaxies in our model (Fig. 3, panel E). Around 18 per cent of the observational subsample appears to be edge-on disc galaxies. These are likely assigned low SFRs and low gas-phase metallicities due to their greater optical thickness, which reduces the amount of emission observed from their galactic centres. A further \(\sim 18\) per cent of the diluting galaxies are either currently interacting or of uncertain morphology. Only the final \(\sim 2\) per cent is made up of objects that appear to be nearly face-on disc galaxies with some blue emission. We note, of course, that by-eye classification using only low-resolution optical images can only give a rough indication of the typical morphologies for a sample of nearby galaxies.

Fig. 17 shows optical images of four representative galaxies in the diluting subsample, along with their SDSS spectra. Although most emission lines are not particularly strong, \([\text{N} \text{ii}]\) and \(\text{H} \alpha\) are well detected in all four spectra and could be dominating the metallicity estimates. To test the significance of the \([\text{N} \text{ii}]\lambda 6584\) line, our analysis was re-run using Bayesian metallicity estimates that do not require \([\text{N} \text{ii}]\) (or \([\text{S} \text{ii}]\)) in the fit. Although this does lower the \(Z_g\) estimate for some massive galaxies, it does not affect the relative median \(Z_g-Z_e\) values between the diluting and enriching subsamples. YKG12 have also shown that removing \([\text{N} \text{ii}]\) from the estimation does not affect the positive correlation between SFR and \(Z_g\) at high \(M_*\). We also note that the majority of galaxies exhibiting low-ionization nuclear emission-line regions (LINERs) have already been removed from our sample via the AGN cut described in Section 4.1. The \([\text{N} \text{ii}]\)/\(\text{H} \alpha\) ratio would not provide an accurate estimate of the host galaxy’s \(Z_g\) in such systems.

Table 1. The minimum, median and maximum values of the properties analysed for diluting and enriching galaxies from our model sample and Main\(Z_e\) observational samples.

|                  | Diluting galaxies | Observations | Enriching galaxies | Observations |
|------------------|-------------------|--------------|--------------------|--------------|
|                  | 318 galaxies      | 136 galaxies | 2160 galaxies      | 28 681 galaxies |
| \(\log(sSFR)\) (yr\(^{-1}\)) | 0.00 0.05 0.17 | 0.00 0.12 0.17 | 0.00 0.12 0.17 | 0.00 0.27 0.33 |
| \(Z_g\)          | 8.10 8.74 8.85   | 8.28 8.69 8.84 | 8.84 8.85 9.13   | 8.85 9.08 9.40 |
| \(Z_e\)          | 8.66 8.79 8.98   | 7.77 8.94 9.24 | 8.66 9.29 10.17  | 8.83 9.26 12.0 |
| \(\log(M_*)\) (M\(_\odot\)) | 0.00 0.015 0.063 | 0.00 0.021 0.245 | 0.00 0.03 0.26  | 0.00 0.067 1.1 |
| SFR (M\(_\odot\) yr\(^{-1}\)) | 0.0 0.021 0.17 | 0.03 0.33 6.22 | 0.65 3.8 52.9 | 0.66 6.1 276.0 |
| \(z\)            | 7.7 9.1 9.9     | 0.022 0.087 0.195 | 0.017 0.119 0.250 |
| \(\log(M_{\text{cold}})\) (M\(_\odot\)) | 0.16 1.0 1.0 | 0.0 15.0 73.0 | 0.0 15.0 73.0 |
| \(M_{\text{H}I}/M_*\) | 7.5 11.0 12.3 | 3.6 7.2 12.0 | 3.6 7.2 12.0 |
| \(D_{4000}\)     | 6.5 8.2 9.1 | 1.0 7.8 11.9 5.7 6.9 8.9 | 1.0 6.8 11.9 |
| \(\log(M_{\text{H}I})\) (M\(_\odot\)) | 0.0 0.17 1.7 | 0.0 15.0 73.0 | 0.0 15.0 73.0 |

\(^{a}\)For the observational data, only the 43 diluting galaxies and 7,475 enriching galaxies present in the \(Z_e\) sample are considered. \(Z_e\) is converted into units of \(12 + \log(O/H)\) using solar metallicity and oxygen abundance values from Asplund et al. (2009) accordingly: \(Z_g - \log(0.0134) + 8.69\).

\(^{b}\)Using the H\(_I\)-to-stellar mass fractions obtained via the \(Z09\) scaling relation (equation 5) for the observational sample, and using \(M_{\text{cold}}/M_*\) for the model sample.

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**Figure 16.** The relation between \(D_{4000}\) (a proxy for time since the last starburst) and \(Z_g-Z_e\) for our observational \(Z_e\) sample. Red points represent the median \(Z_g-Z_e\) in bins of \(D_{4000}\) for the enriching galaxies. Error bars indicate the 16th and 84th percentiles. Black points represent individual diluting galaxies. The oldest diluting galaxies have lower values of \(Z_g-Z_e\) than the youngest diluting galaxies, indicating dilution of the gas phase after a bout of star formation.

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\(^{13}\)Images and spectra obtained from [http://cas.sdss.org/astrodr7/en/tools/chart/list.asp](http://cas.sdss.org/astrodr7/en/tools/chart/list.asp)
Figure 17. Four example objects from our SDSS-DR7 subsample of diluting galaxies. Thumbnail images and optical spectra are shown for two elliptical galaxies, an edge-on disc and an interacting system.
When removing all galaxies with disc-like morphologies from the diluting subsample, a slight decrease in the average SFR, $M_{BH}/M_*$, and $Z_{\text{r}}-Z_*$, along with a slight increase in $R_{\text{HI}}/R_{\text{SFR}}$, $D_{4000}$ and $M_{BH}$ is seen, as would be expected. For example, the median $Z_{\text{r}}-Z_*$ drops by 0.006 dex, the median $D_{4000}$ rises by 0.02 and the median $M_{BH}$ rises by 0.27 dex.

To conclude this section, we can say that all the signatures of post-merger dilution seen in our model sample are also found in low-SFR, low-$Z_*$, massive galaxies in the SDSS. This is strong, indirect evidence for claiming that real, elliptical galaxies have also undergone a gradual dilution of their gas phase, after the truncation of continuous star formation following a merger-induced starburst. However, direct measurements of metal-poor gas infall on to these galaxies have not yet been made, and so further observational studies are required to confirm or deny the conclusions drawn from this work.

6 COMPARISONS TO OTHER WORKS

6.1 Accretion on to elliptical galaxies

There is already a class of spheroidal galaxy identified as possibly undergoing accretion of metal-poor gas, known as polar ring galaxies (PRGs; Schweizer, Whitmore & Rubin 1983). PRGs tend to exhibit extended rings or discs of H I gas, dust and sometimes young stars, lying perpendicularly to the equatorial plane of the central spheroid, with the kinematics of the two components decoupled (Whitmore et al. 1990). One explanation for the formation of the rings is the latter accretion of cold gas, which is either stripped from nearby or merged satellites (e.g. Reshetnikov & Sotnikova 1997; Bournaud & Combes 2003; Hancock et al. 2009), or accreted from cosmic filaments (e.g. Macciò, Moore & Stadel 2006; Spavone et al. 2010; Spavone & Iodice 2013). However, a scenario where a major, gas-rich merger forms both the central spheroid and the outer polar ring together is also possible (e.g. Bekki 1998; Iodice et al. 2002a).

Moiseev et al. (2011) have recently compiled the Sloan-based Polar Ring Catalogue (SPRC) of 275 nearby PRGs also observed by the SDSS. We find that 61 of these PRGs are also present in our Main observational sample, 20 of which have $M_*>10^9$. Of these 20 massive PRGs, only 2 are present in our diluting subsample: SPRC-37 and SPRC-183. The first has $\log(\text{sSFR}) = -11.7\text{yr}^{-1}$ and $Z_{\text{r}} = 8.5$, and the second has $\log(\text{sSFR}) = -11.57\text{yr}^{-1}$ and $Z_{\text{r}} = 8.5$.

Interestingly, these two systems have the first and third oldest ages of all the PRGs in our Main sample, with $D_{4000} = 1.79$ and 1.67, respectively (the median value for the diluting subsample is 1.64). In addition, they also have the first and third lowest metallicity differences, with $Z_{\text{r}}-Z_* = -0.13$ and $-0.52$, respectively (the median value for the diluting subsample is $-0.19$). This could be an indication that metal-poor gas is gradually accreted on to such systems over time, again supporting the dilution scenario described in this work.

We note that, for the 20 massive PRGs in our Main sample, the median $r$-band covering fraction is 0.24 (where the median for all galaxies with $\log M_* > 10.5$ is 0.25). This means that some of the metal-poor gas in the outer polar rings may not fall within the 3 arcsec SDSS fibre. Therefore, these objects may have even lower overall $Z_*$ than is observed.

The fact that only two of our observed diluting galaxies are confirmed as PRGs in the SPRC suggests that this is not the main mechanism by which elliptical galaxies accrete metal-poor gas. Indeed, the presence of an AGN, which is often the case for our model diluting subsample, would likely preclude the accretion and cooling of gas from filaments (although not necessarily from satellite stripping or mergers).

Russell et al. (2013) have recently suggested that the BCG of Abell 1664, which hosts an AGN, could be undergoing inflow of two molecular gas clumps, which could settle into a disc over several hundreds of Myr (although, they also point out that this material could be part of an outflow, driven by AGN feedback). Such a mode of accretion is much more common for diluting galaxies in our semi-analytic model than smooth infall and cooling from the intergalactic medium (see Fig. 9). The advent of the Atacama Large Millimeter Array survey should hopefully facilitate many more observations of infalling molecular gas on to massive ellipticals in the future.

Similarly, Husemann et al. (2011) have found a massive ($M_{\text{bulge}} \lesssim 3.4 \times 10^{10} M_\odot$) host galaxy of a quasi-stellar object (QSO) at $z \sim 0.2$ with a large BH ($M_{BH} \sim 3 \times 10^9 M_\odot$) and very low gas-phase metallicity ($Z_0 \lesssim 8.4$). The low metallicity in this system is believed to be due to dilution, either from accretion of metal-poor gas stripped from satellites or smooth accretion from the ambient gas reservoir. Husemann et al. (2012) have further found that bulge-dominated, QSO-host galaxies typically have lower $Z_*$ than their disc-dominated counterparts, and that both have lower $Z_*$ than ‘non-active’ star-forming galaxies of the same mass [although Stern & Laor (2013) suggest that $Z_*$ can be underestimated in active galaxies]. These low-$Z_*$ objects are quite distinct from the majority of massive AGN hosts which have supersolar $Z_*$ (e.g. Hamann & Ferland 1993; Groes, Heckman & Kauflmann 2006), but they do exhibit properties seen in diluting galaxies in our semi-analytic model.

6.2 Interacting galaxies

Around $\sim 8$ per cent of the massive, ‘diluting’ galaxies in our observational sample appear, from their SDSS images, to be interacting. Kewley et al. (2010) have shown that four close pairs of galaxies in the local Universe have lower-than-expected central $Z_*$, likely due to rapid migration of metal-poor gas from larger radii into the centres of each galaxy during the interaction (see also Kewley, Geller & Barton 2006; Rupke, Veilleux & Baker 2008). Such a process is most effective when the interacting galaxies are of similar mass (Woods, Geller & Barton 2006; Ellison et al. 2008a; Michel-Dansac et al. 2008). Montouri et al. (2010) and Torrey et al. (2012) have also shown that this process occurs in their smoothed particle hydrodynamics simulations of equal-mass, interacting, disc galaxies.

One of the close pairs investigated by Kewley et al. (2010) is also present in our main observational sample, comprising NGC 3994 and NGC 3995. We find that, although these two galaxies have relatively low central $Z_*$ (9.01 and 8.67, respectively), they also have high $\log(\text{sSFR})$ ($\sim 8.28$ and $\sim 8.41\text{yr}^{-1}$), high $M_{BH}/M_*$ (2.55 and 1.40), and young ages ($D_{4000} = 1.16$ and 1.01). High SFRs were also found for the majority of the 42 low-$Z_*$ interacting SDSS galaxies studied by Peeples, Pogge & Staneck (2009). These properties are to be expected for galaxies with metal-poor gas flowing into the central regions inducing a nuclear starburst. However, they are not found in any of the small number of interacting systems in our diluting subsample. Such a sudden dilution of the ISM is therefore unlikely to be the sole cause of low-$Z_*$ in massive galaxies with disturbed morphologies.

It could be that the interacting galaxies studied by Kewley et al. (2010) are in an initial phase of the evolution seen in our model, and will undergo a gradual dilution in the future. However, the simulations of Montouri et al. (2010) and Torrey et al. (2012), as
well as L-GALAXIES, show that $Z_{\text{cold}}$ increases again shortly after a merger event, due to metal enrichment from the first SNe following the starburst. Therefore, any dilution after this time would not be due to the initial interaction, and would have to occur through a second process (such as accretion), in the absence of strong star formation.

6.3 The relation between $M_*$, $Z_g$ and $M_{\text{HI}}$

As mentioned in Section 4.5, Z09 also studied the dependence of the $M_*$–$Z_g$ relation on $\text{H}_\text{I}$ gas mass fraction. They found that, at fixed $M_*$, metal-rich galaxies have lower gas fractions than metal-poor galaxies. This may seem to contradict the findings in this work at high mass. However, these two results are compatible with each other due to the difference in the sample selection; Z09 selected galaxies with log(sSFR) $\geq$ 11.0 yr$^{-1}$, meaning that none of the diluting galaxies in either our observational or model analysis meet the same criterion.

When we also select a sample of massive galaxies with log(sSFR) $\geq$ 11.0 yr$^{-1}$, we recover similar trends to those found by Z09, for both our observational and model samples. It is the particular class of low-sSFR galaxies – that is not present in the Z09 sample – which deviate from these trends by having low-$Z_g$ and low gas fractions at $z = 0$.

The case is similar when comparing our results to those of Hughes et al. (2013) and Bothwell et al. (2013), who have also observed an anticorrelation between gas fraction and gas-phase metallicity. Hughes et al. (2013) selected galaxies with log(sSFR) $\geq$ 10.9 yr$^{-1}$, which also excludes all the diluting galaxies analysed in this work. Likewise, Bothwell et al. (2013) only selected galaxies from the ALFALFA survey, of which we find only two in our diluting subsample.

The hydrodynamical simulations of Duffy et al. (2012) and Davel et al. (2013) also report an anticorrelation at high mass. In both cases, AGN feedback is modelled, although for Davel et al. (2013) this is not directly tied to BH growth. Again, only a comparison with galaxies from the ALFALFA and GASS surveys is made, so the low-sSFR, gas-poor ellipticals in our diluting subsample are not considered. These results, together with those discussed in this work, point to the fact that such massive, elliptical galaxies do not behave like 'typical', secularly evolving disc galaxies on the main sequence, because their infall and SFRs have not been in equilibrium for a number of Gyr.

Pleasingly, our findings do support the cartoon model described by Lara-López et al. (2013). In that work, it was postulated that massive, low-sSFR, low-$Z_g$ galaxies should have low gas fractions. Our results, using a wide range of observational data and our galaxy formation model, show that this is indeed the case. We further argue that the cause of this trend is a gradual dilution of the gas phase after a merger-induced starburst.

6.4 The FMR at $z = 0$

The FMR at $z = 0$ is an important tool for understanding galaxy evolution. In this work, we have compared various physical properties of two classes of massive galaxy in the SDSS-DR7 and Munich semi-analytic model of galaxy formation, L-GALAXIES. These two classes are selected by their sSFRs and gas-phase metallicities; low-sSFR, high-$Z_g$ systems are labelled as ‘enriching’ galaxies and low-sSFR, low-$Z_g$ systems are labelled as ‘diluting’ galaxies. The following results were obtained from this comparison.

(i) Diluting galaxies in the semi-analytic model have higher bulge-to-total mass ratios, mass-weighted ages and central BH masses than model enriching galaxies at $z = 0$, and lower cold gas masses, gas-to-stellar mass ratios, and differences between their gas-phase and stellar metallicities.

(ii) These properties are all signatures of the specific evolution undergone by such galaxies – a gas-rich merger and subsequent starburst, followed by a cessation in secular star formation. A gradual dilution of the gas phase then takes place for up to several Gyr, via the accretion of metal-poor, cold gas in clumps and low-mass merging satellites. This gradual dilution drives the positive correlation between SFR and $Z_{\text{cold}}$ seen in massive galaxies at $z = 0$ in the model.

(iii) All the signatures of the evolution described above are also seen in low-sSFR, low-$Z_g$, massive galaxies in the SDSS-DR7. Of particular note are their elliptical morphologies, low gas fractions and low $Z_g - Z_*$, which suggest dilution of the gas phase in the absence of star formation. This is strong, indirect evidence that gradual dilution after a gas-rich merger event is taking place in elliptical galaxies in the local Universe.

(iv) These results suggest an alternative mechanism by which galaxies can fall off the $M_* - Z_g$ relation to lower metallicities. In this scenario, galaxies remain at low-$Z_g$ for a longer period than possible via rapid dilution (and re-enrichment) during mergers and interactions.

(v) The positive correlation found between SFR and $Z_g$ in the local Universe shows that current formulations of the FMR (which assume a weak anticorrelation between SFR and $Z_g$ at high mass) do not accurately represent the whole galaxy population.

We close by highlighting some important limitations of the observational analysis in this work. First, the gas-phase metallicities used are measured from light falling within the 3 arcsec aperture...
of the SDSS fibres. This covers the inner ~1 to 9 kpc of galaxies in our Main sample. Gas lying at larger radii will therefore not be included in the metallicity estimates.

Secondly, a significant amount of high-\(M_\star\), low-\(Z_g\) galaxies are missing from our observational analysis because of poorly constrained estimates of their key physical properties. Future observations of such galaxies’ gas content from near-infrared (IR) absorption lines in the CGM (e.g. Péroux et al. 2013), and gas-phase metallicity from temperature-insensitive emission lines in the far-IR (e.g. Croxall et al. 2013) would greatly help us probe this important part of the galaxy population. Likewise, the wealth of information tapped, due to the contamination of their spectra by emission from other objects (e.g. Russell et al. 2013), or of the molecular gas in and around these objects (e.g. Russell et al. 2013), would open-up these systems for future analysis.

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APPENDIX A: CROSS-MATCHING SDSS AND GASS SAMPLES

In the GASS data, objects are linked to their SDSS counterparts via an SDSS identifier, which is simply the concatenation of the right ascension (ra) and declination (dec) of the object in hexadecimal format, such that, SDSS ID = Jhhmms.ssdxxyy.y. In these IDs, J indicates the use of the J2000 standard equinox, ra = hhmmss.ss in hours, minutes and seconds, and dec = dxxyy.y in days, arcminutes (xx) and arcseconds (yy.y). The + sign before the declination indicates that the object lies in the Northern hemisphere (there are no Southern hemisphere objects in GASS). Once decomposed from the SDSS ID, ra and dec from GASS can be compared to those from any SDSS data release following the straightforward conversion to degrees; ra_{deg} = (360/24) \cdot \left[ hh + \left( mm/60 \right) + \left( ss.ss/3600 \right) \right] and dec_{deg} = dd + \left( xx/60 \right) + \left( yy.y/3600 \right).

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