Galaxy evolution in cosmological simulations with outflows – II. Metallicities and gas fractions

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ABSTRACT

We use cosmological hydrodynamic simulations to investigate how inflows, star formation and outflows govern the gaseous and metal content of galaxies within a hierarchical structure formation context. In our simulations, galaxy metallicities are established by a balance between inflows and outflows as governed by the mass outflow rate, implying that the mass–metallicity relation reflects how the outflow rate varies with stellar mass. Gas content, meanwhile, is set by a competition between inflow into and gas consumption within the interstellar medium, the latter being governed by the star formation law, while the former is impacted by both wind recycling and preventive feedback. Stochastic variations in the inflow rate move galaxies off the equilibrium mass–metallicity and mass–gas fraction relations in a manner correlated with the star formation rate, and the scatter is set by the time-scale to re-equilibrate. The evolution of both relations from $z \sim 3 \to 0$ is slow, as individual galaxies tend to evolve mostly along the relations. Gas fractions at a given stellar mass slowly decrease with time because the cosmic inflow rate diminishes faster than the consumption rate, while metallicities slowly increase as infalling gas becomes more enriched. Observations from $z \sim 3 \to 0$ are better matched by simulations employing momentum-driven wind scalings rather than constant wind speeds, but all models predict too low gas fractions at low masses and too high metallicities at high masses. All our models reproduce observed second-parameter trends of the mass–metallicity relation with the star formation rate and environment, indicating that these are a consequence of equilibrium and not feedback. Overall, the analytical framework of our equilibrium scenario broadly captures the relevant physics establishing the galaxy gas and metal content in simulations, which suggests that the cycle of baryonic inflows and outflows centrally governs the cosmic evolution of these properties in typical star-forming galaxies.

Key words: methods: numerical – galaxies: abundances – galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: statistics.
Cosmological hydrodynamic simulations have advanced rapidly over the past decade, to a point where they can plausibly match a wide range of properties of galaxies and the intergalactic medium (IGM) across cosmic time. One recently explored physical process that greatly improves concordance with observations is strong and ubiquitous galactic outflows. These outflows are powered by supernovae, stellar winds and/or photons from young stars, that is, they result from the SF process itself, leading to self-regulated growth. Qualitatively, observations indicate that galaxy formation must be increasingly suppressed towards small masses. Outflows are now directly observed in most star-forming galaxies at $z \geq 1$ (e.g. Weiner et al. 2009; Davé et al. 2001). By incorporating outflows as observed into simulations, it is possible to yield galaxy populations that significantly more closely resemble those observed.

Recently, it has been found that simulations employing outflow scalings as expected for momentum-driven winds (Murray, Quataert & Thompson 2005; Zhang & Thompson 2010) are among the most successful at matching a wide range of data on galaxies (e.g. Davé, Finlator & Oppenheimer 2006; Finlator & Davé 2008; Oppenheimer et al. 2010) and the IGM (e.g. Oppenheimer & Davé 2006, 2008, 2009; Oppenheimer, Davé & Finlator 2009), although notable discrepancies remain. These scalings assume that the mass outflow rate scales inversely with galaxy circular velocity, providing increased suppression of the SF in smaller systems. Such outflows also have scales inversely with galaxy circular velocity, providing increased feedback processes must strongly regulate galaxy growth. Such feedback processes are expected to manifest themselves in the evolution of the mass, metal and gaseous content of galaxies. Hence, understanding the origin and evolution of scaling relations between these constituents provides key insights into accretion and feedback processes that govern galaxy growth.

In this series of two papers, we investigate the way in which inflows and outflows within a hierarchical structure formation context govern the main constituents of galaxies, namely stars, gas and metals. In Davé, Oppenheimer & Finlator (2011, hereinafter Paper I), we focused on stellar masses and SFRs. We argue that many of the trends seen in simulations can be understood within the framework of galaxies living in a slowly evolving equilibrium between inflow, outflow and SF. The inflow is at early epochs supplied primarily from the (relatively) pristine IGM, while at later times wind recycling brings back gas in a mass-dependent fashion. As in Oppenheimer et al. (2010), we showed that outflows produce three-tiered stellar mass and SFR functions, where the middle tier is established by the onset of differential (i.e. mass-dependent) wind recycling. The evolution and mass dependence of the specific SFR (sSFR) follows trends arising from the mass accretion rate into haloes, modulated by outflows. We further examined the satellite galaxy population and found that in models they are not particularly more common or more bursty than central galaxies at a given mass, and that the main difference versus centrals is that satellites have increasingly suppressed SF to small masses. We showed that momentum-driven wind scalings provide the best overall fit to available observations, but the agreement is only good in the range of $\sim(0.1-1)\mathcal{L}^*$. At lower masses, SF in dwarfs seems to occur at too early epochs in the models, and at higher masses, some additional mechanism is required to quench SF in massive galaxies (e.g. black hole feedback; Di Matteo, Springel & Hernquist 2005; Bower et al. 2006; Croton et al. 2006; De Lucia et al. 2006; Fontanot et al. 2007; Somerville et al. 2008; Gabor et al. 2011). Overall, comparing these simulations to observations helps constrain the way in which inflows and outflows work together to govern the growth of galaxies' stellar components, while highlighting key failures of current models.

In this paper, Paper II in this series, we extend the analysis of our suite of cosmological hydrodynamic simulations with outflows to examine galaxy metallicities and gas fractions. The primary goal is to understand how outflows govern scaling relations between these quantities and their stellar content. We will show that the equilibrium scenario introduced in Paper I also provides the basic intuition for understanding gas and metal growth. We outline a simple analytic formalism that captures the main features of the simulation results. In it, the metallicity of galaxies is governed primarily by outflows with a secondary effect from enriched inflow, while the gas content is governed by a competition between cosmological gas supply and the gas consumption rate set by the SF law. Both the metallicity and gas fraction are driven by cosmic inflows, which diminish rapidly with cosmic time, and fluctuate on shorter time-scales, resulting in deviations from the mean relations that correlate with SF. By comparing to observations, we find that the momentum-driven wind scalings provide the best match to data among the models examined here, but once again there are significant discrepancies at the highest and lowest masses. These results highlight how galactic outflows are a key moderator of the stellar, metal and gas content of galaxies at all epochs, and in turn observations of these properties provide valuable insights into the cosmic ecosystem within which galaxies form and grow.
This paper is organized as follows. In Section 2, we briefly describe our hydrodynamic simulations including our galactic outflow models. In Section 3, we examine simulated MZRs across cosmic time and present a simple framework for understanding their physical origin. In Section 4, we similarly examine galaxy gas fractions. In Section 5, we compare to observations of the metal and gas contents to identify broad constraints on feedback processes. In Section 6, we discuss second-parameter dependences of the MZR and gas fractions on the SFR and environment. In Section 7, we explore how individual galaxies evolve in the mass–metallicity and mass–gas fraction planes. Finally, we summarize and discuss the broader implications of our work in Section 8.

2 SIMULATIONS

The suite of simulations employed are identical to that employed in Paper I. We refer the reader to that paper for a full discussion of all details, and here we briefly review some of the key aspects.

2.1 Runs

Our simulations are run with an extended version of the GADGET-2 N-body + smoothed particle hydrodynamic (SPH) code (Springel 2005). We assume a Λ cold dark matter cosmology (Hinshaw et al. 2009): \( \Omega_m = 0.28 \), \( \Omega_\Lambda = 0.72 \), \( h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.7 \), a primordial power spectrum index \( n = 0.96 \), an amplitude of the mass fluctuations scaled to \( \sigma_8 = 0.82 \) and \( \Omega_b = 0.046 \). We call this the r-series, where our general naming convention is \( \text{rboxsize}][\text{n}][\text{particles}/\text{side}][\text{wind model}] \). Our primary runs use a boxsize of \( 48 h^{-1} \text{ Mpc} \) on a side with \( 384^3 \) dark matter and \( 384^3 \) gas particles, and a softening length of \( \epsilon = 2.5 h^{-1} \text{ kpc} \) (comoving, Plummer equivalent). To expand our dynamic range, we run two additional sets of simulations with \( 2 \times 256^3 \) particles identical to the primary runs, except one having a boxsize of \( 24 h^{-1} \text{ Mpc} \) and \( \epsilon = 1.875 h^{-1} \text{ kpc} \), and the other with a boxsize of \( 48 h^{-1} \text{ Mpc} \) and \( \epsilon = 3.75 h^{-1} \text{ kpc} \). SPH particle masses are \( 3.6 \times 10^7 \), \( 1.5 \times 10^7 \) and \( 12 \times 10^7 \) M⊙ for the \( r48n384, r24n256 \) and \( r48n256 \) series, respectively, and dark matter particle masses are approximately five times larger.

Our version of GADGET-2 includes cooling processes using the primordial abundances as described in Katz, Weinberg & Hernquist (1996) and metal-line cooling as described in Oppenheimer & Davé (2006). We include heating from a metagalactic photoionizing flux from Haardt & Madau (2001), but this has essentially no effect on galaxies that we can resolve since their halo masses are well above the mass where photoionization strongly suppresses galaxy formation (e.g. Okamoto, Gao & Theuns 2008). SF is modelled using a subgrid recipe introduced in Springel & Hernquist (2003a) where a gas particle above a density threshold of \( n_H = 0.13 \text{ cm}^{-3} \) is modelled as a fraction of cold clouds embedded in a warm ionized medium, following McKee & Ostriker (1977). SF follows a Schmidt law (Schmidt 1959) with the SF time-scale scaled to match the z = 0 Kennicutt law (Kennicutt 1998). We use a Chabrier (2003) initial mass function (IMF) throughout. We account for metal enrichment from Type II supernovae (SNeII), SNeIa and asymptotic giant branch stars, and we track four elements (C, O, Si, Fe) individually, as described in Oppenheimer & Davé (2008).

Galactic outflows are implemented using a Monte Carlo approach analogous to SF. Outflows are directly tied to the SFR, using the relation \( M_{\text{wind}} = \eta M_{\text{SF}} \), where \( \eta \) is defined as the mass loading factor. The probabilities for a gas particle to spawn a star particle are calculated from the subgrid model described above, and the probability to be launched in a wind is \( \eta \) times that. If the particle is selected to be launched, it is given an additional velocity of \( v_w \) in the direction of \( \mathbf{v} \times \mathbf{a} \), where \( \mathbf{v} \) and \( \mathbf{a} \) are the instantaneous velocity and acceleration, respectively. Choices of the parameters \( \eta \) and \( v_w \) define the ‘wind model’. Once a gas particle is launched, its hydrodynamic (not gravitational) forces are turned off until either \( 1.95 \times 10^{40}/[v_w(\text{ km s}^{-1})] \) yr have passed or, more often, the gas particle has reached 10 per cent of the SF critical density. This attempts to mock up chimneys generated by outflows that allow relatively unfettered escape from the galactic ISM and which are not properly captured by the spherically averaging SPH algorithm at \( \gtrsim 1 \text{ kpc} \) resolution; it also yields results that are less sensitive to numerical resolution (Springel & Hernquist 2003b). For a further discussion of hydrodynamic decoupling, see Dalla Vecchia & Schaye (2008) and Paper I.

For this paper, we run the following four wind models:

(i) No winds (nw), where we do not include outflows (i.e. \( \eta = 0 \));
(ii) Constant winds (cw), where \( \eta = 2 \) and \( v_w = 680 \text{ km s}^{-1} \) for all galaxies;
(iii) Slow winds (sw), where \( \eta = 2 \) and \( v_w = 340 \text{ km s}^{-1} \) for all galaxies; and
(iv) Momentum-conserving winds (ucw), where galaxies are identified on-the-fly and their velocity dispersion \( \sigma \) is estimated (see Oppenheimer & Davé 2008) and then

\[
\nu_w = 3\sigma \sqrt{f_L - 1},
\]

\[
\eta = \frac{\sigma_0}{\sigma},
\]

where \( f_L = [1.05, 2] \) is the luminosity factor in units of the galactic Eddington luminosity (i.e. the critical luminosity necessary to expel gas from the galaxy potential) and \( \sigma_0 = 150 \text{ km s}^{-1} \) is the normalization of the mass loading factor. Choices for the former are taken from observations (Rupke, Veilleux & Sanders 2005), while the latter is broadly constrained to match high-redshift IGM enrichment (Oppenheimer & Davé 2008). The velocity dispersion \( \sigma \) is estimated from the baryonic galaxy mass \( M_{\text{gal}} \) using (Oppenheimer & Davé 2008)

\[
\sigma = 200 \left[ \frac{M_{\text{gal}}}{5 \times 10^{12} h^{-1} \text{ M}_\odot} \frac{\Omega_{\text{in}}}{\Omega_b} \frac{H(z)}{H_0} \right]^{1/3} \text{ km s}^{-1}.
\]

See Paper I for further details. We particularly refer to Section 2.2 for a discussion about issues related to the momentum budget in the vzw model. To reiterate, while the energy budget of this model is well within that provided by SNe, the momentum required to eject gas from young stars. A physically realistic model would then need to either invoke gas that is optically thick in the far-infrared in order to extract additional momentum from photons after reprocessing by dust (e.g. as in the models of Hopkins, Quataert & Murray 2011), or be a combination of SNe and young stars that drives the outflow (e.g. as forwarded by Murray, Ménard & Thompson 2010).

2.2 Computing galaxy metallicities and gas fractions

We use SKID\(^1\) (Spline Kernel Interpolative Denmax) to identify galaxies as bound groups of star-forming gas and stars (Kereš et al.

\(^1\) http://www-hpcc.astro.washington.edu/tools/skid.html
2005; Oppenheimer et al. 2010). Our galaxy stellar mass limit is set to be $\geq 64$ star particles (Finlator et al. 2006), resulting in a minimum resolved mass of $M_{\text{gal}} = 1.1 \times 10^{9} M_{\odot}$ in our r48n384 series of runs. We will only consider galaxies with the stellar mass $M_{\ast} \geq M_{\text{gal}}$ in our analysis. We separate galaxies into central and satellite galaxies by associating each galaxy with a halo, where we identify haloes via a spherical overdensity algorithm (Kereš et al. 2005).

To compute gas fractions, we set $M_{\text{gas}}$ to be the mass of all star-forming gas in a skid-identified galaxy. We then define

$$f_{\text{gas}} = \frac{M_{\text{gas}}}{M_{\ast} + M_{\text{gas}}},$$

where $M_{\ast}$ is the stellar mass of the galaxy. Note that some authors choose $f_{\text{gas}} = M_{\text{gas}}/M_{\ast}$, and, for instance, Peeples & Shankar (2010) argue that this definition is more natural in terms of understanding the origin of the MZR. Nevertheless, we prefer the above definition because it intuitively translates into the fraction of a galaxy’s (baryonic) mass that is in gas. In the end, so long as models and data are compared using the same quantity, the exact definition is not critical.

Our gas mass includes all phases of the ISM, including the cold neutral medium, molecular gas and the warm ionized medium. The latter typically makes a small mass contribution, but the relation between the first two depends on the internal physics of the ISM (particularly self-shielding) that our simulations do not accurately track (see Popping et al. 2009, for further discussion). It is therefore important to compare to data that account for both neutral (H I) and molecular (H$_2$) components, as well as having been corrected for helium. Furthermore, gas mass measurements can be sensitive to surface brightness effects in the outer regions of galaxies.

The determination of the gas content in simulated galaxies depends on the density threshold for SF. Here we assume the density threshold $n_{\text{HI}} = 0.13 \text{ cm}^{-3}$, which is a somewhat arbitrary choice motivated by resolution considerations (Springel & Hernquist 2003b). This assumption makes little difference for galaxy SF histories, because dynamical perturbations are typically so frequent that gas is rapidly driven inwards until it forms stars, and thus raising (lowering) the threshold would only introduce a small delay (advancement) in processing gas into stars (Schaye et al. 2010). Naively, gas fractions would be more affected since changing the threshold density will include more or less gas as ‘star forming’. However, it is not straightforward to even determine the sign of the effect. For instance, lowering the threshold would provide more gas eligible for SF, but would also increase the SFR, thus lowering the gas fraction. In high-resolution simulations of individual galaxies (e.g. Guedes et al. 2011), it is seen that raising the threshold density does lower the gas fraction, but this is also sensitive dependent on their feedback algorithm which is quite different from ours. Hence, gas fraction comparisons should be done with some caution and are mainly intended to illustrate trends.

The galaxy gas-phase metallicity is defined as the SF-weighted metallicity of all gas particles in skid-identified galaxies. This definition most closely mimics how metallicities are measured observationally using nebular emission lines emanating from star-forming regions. We use the oxygen abundance as a metallicity tracer in our models, since this is also typical of observational determinations. We assume a solar oxygen mass fraction of 0.00574 (Asplund et al. 2009), or [O/H]$_{\odot} + 12 = 8.69$. The weighting of metallicity by SF mitigates the issues regarding the outer regions of galaxies that plague gas fractions, since SF is typically concentrated in the central region of the galaxy.

3 GALAXY METAL CONTENT

In this section, we will examine the drivers behind the MZR and its evolution out to high redshifts. We will focus on the physical mechanisms that connect inflows and outflows to the observable metal content of galaxies, in particular placing the form and evolution of the MZR within the context of the equilibrium scenario for galaxy evolution.

3.1 The $z = 0$ MZR

Fig. 1 shows the $z = 0$ relation between stellar mass and gas-phase metallicity, the MZR, in our simulations. The simulation data points are colour-coded by the SFR within bins of stellar mass, which we will discuss in Section 6. The main body of points comes from the r48n384 runs; the smaller volume r24n256 run galaxies are shown as the sparser set of points at $M_{\ast} < 1.1 \times 10^{9} M_{\odot}$ to extend the dynamic range. The magenta curve shows a running median and the error bars show $\sigma$ deviations about the median. For comparison, the SDSS MZR mean (thick line) and $\sigma$ scatter (dashed lines) are overlaid, but we will defer the discussion of comparisons to observations until Section 5.

Metallicity measures have an uncertain normalization. This comes from uncertainties in metallicity determinations (e.g. Kewley & Ellison 2008), uncertainties in adopted metal yields (see discussion in Oppenheimer & Davé 2008) and uncertainties in the solar metal abundance (Asplund et al. 2009). Hence, we treat the overall metallicity normalization as a free parameter. Given that we do not have any form of feedback that quenches massive galaxies in these runs (e.g. Gabor et al. 2011), our simulations most robustly model star-forming galaxies at masses below $M_{\ast}$. Therefore, we normalize our metallicities to the observed MZR at $M_{\ast} \sim 10^{10} M_{\odot}$, where it so happens that all our wind simulations predict roughly similar metallicities. This normalization requires us to multiply all simulated metallicities by an arbitrary factor of 0.8. We apply this same factor at all redshifts and for all models. Hence, the independent predictions of our simulations are the shape, slope, scatter and evolution of the MZR, but not its overall amplitude.

All the wind models produce a general trend of increasing metallicity with mass and a turnover to flat at high masses. The nw case in contrast produces a nearly flat MZR, as one would expect from, for example, closed box evolution. All the wind models approach the nw case at $M_{\ast} \gtrsim 10^{11} M_{\odot}$, as these wind models all eject proportionally less material from the most massive galaxies, and the material that is ejected tends to quickly fall back in (Oppenheimer et al. 2010). If some form of ejective feedback to quench massive galaxies were included in our models (e.g. Gabor et al. 2011), then this plateau metallicity may be lower.

While broadly similar, there are clear differences between various wind models. The cw model yields another turnover at low masses ($M_{\ast} \lesssim 10^{10} M_{\odot}$) towards a flat MZR. The sw model produces a similar turnover at somewhat smaller masses. The momentum-driven scalings case does not produce such a flattening, at least within the mass range probed by these simulations; the MZR slope here is nearly constant at $Z \propto M_{\ast}^{-0.3}$ for $M_{\ast} \lesssim 10^{10.5} M_{\odot}$.

To understand the origin of these features for the various wind models, we review the findings from Finlator & Davé (2008) who developed a simple analytic understanding of the MZR. In their model, the gas-phase metallicity of a galaxy is set by a balance between inflow and outflow plus SF. Inflow brings in low-metallicity gas, SF enriches that gas, while outflows modulate the fraction of inflow that turns into stars. In equilibrium, the three terms are related
Figure 1. The MZR at $z=0$ in our r48n384 cosmological hydrodynamic simulations employing our four galactic outflow scalings models: momentum-driven scalings (upper left-hand panel), cw (upper right-hand panel), nw (lower left-hand panel) and sw (lower right-hand panel). The coloured points represent individual simulated galaxies, colour-coded by SFR within bins of $M_*$ into upper (blue), middle (green) and lower (red) thirds. The magenta lines show a running median of the simulated points, with 1σ scatter about the median. The thick solid line is the $z\approx0$ MZR from the SDSS (Tremonti et al. 2004) with the dashed lines showing the range enclosing 16–84 per cent of the data. Note that all model oxygen abundances have been multiplied by 0.8 in order to match the amplitude of the observed MZR at $M_*\approx10^{10}M_\odot$, which is within systematic uncertainties in metallicity measures; the shape, scatter and evolution are independent predictions.

Here we have, for simplicity, assumed that the infalling gas has negligible metallicity; we will relax this assumption in Section 7 (see equation 11).

A key assumption in this formalism is that the mass loading factor reflects the amount of the material that is ejected from the galaxy without returning quickly. In this sense, $\eta$ should be regarded as an ‘effective’ mass loading factor, which Finlator & Davé (2008) showed generally tracks the input value of $\eta$ in our simulations when the wind velocity is comparable to or exceeding the escape velocity. We reiterate that our simulations hydrodynamically decouple outflowing gas; simulations that choose not to do so can have significantly different effective $\eta$ despite having the same input $\eta$ (e.g. Dalla Vecchia & Schaye 2008). The similarity between our input $\eta$ and effective $\eta$ (at least above the escape velocity) thus reflects this particular modelling choice.
It is worth noting that equation (7) does not have any explicit dependence on stellar mass, but only depends on inflow and outflow rates. The physical interpretation is that the gas-phase metallicity does not reflect a historical record of the SF in a galaxy (as in a closed-box scenario), but rather reflects its recent (i.e. over a gas depletion time-scale; Section 4.2) balance between inflows and outflows. This then distinguishes stellar metallicities, which must reflect the history of metal buildup, from gas-phase ones. In practice, however, the fairly slow evolution of the MZR (Section 3.2) means that galaxy stellar metallicities are only slightly lower than gas-phase ones. We leave a detailed examination of stellar versus gas-phase metallicities for future work.

Using equation (7), we can understand the behaviour of the various wind models. In the nw case, \( \eta = 0 \), and the metallicity is therefore close to constant. Although the MZR is close to flat, there remains a slight slope owing to the rapidity of inflow and the lack of reduction of fresh gas by outflows, which results in galaxies being not quite able to attain equilibrium. We will see in the next section that this effect becomes exacerbated at higher redshifts. Furthermore, there is more enriched inflow into higher mass galaxies, as we discuss in Section 7.

The momentum-driven wind scalings assume \( \eta \propto v_w^{-1} \propto M_*^{-1/3} \) (approximately). Hence, when \( \eta \gg 1 \), this approximates \( Z \propto M_*^{1/3} \). The turnover at high masses is set by the normalization of \( \eta \), namely \( \sigma_0 \), which produces \( \eta \lesssim 1 \) for \( M_* \gtrsim 10^{11} \, M_\odot \) (at \( z = 0 \); this mass evolves mildly upwards with redshift).

The cw and sw cases introduce another consideration – the competition between wind speed and escape velocity. Unlike in the momentum-driven scalings where \( v_w \approx v_{\text{esc}} \), here there is a transition mass above which the winds cannot escape and fall quickly back into the galaxy. Hence, the wind recycling time is very short, meaning that winds have little effect (Oppenheimer et al. 2010). Stated in terms of the above formalism, the effective mass loading factor in these models approaches zero above that threshold mass (see Finlator & Davé 2008, and section 2.2 of Paper I), so that at low masses \( \eta \approx 2 \), while at high masses \( \eta \approx 0 \), with a steep transition between these regimes across which the metallicity changes by a factor of \( 1 + \eta \approx 3 \). Because the wind speed is twice as fast in the cw case, the transition occurs at a higher mass than in the sw case. Although the transition to the low-mass regime is not well probed at the dynamic range of these simulations (particularly in the sw case), it is still evident. This transition is also evident in the stellar mass and SFR functions in Paper I. This equilibrium scenario strongly predicts that the low-mass MZR will continue to be flat to small masses in this model.

These simulations and the associated equilibrium model indicate that the MZR is critically governed by the mass outflow rate from galaxies (i.e. \( \eta \)) and its scaling with \( M_* \). This differs fundamentally from the canonical explanation for the MZR that invokes a competition between the galaxy potential well and the outflow velocity to modulate the metals retained within a galaxy (e.g. Dekel & Silk 1986; Dekel & Woo 2003; Tremonti et al. 2004); here, there is no mention of the potential well depth except indirectly via its effects on the mass loading factor. It is often canonically stated that low-mass galaxies preferentially eject more of their metals and hence have lower metallicity. In our scenario, it is not the ejection of metals that is modulated by outflows, but the production of metals from a given amount of hierarchical inflow that is regulated by outflows.

The turnover in the MZR at high masses has typically been thought to reflect the transition to a regime where outflows can no longer escape the galaxy (Dekel & Silk 1986; Tremonti et al. 2004). In our constant-\( \eta \) cases, this is accurate. However, in our momentum-driven wind scalings case, the wind speed scales with the escape velocity. Hence, the turnover is instead caused by \( \eta \) becoming less than unity at large \( M_* \) in equation (7). Since this model seems to predict an MZR that is overall in better agreement with data, particularly to low masses, this suggests that the conventional interpretation of the MZR being governed by the potential well depth may not be accurate.

In summary, the MZR is governed by the ‘SF efficiency’, where here we mean this in the cosmological sense as the amount of infalling material that is converted into stars. This interpretation agrees with the simulations of Brooks et al. (2007), who also found that the MZR is governed by the cosmological SF efficiency that is modulated by SN feedback. In our models, this SF efficiency, and hence the metallicity, is directly controlled by the rate at which mass is ejected in outflows.

### 3.2 MZR evolution

Fig. 2 depicts the evolution of the MZR from \( z = 3 \to 0 \) in our four wind models. We show the running median at each redshift in the large panel, and the small panel below shows the 1\( \sigma \) variance about the median within each mass bin. The cyan points in the lower panels show the observed 1\( \sigma \) variance at \( z \approx 0 \) from SDSS data (Tremonti et al. 2004) for comparison; we will discuss this further in Section 6. We separately show the results for the r48n384 (solid lines), r24n256 (dotted) and r48n256 (dashed) runs; the good agreement at all overlapping masses indicates that these results are resolution converged at least over the range of resolutions and volumes probed here. Although we do not show it here, all models at all epochs retain the second-parameter trend shown in Fig. 1 wherein lower SFR galaxies at a given \( M_* \) have higher metallicities.

All the wind models have the general shape of their MZR as expected from the equilibrium model and described in the previous section. The shapes remain similar at all redshifts, because the form of \( \eta(M_*). \) for each model does not change, and this governs the MZR shape as described in Section 3.1. The nw case appears further out of equilibrium at earlier epochs, as it deviates more strongly from the expected behaviour of a constant metallicity at all masses. This is expected because accretion rates are higher at early epochs in comparison to gas processing rates within the ISM; we will discuss this further in Section 4.3. The trend of metallicity increasing with time at a given \( M_* \) is quite generic, at least among the models considered here. This is not trivial; it is possible to design models that are quite reasonable in many ways but yield the opposite evolution (Arrigoni et al. 2010; M. Arrigoni, private communication).

In detail, the evolutionary rate at a given \( M_* \) varies somewhat with the wind model. The momentum-driven wind scalings produce little early evolution and more evolution from \( z \gtrsim 2 \to 0 \). The constant-\( v_w \) models have less late evolution, particularly in the sw case, and more rapid evolution at early epochs. In Paper I, we saw that such trends are also seen in the evolution of the galaxy SFR functions (fig. 2 of Paper I), where the constant-\( v_w \) cases evolved less out to \( z \sim 2 \) compared to the momentum-driven scalings case. This qualitative similarity in evolution is consistent with the interpretation that the MZR is governed primarily by galaxies’ SFs, as suggested by equation (7). We will discuss the evolution of the MZR further in

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2This is notably different from the definition of SF efficiency in the ISM, which describes how quickly molecular gas is processed into stars.
Figure 2. The large panels show the evolution of the MZR in our four wind models at \(z = 0, 1, 2\) and 3. The lines show the running median within mass bins at each redshift. The solid lines show the results from our r48n384 simulations, dotted lines show r24n256 runs and dashed lines show r48n256 runs; the general consistency between the three indicates that the results are numerically converged, though the lowest resolution runs show notably lower metallicities. All models show an upward evolution of metallicity at a given mass (at a rate that depends on the wind model), although the characteristic MZR shape unique to each model does not change with redshift. The smaller panels below each large panel show the \(1\sigma\) scatter about the median relation for all the models. The cyan points show the \(\approx 1\sigma\) scatter in observations of the \(z = 0\) MZR from Tremonti et al. (2004).

Section 7, when we study how individual galaxies evolve in mass–metallicity space.

4 GALAXY GAS CONTENT

In this section, we examine galaxy gas fractions and their evolution across cosmic time. As with the MZR, we attempt to provide physical intuition for what establishes a galaxy’s gas fraction and its evolution by connecting it to gas inflow and outflow processes.

4.1 Gas fractions at \(z = 0\)

Fig. 3 shows the \(z = 0\) gas fractions in our suite of simulations as a function of stellar mass [the mass–gas fraction \((M_\star - f_{\text{gas}})\) relation (MGR)]. The points are colour-coded by SF within a given mass bin as in Fig. 1; this will be discussed in Section 6. For comparison, the data points with errors show observed gas fractions (\(\text{H}_1 + \text{H}_2\)), corrected for helium, compiled and binned by Peeples & Shankar (2010).

At the massive end, all models show decreasing gas fractions with stellar mass. At lower masses, however, all wind models eventually deviate from this trend, displaying a maximum typical gas fraction below which the gas fraction becomes lower to smaller masses. The nw case shows no such maximum. The mass at which this maximum occurs appears to be related to wind recycling, that is, the return of the previously ejected material back into a galaxy. Oppenheimer et al. (2010) showed that the recycling time becomes long at smaller masses, eventually exceeding a Hubble time. The mass at which the recycling time becomes longer than the Hubble time in each wind model is, to a good approximation, the mass at which the maximum
Figure 3. The relation between $f_{\text{gas}}$ and $M_*$ (MGR) at $z = 0$ in our four wind models, with the magenta lines showing the median and 1σ scatter as in Fig. 1. The points are colour-coded by SFR within stellar mass bins: blue for the upper third, green for the middle third and red for the bottom third. Data points show mean values as a function of $M_*$ from a compilation of observations by Peeples & Shankar (2010).

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gas fraction is seen. This suggests that the lower gas fractions at small masses occurs at least in part because ejected winds never return to these galaxies.

As emphasized by van de Voort et al. (2010) and Faucher-Giguere et al. (2011), feedback adds energy to the surrounding gas and prevents material from entering into smaller galaxies. Since much of the material entering into galaxies’ ISM at $z = 0$ is recycled wind (Oppenheimer et al. 2010), the majority of the effect is that small galaxies do not re-accrete their winds. The cw model shows the highest turnover mass in $f_{\text{gas}}$, while the sw and momentum-driven scalings cases occur at lower masses. The latter wind model also shows a somewhat slower drop-off in $f_{\text{gas}}$ to lower masses, reflecting its less steep dependence of recycling time on mass.

Another possible issue is that perhaps many low-mass galaxies are satellites that have lower gas content owing to stripping or strangulation processes. However, we will show in Section 6.3 that the satellite fraction does not increase appreciably to small masses, and we will demonstrate that the turn-down in gas fractions to small masses is present in both satellites and centrals. Hence, this particular trend does not arise from satellites, although other interesting trends do that we will explore in Section 6.3.

The non-monotonic behaviour of gas fractions in wind models reflects a similar behaviour, with similar characteristic scales, as the sSFR (≡ SFR/$M_*$) examined in Paper I. There we saw that low-mass galaxies had depressed sSFRs relative to an extrapolation from higher masses in all wind models; the nw case showed no such deviation. This trend arises because of a combination of wind recycling, which brings extra accretion at high masses (Oppenheimer et al. 2010), and preventive feedback which suppresses accretion onto galaxies at the lowest masses (e.g. van de Voort et al. 2011). The suppression of gas fractions is seen to be directly proportional to the suppression in sSFRs, which we will explain in Section 4.3. Hence, the discrepancies of models relative to observed sSFRs of dwarf galaxies noted in Paper I are directly traceable to lowered gas fractions in dwarfs predicted in models.

In summary, gas fractions fall with mass at the highest masses but show a turnover at low masses in all the wind models. This turnover is not seen in observations, which we will discuss in Section 5.
To understand the origins of these trends, and also gas fraction evolution, let us examine an instructive quantity for understanding gas processing in galaxies, namely the depletion time.

### 4.2 Depletion time

Fig. 4 shows the gas depletion time $t_{\text{dep}}$ as a function of stellar mass in our four wind models, from $z = 3 \rightarrow 0$. We define $t_{\text{dep}} \equiv M_{\text{gas}}/\text{SFR}$, which is the time that a galaxy would take to consume its current gas supply at its current SFR. Our three sets of simulations for each wind model are shown to demonstrate good resolution convergence over the dynamic range probed. To illustrate a useful trend, we divide $t_{\text{dep}}$ by the Hubble time $t_{\text{H}}$ at each redshift.

Several general features of $t_{\text{dep}}(M_*, z)$ are evident in Fig. 4: first, higher mass galaxies have shorter depletion times; secondly, depletion times are, to first order, independent of the wind model; and, finally, $t_{\text{dep}}/t_{\text{H}}$ is essentially invariant over most of cosmic time. The insensitivity to the wind model and invariance when scaled to the Hubble time provide key clues into the physics governing $t_{\text{dep}}$ and, in turn, galaxy gas contents.

We can broadly understand these trends using a straightforward argument based on our SF law. The depletion time measures how gas, once within a galaxy, gets consumed into stars. Our simulations model conversion of gas to stars by assuming a Kennicutt–Schmidt law, which equivalently follows the relation that the SFR is the gas mass divided by the dynamical time $t_{\text{dyn}}$ (of the star-forming disc), times some overall efficiency factor that is measured to be around 2 per cent both locally and in distant galaxies (e.g. Genzel et al. 2010). Hence, the depletion time should scale as the dynamical time. In a canonical disc model (Mo, Mao & White 1998), the dynamical time evolves as $t_{\text{H}}$ and hence we expect $t_{\text{dep}}/t_{\text{H}}$ to be approximately constant, which is generally confirmed in Fig. 4, although with deviations at low masses at $z = 0$ that we discuss below.

The mass dependence of $t_{\text{dep}}$ depends on the conversion rate of gas into stars. This is set by the details of the internal structure of galaxies within our simulation along with the assumed Kennicutt–Schmidt SF law, which is $\Sigma_{\text{SF}} \propto \Sigma_{\text{gas}}^{1.4}$, where $\Sigma_{\text{SF}}$ and $\Sigma_{\text{gas}}$ are the...
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Figure 5. Gas surface density \( \Sigma_{\text{gas}} \) (comoving) versus stellar mass \( M_* \) in galaxies from our r48n384 vzw simulation, at \( z = 0 \) (blue) and \( z = 3 \) (red). The gas surface density is taken to be the gas mass divided by \( \pi R^2 \), where \( R \) is the stellar half-mass radius of the galaxy. This relation is reasonably well described by \( \Sigma_{\text{gas}} \propto M_*^{1/4} \), as shown by the arrow.

The gas surface densities of SF and star-forming gas, respectively. Hence, 
\[
\tau_{\text{dep}} = \frac{\Sigma_{\text{gas}}}{\Sigma_{\text{SF}}} \propto \Sigma_{\text{gas}}^{-0.4}.
\]

We then employ an empirical relation measured in our simulations of \( \Sigma_{\text{gas}} \propto M_*^{1/4} \) that we show in Fig. 5. It does not evolve appreciably with redshift. While we do not explicitly show it, this relation holds reasonably well for all the wind models. Observations of the stellar mass density profile in late-type SDSS galaxies indicate \( \Sigma_* \propto M_*^{0.24} \) (Kauffmann et al. 2003), which is slightly shallower. Gas profiles are more difficult to measure, but at least in our models, star-forming gas generally traces stars. Using this shallower slope would not significantly change our results, but we prefer to use the simulated slope since we are trying to develop an analytic understanding of the simulation results. Our r24n256 and r48n256 simulations have slightly different amplitudes for this relation but the slope is identical, suggesting that the trend with \( M_* \) is insensitive to resolution at least over the (admittedly narrow) range probed by these simulations.

Putting this together, we obtain
\[
\tau_{\text{dep}} \propto t_\text{hi} M_*^{-0.3}.
\]  
This scaling provides a good match to \( \tau_{\text{dep}}(M_*) \) in our simulations at most epochs and masses as shown in Fig. 4. Since we assume the same SF law in all our wind models, there is little sensitivity to outflows in this relation.

We note that \( \tau_{\text{dep}} \propto t_\text{hi} \) does not necessarily have to be the case – for instance, in mergers, \( t_\text{dyn} \) is quite small within the dense central star-forming region during the starburst phase, meaning that \( \tau_{\text{dep}} \) of such starburst galaxies should lie below the mean relation. The relatively tight relation of \( \tau_{\text{dep}}(M_*) \) in our models indicates that, in analogy with the tight main sequence (Dave 2008; Paper I), mergers are not a dominant population at any redshift. Hence, even though we have not explicitly used the equilibrium condition in deriving \( \tau_{\text{dep}} \), the connection between global virialization and the properties of the star-forming region in galaxies only holds when galaxies are in a steady-state situation.

\( \tau_{\text{dep}} \) is to first order insensitive to outflows; all models, regardless of winds, show a roughly similar \( \tau_{\text{dep}}(M_*) \). This is expected since the derivation of equation (8) does not involve any aspect that depends on outflows, effectively employing only the SF law and virial arguments. This supports the idea of Paper I that SF is supply regulated, that is, SF occurs in proportion to the gas available to form stars. This differs relative to expectations from models in which galaxies begin with a large reservoir of gas and consume them rapidly (e.g. Eggen, Lynden-Bell & Sandage 1962; Maraston et al. 2010).

At \( z = 0 \), we see a systematic departure from the mean trend towards lower \( \tau_{\text{dep}} \) at low masses. Part of this owes to satellite galaxies that are increasingly starved of gas to low masses at low redshifts (fig. 6 of Paper I), which occurs even in the nw case. In the wind models, an additional role is played by preventive feedback involving wind recycling, the departure from the canonical relation occurs at a higher mass in the cw case relative to the sw vzw case, and is more gradual at earlier epochs when wind recycling is not as common.

The depletion time has sometimes been interpreted as a measure of SF efficiency variation with galaxy mass, such that more massive galaxies more efficiently convert gas into stars. However, in our models, the SF efficiency is an input constant that is calibrated to match observations of present-day discs (Springel & Hernquist 2003b; Oppenheimer & Dave 2008) and does not vary with galaxy mass. The trend of \( \tau_{\text{dep}} \) with \( M_* \) arises from the assumed SF formation law, which is why it is very weakly dependent on details of feedback.

4.3 Gas fraction evolution

Fig. 6 shows the evolution of the MGR from \( z = 3 \rightarrow 0 \) in our simulation suite. Following Fig. 2, the solid lines show medians with 1σ spread for the r48n384 runs, while the dotted and dashed lines show likewise for the r24n256 and r48n256 runs, respectively. Once again, good resolution convergence is seen, as all the key features are reproduced at each resolution, although we emphasize that the dynamic range probed here is only a factor of 8 in mass. The smaller panels show the running 1σ variance about the median and the cyan points show the observed scatter from Peeples & Shankar (2010).

All models display a slowly falling gas fraction with time at a given mass, while the variances (small lower panels) become slightly higher with time. Hence, higher \( z \) galaxies are more gas-rich, in qualitative agreement with observations. The fundamental physics governing this are a competition between gas inflow and gas consumption rates. In the cold-accretion paradigm, the amount of the gas inflowing into the star-forming region is proportional to that of the gas inflowing at the halo virial radius, since cold streams channel material to the centre of the halo (Dekel et al. 2009). In detail, preventive feedback mechanisms can reduce ISM inflow (Faucher-Giguere et al. 2011; van de Voort et al. 2011) particularly at low masses.

The amount of the gas entering the virial radius can be estimated by the total mass accretion rate times the baryon fraction, which scales as \( (1 + z)^{2.25} \) (Dekel et al. 2009). Meanwhile, the gas consumption rate is given by how fast gas can be processed into stars or an outflow, which is given by \( \tau_{\text{dep}}/(1 + \eta) \). Since \( \tau_{\text{dep}} \propto t_\text{hi} \), at any given mass (which approximately corresponds to a given \( \eta \)), the consumption rate is given by \( t_\text{hi}^{-1} \). Since \( t_\text{hi}^{-1} \) evolves with \( z \) slower than \( (1 + z)^{2.25} \) (in the matter-dominated era), it is straightforward to see that the gas supply rate drops faster with time than the gas consumption rate. This explains why galaxies start out gas-rich but then the gas fraction drops as the gas consumption rate catches up.

While the naive notion that galaxies simply ‘consume their gas’ is qualitatively in accordance with observations, the rapid
Figure 6. Like Fig. 2, only for the gas fraction, showing the evolution of the MGR in our four wind models at $z = 0, 1, 2$ and 3. The cyan points show the observed scatter from Peeples & Shankar (2010). The arrow in the no-wind panel shows a slope of $-0.5$, as is roughly expected at the high-mass end (see text).

consumption times (Tacconi et al. 2010) imply that gas must be continually supplied. In our simulations, this indeed happens, but at a rate that becomes slower with time (relative to the consumption rate), causing a gas fraction that slowly drops. The nw case in Fig. 6 shows a self-similar (in $M_*$) downward evolution in $f_{\text{gas}}$ arising from this scenario.

We can quantify these scalings and gain more insight into gas fractions by first using the definition of $t_{\text{dep}}$ to rewrite

$$f_{\text{gas}} = \frac{1}{1 + t_{\text{SF}}/t_{\text{dep}}},$$

(9)

where $t_{\text{SF}} \equiv M_*/\text{SFR} = 1/\text{sSFR}$. Thus, the dependence of $f_{\text{gas}}$ on mass and redshift reflects the dependence of the ratio $t_{\text{SF}}/t_{\text{dep}}$ on these quantities.

Let us consider the redshift evolution first. In Paper I, we showed that the observed $t_{\text{SF}}$ at $M_* = 10^{10} M_\odot$ was consistent with following the trend predicted by halo accretion, namely $t_{\text{SF}} \propto (1 + z)^{-2.25}$, from $z \sim 2 \to 0$. Fig. 4 shows that $t_{\text{dep}} \propto t_\text{H}$ over that time, albeit with some deviations at low $z$ at low masses. Hence, the ratio $t_{\text{SF}}/t_{\text{dep}}$ rises with time, approximately as $(1 + z)^{0.75}$ at high $z$ and as $(1 + z)$ at low $z$, resulting in a dropping gas fraction. Since $t_{\text{SF}}$ and $t_{\text{dep}}$ are to rough order independent of winds, this explains the basic behaviour of $f_{\text{gas}}$ dropping with time in all models.

Equation (9) can also be used to gain insights into the mass dependence of $f_{\text{gas}}$. At larger masses (e.g. $M_* \gtrsim 10^{10} M_\odot$), $t_{\text{dep}} \ll t_{\text{SF}}$, so we can approximate $f_{\text{gas}} \approx t_{\text{dep}}/t_{\text{SF}}$. Considering first the nw case, we have sSFR $\propto M_*^{-0.2}$ (approximately; see fig. 2 of Paper I). Combined with $t_{\text{dep}} \propto M_*^{-0.3}$ (equation 8), this then roughly predicts $f_{\text{gas}} \propto M_*^{-0.5}$. This slope is indicated in the no-wind panel of Fig. 6 and provides a good fit to the high-mass slope of $f_{\text{gas}}(M_*)$. At lower masses, once $t_{\text{dep}}/t_{\text{SF}}$ becomes a significant fraction of unity, the gas fraction levels off.

In the wind models, $f_{\text{gas}}$ will reflect features seen in the sSFR, and at $z = 0$, there are additional deviations owing to $t_{\text{dep}}$. In general, sSFRs in the wind models show a turnover to lower sSFRs at low masses (fig. 3 of Paper I). The location and strength of that turnover depends on the particular wind model, owing to wind recycling as discussed in Paper I. At high masses, the sSFR in wind models is
raised over the nw case by wind recycling, which is more rapid in higher mass galaxies. At low masses, the sSFR is lowered owing to preventive effects of winds adding energy to the surrounding gas (e.g. Oppenheimer et al. 2010; van de Voort et al. 2011). These trends are directly reflected in $f_{\text{g}}(M_*)$: at high masses, they are somewhat larger than the nw case, while they all show a turnover to low gas fractions at low masses. At $z = 0$, this reduction at low masses is exacerbated by the drop in $t_{\text{dep}}$ to low masses.

An interesting regime that is not probed here is the very high $z$ epoch ($z \gtrsim 3$). At sufficiently high redshifts, the rapidly rising accretion rate will begin to exceed the less rapidly rising gas consumption rate. In that case, SF cannot keep up with the gas supply, and the galaxies will no longer be in equilibrium. This is then the gas accumulation phase. The exact epoch where this happens depends on feedback; when outflows are highly mass loaded, the amount of infalling gas that needs to be processed into stars is reduced, and equilibrium can occur earlier on. Also, there is some mass dependence because $t_{\text{dep}}$ has a significant mass dependence (Fig. 4), but $t_{\text{SF}}$ (or sSFR) is essentially independent of mass at high $z$ (González et al. 2010). Interestingly, there are now empirical constraints on the gas accumulation epoch: Papovich et al. (2011) showed, based on modelling the evolution of the luminosity and sizes of high-$z$ Lyman break galaxies, that at $z \gtrsim 4$ the global gas accretion rate exceeds the SFR, while below that redshift they track each other.

In summary, the evolution of gas fractions reflects a competition between cosmic inflow and gas consumption rates. A quick estimate of their scalings shows that cosmic inflow abates faster than gas consumption, resulting in dropping gas fractions with time in all models. Analytic models based on this scenario by Dutton et al. (2010) show a similar result. Outflows provide higher order modifications to this picture, particularly owing to wind recycling and preventive feedback effects at late times. These trends can be understood by considering the dependence of the sSFR (i.e. $t_{\text{SF}}$) and the depletion time $t_{\text{dep}}$ on mass and redshift. At sufficiently early epochs, inflow will be so rapid that gas processing cannot keep up, resulting in a gas accumulation phase.

5 COMPARISONS TO DATA

While the main purpose of this paper is to understand how galactic inflows and outflows impact the gas and metal content of galaxies, it is instructive to see how our suite of models compare to key observations of these quantities out to high redshifts. We have already seen that different outflow models generate significantly different predictions for the gas and metal content. Here we compare to a recent sample of forefront observations to see how they constrain our outflow models.

Fig. 7 shows a comparison of the MZR (top panels) and the mass–gas fraction relation (bottom panels) to observations (in black and cyan) at $z = 0$, 2 and 3. The $z = 0$ metallicity observations are taken from Tremonti et al. (2004) and the gas fraction data from a compilation by Peebles & Shankar (2010). At $z = 2$, we show metallicities and gas fractions from Erb et al. (2006a); the gas fractions here are inferred from the SFR surface density and by assuming the Kennicutt–Schmidt law. We also show (in cyan) ‘direct’ gas fraction measures from Tacconi et al. (2010) using CO measurements plus an assumed conversion of CO to H$_2$. At $z = 3$, we compare to data from Mannucci et al. (2010), which is from a sample of Lyman break galaxies at $z \sim 3$–4 (black points), and from Richard et al. (2011) from a sample of lensed galaxies at $z = 2.5$–3.1 (cyan points, metallicities only).

Looking at the $z = 0$ MZR, the only model that is clearly discrepant is the one with no winds. Galaxies are (not surprisingly) overenriched, because this model greatly overproduces the stellar content of galaxies (see e.g. Paper I). Other works have argued that the $z = 0$ MZR can be reproduced by varying the ISM SF efficiency (Mouhcine et al. 2008; Tassis, Kravtsov & Gnedin 2008), or the IMF (Köppen, Weidner & Kroupa 2007), or that hierarchical assembly naturally leads to this shape of the MZR (De Rossi, Trissler & Scannapieco 2007). In our simulations, the IMF is always assumed to follow that of Chabrier (2003), and the gas depletion time-scale $t_{\text{dep}}$ is essentially the same in all our models including the nw model. Hence, in our models, these factors are not responsible for the differences in the MZR. In our equilibrium model (equation 7), the nw model overproduces metals because it does not eject ISM material to suppress SF. This in some sense represents a ‘cosmological’ SF efficiency, that is, the amount of cosmic inflall that is converted into stars. In our models (like those of Brooks et al. 2007), the MZR is governed by the cosmological SF efficiency rather than the ISM one.

The wind models are all generally in the ballpark of the $z = 0$ SDSS data, but they show non-trivial discrepancies. At the massive end, all models overproduce the metallicities in $M_* \gg M^\star$ galaxies. Recall that we have arbitrarily scaled all our metallicities to match the $M_* > M^\star$ one. Discrepancy is particularly clear in the $M_* \approx M^\star$ regime.

In summary, the evolution of gas fractions reflects a competition between cosmic inflow and gas consumption rates. A quick estimate of their scalings shows that cosmic inflow abates faster than gas consumption, resulting in dropping gas fractions with time in all models. Analytic models based on this scenario by Dutton et al. (2010) show a similar result. Outflows provide higher order modifications to this picture, particularly owing to wind recycling and preventive feedback effects at late times. These trends can be understood by considering the dependence of the sSFR (i.e. $t_{\text{SF}}$) and the depletion time $t_{\text{dep}}$ on mass and redshift. At sufficiently early epochs, inflow will be so rapid that gas processing cannot keep up, resulting in a gas accumulation phase.

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Figure 7. A comparison to observations for the MZR (top panels) and MGR (bottom panels) in our four wind models at z = 0, 2 and 3 (left-hand to right-hand side). The lines with error bars show the running median and 1σ variance within mass bins from our r48n384 runs. Data points show the MZR at z = 0 from the SDSS (Tremonti et al. 2004, solid line with 16–84 per cent enclosing error bars), at z = 2 from Erb et al. (2006a) and at z = 3 from Mannucci et al. (2010, z ∼ 3–4; black points) and Richard et al. (2011, z ∼ 2.5–3.1; cyan points). The momentum-driven wind scalings case comes closest to matching at both z = 0 and 2 of the models here. For gas fractions, z = 0 data are shown from a compilation by Peeples & Shankar (2010), at z = 2, indirect gas fractions from Erb et al. (2006b, black points) and direct (CO-based) gas fractions from Tacconi et al. (2010, cyan), and at z = 3 from Mannucci et al. (2010). The momentum-driven wind scalings provide the overall best match, but are still discrepant at $M_\ast \lesssim 10^{10.5} M_\odot$; note that current samples measuring gas fractions generally do not include gas-poor galaxies that are often (in our models) satellites.

However, we disfavour this idea because the nw model also grossly overproduces the amount of stellar mass at z = 2 (as at all redshifts; see e.g. Paper I), so it would be highly surprising if it produces the proper metal content in galaxies.

In terms of wind models, at z = 0, the sw model was a reasonable fit, but at z = 2, it substantially over-enriches galaxies. Since there are few red and dead galaxies at this epoch, over-enrichment at the massive end is likely to be a serious defect that will not be alleviated by quenching [e.g. active galactic nucleus (AGN)] feedback. The cw model also produces the wrong shape for the MZR, as discussed in Finlator & Davé (2008). Recall that the MZR shape is probably the most robust predictions of our simulations, so again this is a serious defect. Meanwhile, the momentum-driven scalings case is a reasonable match in terms of shape and amplitude (modulo that we have scaled all our metallicities in all wind models by a factor of 0.8).

At z = 3, the metallicity data from Mannucci et al. (2010) lie well below all model predictions, while the data from Richard et al. (2011) are in good agreement. Since the former sample averages a slightly higher redshift, this might imply very rapid evolution in the MZR during the short time from $z \sim 3.5 \rightarrow 2.5$, but this is very difficult to reconcile with the observed (and predicted) slow evolution from $z \sim 2.5 \rightarrow 0$. Models can usually match data at two of the three epochs, but no model that we are aware of can match all three epochs when considering the Mannucci et al. (2010) data. One possibility is that there are observational selection effects coming into play, because the Mannucci et al. (2010) $z > 3$ sample consists of rest-ultraviolet (rest-UV) selected galaxies, while the
Turning to gas fractions, at $z = 0$ all models produce the observed trend of lower gas fractions in more massive systems. As discussed in Section 4.3, the trend in massive (i.e. low-$f_{\text{gas}}$) galaxies is set by the depletion time times the sSFR; both these drop with mass, albeit mildly. The gas fractions in the nw case follow the observed shape but are too low. One might try to reconcile this by noting that the model definition of the gas fraction as all star-forming gas (i.e. gas above $n = 0.13 \text{ cm}^{-3}$) may not be directly comparable to observational measures of $f_{\text{gas}}$. However, at least at face value, the no wind model appears to consume too much of its gas into stars by $z = 0$, leaving galaxies too gas poor; this is consistent with its overproduction of stars and metals.

At $z = 0$, the wind models are broadly in the range of observations at high masses, but in all cases, they show a turnover in gas fractions at low masses that is clearly in disagreement with observations. Hence, something in the current wind simulations is removing too much gas from dwarfs, not supplying enough gas to them and/or consuming their gas too quickly. Simulations by Kobayashi, Springel & White (2007) and Mouhcine et al. (2008) likewise find that dwarf galaxies generally tend to be too old with too little present-day SF, so this seems to be a rather generic problem in galaxy formation simulations within a hierarchical paradigm. In Paper I, we suggested that one explanation may be that the SF law is different in these systems (as argued by e.g. Robertson & Kravtsov 2008), particularly at low $z$ when they are typically fairly low surface brightness objects, or that the conversion of neutral into molecular hydrogen is less efficient (Krumholz, Leroy & McKee 2011). It is curious that the simulation without winds at least generally shows the correct trend to the lowest masses, and hence another possibility is that preventive feedback effects owing to winds are incorrectly modelled in these outflow simulations.

There are other possibilities for the low-mass $f_{\text{gas}}$ discrepancy. For instance, there are more quenched satellites at low masses (fig. 4 of Paper I) which have been depleted of gas. However, as we will show in Section 6.3, even central dwarf galaxies show a turnover in $f_{\text{gas}}$. Finally, there may be observational selection effects in the data as gas mass observations (particularly of small systems) tend to focus on gas-selected (e.g. H I) galaxies. For instance, to reconcile the vzw model at the lowest mass bin ($M_{\ast} \sim 10^{9} M_{\odot}$) requires that observed galaxies are typically 2r outliers in gas fractions, which is not impossible. Upcoming surveys, such as the GALEX Arecibo SDSS Survey (GASS; Catinella et al. 2010), that measure the gas content in an unbiased sample will be helpful, but are not targeted to the lowest mass systems where the largest discrepancies arise. The gas content of low-mass galaxies is therefore an important barometer for models, and further data and modelling are needed to shed light on whether this is indeed a serious discrepancy.

At higher redshifts, gas fraction measurements become quite uncertain. At $z \sim 2$, all models are in fair agreement with observations, although the data overall tend to show somewhat higher gas fractions. Selections effects again may play a role, since these galaxies tend to be selected as having either high gas content (so that direct measures are feasible) or high SFR (which implies high gas content; Fig. 3). Indirect gas fractions as used by Erb et al. (2006a) and Mannucci et al. (2010) have additional systematic uncertainties associated with the validity of using the Kennicutt–Schmidt law to infer gas content, while direct gas measures must use an uncertain conversion between CO and $H_{2}$ mass. Combined with the broadly similar $f_{\text{gas}}$ predictions among the models, this precludes any meaningful constraints as of yet from high-$z$ gas fractions. The overall rate at which gas fractions go down with time at a given $M_{\ast}$ is consistent with observations in all models (modulo at low masses at $z = 0$), suggesting that the basic physics governing gas fraction evolution have more to do with cosmological infall that is the same among all models, as argued in Section 4.3, as opposed to feedback mechanisms.

In summary, all simulations with outflows qualitatively reproduce the observed evolution of metallicity and gas fraction in galaxies. At a given $M_{\ast}$, all models produce rising metallicities and falling gas fractions with time. Quantitatively, the momentum-driven wind scalings model appears to be the best overall fit to the ensemble of observations. Nevertheless, significant discrepancies remain even in this case, particularly at the lowest and highest masses, which may be owed to systematic uncertainties in metal and gas measures, observational selection effects and model deficiencies.

6 SCATTER AND ITS SECOND-PARAMETER DEPENDENCES

The small scatter in the MZR is a strong constraint on galactic chemical enrichment scenarios. While models have historically focused on reproducing the shape of the MZR, the reason for the small scatter, approximately 0.1 dex varying only mildly over more than 5 dex in stellar mass (Lee et al. 2006), remains unclear. Models invoking starburst-induced galactic outflows would predict larger scatter in lower mass galaxies owing to the more stochastic nature of ejection from these systems.

As is evident from Fig. 2, the situation in simulations with outflows is more complex; for instance, our momentum-driven wind scalings model produces an MZR scatter at $z = 0$ that is in good agreement with data, and other models less so. Here we examine what governs the scatter in the MZR and MGR within the context of our equilibrium model, particularly focusing on second-parameter correlations of the metallicity and gas fraction with the SFR and environment.

6.1 Star formation rate

The MZR is observed to have second-parameter dependences (i.e. correlated scatter) with other galaxy properties. A particularly strong one that has been explored recently is the second-parameter dependence of the MZR on the SFR. Ellison et al. (2008a) noted that galaxies with higher SFRs tend to lie below the mean MZR. Mannucci et al. (2010) developed this idea further and noted that a specific combination of $M_{\ast}$ and SFR, which they called the fundamental metallicity relation (FMR), led to a significantly smaller...
scatter. Lara-López et al. (2010) independently found a similar relation. Furthermore, this relation appears to be invariant in redshift out to $z \sim 2.5$. Hence, the relation between mass, metallicity and SFR provides an even more stringent test of model predictions.

Fig. 1 shows galaxies colour-coded by SFR into high (blue), medium (green) and low (red) SFR relative to the mean within each stellar mass bin. It is a generic result from all simulations that high-SFR galaxies tend to lie below the mean MZR and low-SFR systems lie above. Hence, the observed second-parameter trend of the MZR on the SFR is naturally reproduced in all simulations. This suggests a fundamental process at work, independent of feedback, that yields this trend. We will now argue that it is a natural outcome of the equilibrium model for the MZR discussed in Section 3.1.

According to the equilibrium model, a galaxy of a given mass prefers to be at an equilibrium metallicity that is established by its current mass loading factor (equation (7)), which sets the amount of enrichment relative to fresh infall. When perturbed from its equilibrium metallicity owing to, say, a merger, this increases the galaxy mass while lowering the metallicity (since smaller galaxies have lower metallicities). This moves the system below the mean MZR. Concurrently, it results in a more gas rich galaxy (i.e. a high outlier in the MGR), which in turn stimulates SF. This correlated behaviour is the origin of the trend that high-SFR galaxies lie at lower metallicity.

Conversely, a galaxy that suffers a lull in accretion will consume its gas into stars and form more metals, enriching itself along the locus of $Z \propto M^{2.5}$ (when the metallicity is significantly below the true yield). This is steeper than the MZR slope, and thereby the galaxy moves above the mean MZR. Once accretion restarts, the metals become diluted, and the galaxy is able to return to the equilibrium relation. In some cases, the galaxy is a small satellite dwarf that is being environmentally quenched, and it will never restart accretion. In that case, the system can end up quite far above the MZR, as observations by Peebles, Pogge & Stanek (2008) illustrate.

From the discussion above, it is clear that this scenario will yield second-parameter trends of the gas fraction with the SFR as well. As seen in Fig. 3, galaxies with higher SFRs at a given mass tend to have high gas fractions. Such galaxies are undergoing an enhanced rate of SF relative to a typical galaxy along the $M_\ast$-SFR relation and hence will soon consume the gas and return to the mean relation. In this way, galaxies wobble around the mean MZR, MGR and main-sequence relation owing to fluctuations in accretion. Deviations from equilibrium tend to return a galaxy to equilibrium, which is why this scenario is dubbed the `equilibrium model'. While outflows govern the overall shape and amplitude of these relations, the qualitative second-parameter trend with the SFR is not a consequence of outflows, but rather of equilibrium. This is why the nw model shows the same second-parameter trend as the wind models.

Outflows do, however, play a significant role in quantitatively establishing the amount of scatter of the MZR and MGR. A consequence of the equilibrium model, as emphasized in Finlator & Davè (2008), is that the amount of scatter reflects how fast a galaxy can return to equilibrium after it suffers a perturbative event. To do so, there must be sufficient infall to re-equilibrate the galaxy. This can be quantified by the dilution time (Finlator & Davè 2008),

$$t_{\text{dil}} = \frac{M_{\text{gas}}}{M_{\infty}} = (1 + \eta)^{-1} \frac{M_{\text{gas}}}{M_\ast} = (1 + \eta)^{-1} t_{\text{dep}},$$

(10)

where we have used equation (6) and the definition of $t_{\text{dep}}$ (equation 8). So long as $t_{\text{dil}} \lesssim t_{\text{cs}}$, where $t_{\text{cs}}$ is the dynamical time at the halo virial radius, the scatter about the equilibrium relation will be small (Finlator & Davè 2008). As shown in Fig. 4, $t_{\text{dep}}$ becomes larger at smaller masses. If $\eta$ is constant as in our cw and sw simulations, the scatter will eventually rise significantly at low masses when the dilution time becomes longer than the virial time. This can be seen at the lowest masses in the right-hand panels (cw and sw) of Fig. 2. Conversely, in our momentum-driven wind scalings case, the trend of $\eta$ with $M_\ast$ mitigates the increase in $t_{\text{dep}}$ to low masses and keeps the scatter small at smaller masses. Specifically, the vzw model (similar to all models) yields $t_{\text{dep}} \propto M_\ast^{-0.3}$, which at $\eta \gg 1$ (small masses) is almost exactly cancelled by $\eta \propto M_\ast^{-1/3}$ in this model. Thus, one still expects the dilution time, and hence the scatter, to be constant to low masses. Observations by Lee et al. (2006) indicate a fairly constant scatter to low masses, though selection effects may be artificially lowering this (H. J. Zahid, private communication). In any case, the scatter in these relations provides an independent avenue to constrain $\eta(M_\ast)$.

We now examine more quantitatively the second-parameter dependence of the MZR on the SFR. Fig. 8 shows the FMR for our simulated galaxies, namely gas-phase oxygen abundance versus $M_\ast$ (Mannucci et al. 2010), with the scatter indicated in the smaller panels below each main panel. As can be anticipated from Fig. 1, the scatter is lowered using this combination for the $x$-axis. It is not as low as observed ($\sigma = 0.053$ dex), but a somewhat different combination of $M_\ast$ and SFR can lower the model scatter further.

Furthermore, the simulated FMR shows significantly less evolution from $z = 3 \rightarrow 0$ than the MZR (note that the $y$-axis scale is significantly smaller than in Fig. 2). At $z > 3$, Mannucci et al. (2010) observes the FMR to evolve strongly, which is a consequence of the low observed metallicities in $z > 3$ galaxies (see Fig. 7), but observations by Richard et al. (2011) indicate no evolution out to $z \sim 3$. The lack of evolution has been taken to indicate that the FMR has a special significance that transcends cosmic epoch. In our models, however, the lack of (or slow) evolution in the FMR is mostly a coincidence; it just so happens that the increase in metallicity from high $z$ to low $z$ is balanced by the evolution in typical SFRs for that particular combination of parameters. The fundamental principle that drives the FMR at any given epoch, namely the tendency for galaxies to be drawn towards an equilibrium MZR, has little to do with the overall evolution of the SFR at a given mass, which is set by cosmic inflow (e.g. Paper I).

Other observations have noted lower metallicities in merging systems. Ellison et al. (2008b) showed that close pairs tend to have a lower metallicity for their mass. It is possible that this trend is driven by the increase in SFR in these systems as driven by the interaction, although the lack of resolution in our models precludes us from examining this directly. Peebles et al. (2009) similarly found that strong outliers below the MZR tend to be interacting galaxies and are often quite massive. Once again this could be related to their SFR, although massive interacting galaxies often have significant AGN activity that produces a harder radiation field within their ISM, which when using abundance ratios to measure abundances can mimic a lower metallicity (C. Tremonti, private communication). While these trends are interesting, it is unclear whether they are distinct from the overall trend of lower metallicities in higher SFR galaxies (at a given $M_\ast$). Finally, we mention that Ellison et al. (2008a) found that systems with large half-light radii, like with high SFR, also lie below the mean MZR. Unfortunately, our simulations lack sufficient resolution to robustly model galaxy sizes, so we cannot directly examine this second-parameter dependence.

The scatter in $f_{\text{gas}}$ should, according to this scenario, follow the same trend as for the metallicity. Fig. 6 shows that in the compilation
Figure 8. The FMR, $Z_{\text{gas}}$ versus $M_{\ast}SFR^{0.32}$, in our r48n384 runs with four wind models at $z = 0, 1, 2$ and 3. The lines with error bars show the running median. The small panels below each main panel show 1σ variance. The variance is smaller for the FMR as compared to the MZR (Fig. 1). For comparison, observations of the FMR by Mannucci et al. (2010) found a variance of $\sigma = 0.053$.

of Peeples & Shankar (2010), the scatter is lower at small masses. This may be partly a selection effect, since particularly at small masses H\textsuperscript{i}- or CO-selected samples will pick out the most gas-rich systems, artificially lowering the scatter. In the stellar-mass-selected GASS sample of Catinella et al. (2010), there is no obvious evidence for a change in scatter in $f_{\text{gas}}$ versus $M_{\ast}$ among the galaxies that contain gas (excluding gas-poor passive systems), mirroring the roughly constant MZR scatter. In the context of the equilibrium model, this again argues for a mass loading factor that increases to lower masses.

In summary, galaxies in our simulations with high SFRs at a given mass also have lower metallicities and higher gas fractions. This second-parameter dependence of the MZR and MGR is a natural and straightforwardly understood consequence of the equilibrium model. This dependence is independent of outflows and arises purely as a consequence of equilibrium. Quantitatively, the dependence of scatter on $M_{\ast}$ is a function of $\eta$ and $t_{\text{dep}}$, and models that have larger mass loading factors at lower masses better match observations of constant or mildly increasing scatter in the MZR and MGR to the lowest masses. The FMR provides an interesting tool to quantitatively examine the second-parameter trend with the SFR, and simulations yield broadly similar trends to those observed for the FMR.

6.2 Environment

Another second-parameter dependence of the MZR was noted by Cooper et al. (2008) and Ellison et al. (2009), who showed that galaxies within dense environments, such as groups and clusters, tend to have higher metallicities. Galaxies outside such environments, in contrast, tend to have no obvious dependence on local galaxy density. This trend is over and above any trend associated with SF. Our 48.8 h\(^{-1}\) Mpc volume has some galaxy groups up to virial masses of $\sim 10^{14} M_{\odot}$, but not enough to compare directly to observations of clusters. However, we can examine the trend
in metallicity with the environment as measured by local galaxy density.

Fig. 9 shows the \( z = 0 \) MZR for our four wind models, where we have subdivided galaxies by local galaxy density as measured in a \( 1 \, h^{-1} \, \text{Mpc} \) top-hat sphere. Galaxies at densities \( >0.5 \sigma \) above the mean are shown in red, \( <0.5 \sigma \) below the mean in blue and those in between in green. A running median for the MZR, with 1\( \sigma \) variance, is shown for each subpopulation.

The momentum-driven scalings and nw cases display the observed trend: galaxies in high-density regions lie above the mean MZR by \( \sim 0.05 \) dex, while galaxies in medium- and low-density regions show no discernible difference. The constant-\( \eta \) models show significantly less dependence on the environment. The differences disappear at the most massive end in all models.

One reason for this dependence may be that denser environments have more enriched intergalactic gas (e.g. Oppenheimer & Davé 2006), so the accretion on to galaxies in those environments is likely to boost the metallicity over galaxies in a less dense region. We believe this is indeed the trend responsible, but how this operates is subtle, and gives rise to distinct features among the wind models.

The model trends are best understood if the metallicity of infalling gas is governed by wind recycling. Recall that the IGM is almost entirely enriched by winds (e.g. Oppenheimer & Davé 2006), and so any metals falling back into galaxies constitute wind recycling. At high masses, wind recycling is so effective that all galaxies re-accrete their ejected material quickly (Oppenheimer et al. 2010), which is like having no winds at all, so the metallicity approaches the overall yield regardless of the environment (modulo an increase due to enriched infall; see Section 7). At sufficiently low masses, all ejected material escapes, and hence the infalling material is mostly primordial, regardless of the environment. However, in the intermediate regime, the environment plays a critical role in slowing winds (Oppenheimer & Davé 2008), in the sense that denser regions slow winds more and cause faster recycling.

As shown in Oppenheimer et al. (2010), in the case of momentum-driven scalings, this intermediate regime occurs over a protracted range in \( M_* \) since \( v_w \propto v_{\text{esc}} \); this protracted mass range is reflected...
in this model’s dependence of MZR on the environment. In the constant-$v_w$ cases (cw and sw), there is only a small range of masses between the fully escaping and fully recaptured regimes (around the mass where $v_w \approx v_{esc}$), which means that the environmental dependence is only seen over $\sim0.5$ dex in mass. Hence, in these models, the high-density MZR actually shows a peak in metallicity at the mass where recycling is most effective. It occurs at higher $M_*$ in the cw case relative to the sw case since its higher wind speed allows escape up to larger galaxies.

Empirically in our simulations, the dependence of metallicity on the environment seems to be only effective when the environment becomes quite dense; medium- and low-density regions show no difference. This is likely because only these dense environments have hot gaseous haloes (Kereš et al. 2009) that can significantly slow winds. The nw case also shows a dependence on the environment that is obviously not driven by wind recycling, but may be driven by tidal stripping (and subsequent enriched infall) which is more effective in dense regions; indeed, in Section 7, we show that the nw case at $z = 0$ has non-negligibly enriched infall. We leave a more detailed study of these effects for the future. Here we simply suggest that the environmental dependence of wind recycling governs how local galaxy density impacts the MZR, and our momentum-driven wind scalings model generally reproduces the observed trend. If this is true, then studying the environmental dependence of the MZR offers a unique probe into the cycle of baryons in and out of galaxies.

6.3 Satellites

Satellite galaxies are seen to have higher metallicities at a given stellar mass (Peeples et al. 2009). The origin of this trend is qualitatively understood within the equilibrium model: satellites tend to live in dense regions where the infalling gas is more enriched, and furthermore they are not straightforwardly fed by cold streams since they do not lie at the bottom of the halo’s potential well and hence evolve upwards off the MZR. In this section, we quantitatively assess the differences in satellite versus central populations for the various second-parameter trends we have examined above.

Fig. 10 shows the median MZRs for a variety of second-parameter dependences. In order to more easily see the dependences, we have subtracted the overall MZR from each subsample’s MZR. The plot shows $\Delta$[O/H] dependences on three variables: SFR, environment and satellite versus central galaxies. For the first two quantities, we subdivide the overall sample into ‘high’ and ‘low’, which simply means above and below the median within each mass bin. In the left-hand panels, we show the median (differenced) MZR for galaxies with high SFR as blue and with low SFR as red. In the right-hand panels, we analogously show the MZR for high-density-environment galaxies in red, and low in blue. The top panels show the vzw simulation and the bottom panels show the nw run.

We further explore the dependence of the SFR and environment within satellite (dotted lines) and central (dashed lines) galaxy samples. This is done for the full sample (black): high SFR/low density (blue) and low SFR/high density (red). The solid line at 0 represents the original MZR of all galaxies. In all, this figure shows how the dependences on the SFR and environment interplay with the distinction between central and satellite galaxies.

Let us begin examining Fig. 10 by considering the blue and red solid curves, that is, the MZR subdivided by SFR and environment. These trends have been noted earlier, but here the differences are more visible since we have subtracted the overall trend. Comparing the solid red and black curves, we see that, as before, low-SFR and high-environment galaxies lie above the global MZR, at least for galaxies with $M_* \lesssim 10^{11} M_\odot$. The trend with the environment is generally stronger than the trend with the SFR, which may be surprising, given that this second-parameter dependence has received less attention in the literature. In the context of the equilibrium model, this indicates that denser environments result in significant suppression and enrichment of inflow, such that galaxies within dense regions both have lower SFRs (causing higher metallicities) and are accreting higher metallicity gas.

The source of these trends is further clarified when examining the satellite galaxy population. Overall, satellite galaxies (dotted curves) show elevated metallicities at a given mass compared to central galaxies (dashed curves), mimicking observed trends (Peeples et al. 2009). Since satellites have typically lower SFRs (Paper I) and also tend to live in denser environments, both second-parameter dependences discussed previously could be contributing to the satellites’ higher MZR. A particularly striking result is that the second-parameter dependence on the SFR is fairly small in the central galaxies and is dominated by the satellite systems, that is, there is an enormous difference between the metallicities of high-SFR satellites (dotted blue line) versus low-SFR satellites (dotted red line) over most of the sub-$M^*$ mass range. The trend is very strong in the vzw run, but also present in the nw run. The detailed physical origin of this we leave for future work, but here we speculate that galaxies first entering another halo will have enhanced SFR due to interactions and therefore will have lower metallicities, but will then get quenched and quickly build up metallicity to go above the mean MZR. In any case, it is evident that in these simulations, the second-parameter dependence of the MZR on the SFR is driven more by the satellite galaxies, while centrals show only a modest such dependence.

Looking at satellites versus centrals subdivided by environment, it is not as clear here what is driving the overall trend. Both centrals and satellites show higher metallicities in dense regions. In the vzw model, this trend is somewhat stronger for satellites, but not as dramatically as in the case of the SFR. Satellites are affected by both diminished (from strangulation) and enriched inflow, while central galaxies should not have inflow enriched, only diminished since they should still accrete gas normally at the bottom of the halo’s potential well, regardless of the environment. That the strength of the affect is only slightly stronger for satellites indicates that the majority of the change to the MZR in dense regions arises because inflow is more enriched owing to residing in a denser region. It is worth noting that these changes in metallicity are, in an absolute sense, not large: they are typically below 0.1 dex. Therefore, even a modest metallicity–density gradient in the IGM (Oppenheimer et al., in preparation) could preferentially cause galaxies in denser environments to be over-enriched by this amount.

In summary, both the environment and SFR play an important role in driving second-parameter trends in the MZR. The majority of this trend is driven by satellite galaxies, as central galaxies are less affected by these second-parameter trends. This shows, as expected, that satellites have greater fluctuations in their accretion rates that drive SF and are more impacted by environmental effects. The overall trends are consistent with expectations from the equilibrium model, being driven by a competition between recent accretion and outflows. In the case of satellites versus centrals at a given stellar mass, the outflow rates are similar in the simulations (being zero in the nw case), but the accretion rates can vary owing to both general stochastic fluctuations and environmental suppression. The typical
difference in metallicities between satellites and centrals is quite small, typically of the order of 0.1 dex, so particular care is needed to tease out such effects in observed samples.

7 EVOLUTION IN GAS AND METAL CONTENT

We have previously studied the evolution of the overall MZR and MGR, finding that at a given mass, metallicities rise slowly and gas fractions fall slowly with time. In this section, we examine in more detail how particular galaxies evolve within these relations, in order to better understand the nature of the overall evolution. Fig. 11 shows galaxy tracks in MZR space (top panel) and MGR space (bottom panel) from $z = 2 \rightarrow 0$. We choose our vzw model since it does the best job of matching observations (with notable exceptions) of the models considered. To make these tracks, three representative stellar masses were selected at $z = 0$ (specifically $10^{10.13}, 10^{10.57}$ and $10^{9.95} M_\odot$), and 20 galaxies were chosen closest to each mass. The main progenitors of each galaxy were identified in each output back to $z = 2$, where the main progenitor is the galaxy at an earlier epoch hosting the largest fraction of the final galaxy’s particles. The tracks shown are the mean values of the 20 progenitors. Numbers along the tracks indicate the redshift, with the tracks ending in an arrow at $z = 0$.

The most evident trend is that galaxies tend to evolve mostly along the mean MZR and MGR, as noted by Brooks et al. (2007) for the MZR. This directly translates into a slow evolution for these relations. The fact that galaxies move along these relations has sometimes been forwarded as the ‘cause’ for the slow evolution, but this merely begs the question, why do galaxies tend to move along these relations?
Figure 11. Evolution from $z = 2 \rightarrow 0$ of the mean metallicity (top panel) and gas fraction (bottom panel) versus stellar mass for a set of galaxies within three mass bins in our r48n384 vzw run. The cyan and magenta points show the overall galaxy population at $z = 2$ and 0, respectively. The numbers along the tracks indicate the redshift; tracks end at $z = 0$.

To answer this, let us first consider the MZR. It is straightforward to differentiate equation (7) to show that if $\eta \propto M^{-1/3}$, then $d \log Z / d \log M = x$ when $\eta \gg 1$; this is the equilibrium model prediction for the slope of the galaxy track in MZR space at low masses, assuming that the constant of proportionality for $\eta$ for a given galaxy is unevolving.

Hence if a galaxy obeys equation (7) at all times, it will evolve directly along the MZR when $\eta \gg 1$. For example, in the vzw case, $x = 1/3$, which is identical to the MZR slope in the low-$M_*$ regime.

However, Fig. 11 shows that the evolutionary slope is steeper than this: for the lower mass bins, $d \log Z / d \log M \approx 0.6$. The more rapid evolution must arise because an assumption in equation (7) is violated. In particular, it turns out that the infall is not pristine as assumed in that equation. Fig. 3 of Oppenheimer et al. (in preparation) shows that the metallicity just outside star-forming regions (i.e. at $n_H \approx 0.13 \text{ cm}^{-3}$) rises substantially from $z = 2 \rightarrow 0$ and exceeds solar today. They argue that this arises owing to the preponderance of recycled wind accretion at later epochs, which causes the inflow from the IGM to be increasingly enriched.

Following Finlator & Dave (2008), we can extend equation (7) to include the effects of enriched infall. If we define $\alpha_Z$ as the ratio of infalling gas metallicity ($Z_{\text{infall}}$) to the metallicity within the ISM of the galaxy ($Z_{\text{ISM}}$), then

$$Z = \frac{y}{1 + \eta \left(1 - \alpha_Z\right)}$$

(11)

We can directly measure $\alpha_Z$ in our simulations. For a given mass, we take 50 galaxies near that mass and compute the mean metallicity within the ISM (i.e. star-forming) gas. We then compute the mean metallicity in infalling gas. We define infalling gas as all gas within 30 kpc (comoving) that is not star forming and is moving towards the galaxy (i.e. $v \cdot r < 0$). We also tried scaling the infall radius with the virial radius at different masses, with only minor differences.

The evolution of $Z_{\text{ISM}}$ and $Z_{\text{infall}}$ are shown as the solid and dotted lines in the top panel of Fig. 11. We show the vzw model at two masses and the nw case at $M_* \approx 10^{10} M_\odot$. The metallicity is higher around larger galaxies, as expected. The interesting trend is that $Z_{\text{infall}}$ increases faster than $Z_{\text{ISM}}$. This is quantified in the bottom panel where we plot $(1 - \alpha_Z)^{-1}$, which is the extra factor...
in equation (11) accounting for enriched infall. The key point is that, from $z = 2 \rightarrow 0$, this term increases by 0.2–0.3 dex. This is identical to the excess increase in the galaxy metallicity above simply moving up along the MZR (Fig. 11). The perhaps surprising implication is that the rising metallicity at a given stellar mass is not the result of galaxies processing more gas into stars, but rather the result of an increasing metallicity in accreted gas.

The nw case also shows a similar increase in $(1 - \alpha_2)^{-1}$ of about 0.2 dex from $z = 2 \rightarrow 0$. In this case, this arises because tidal interactions distribute metals around galaxies that can later fall back in. This has only become prominent since $z \sim 1$. Overall, the enriched infall term is much lower than in the vzw case, showing that most of the enrichment in the infall is generated by outflows.

The gas fractions of our selected galaxies also show an evolution generally along the relation. The evolution does become notably steeper at low redshifts ($z \lesssim 0.5$–1) and at small masses, which shows that the ‘turnover’ in low-$M_*$ gas fractions is a late-time phenomenon. These dwarf galaxies are apparently depleting their gas reservoir too quickly and are prevented from re-acquiring their ejected material owing to preventive feedback processes. We leave a fuller examination of the interplay between such feedback processes and the gas content in dwarf galaxies for future work.

In summary, the slow evolution of the MZR and MGR procedurally arises from the fact that galaxies tend to evolve mostly along these relations, with only mild deviations towards higher metallicity and lower gas fractions with time. Within the equilibrium model, the higher metallicities arise because gas infall is increasingly enriched to lower redshifts, while the lower gas fractions arise because the depletion time becomes smaller compared to the SF time-scale. While these trends are qualitatively consistent with the idea that galaxies obtain a large reservoir and slowly consume their gas (while generating metals), our simulations suggest that the actual physics are much more complex, driven by a balance between inflow and outflow processes.

8 SUMMARY

In this paper and in Paper I, we have presented a study of how the stellar, gas and metal contents of galaxies are governed by gas inflow and outflow processes within an evolving hierarchical Universe. In Paper I, we investigated how galactic outflows play a key role in modulating the stellar growth of galaxies fed primarily by cold, filamentary accretion from the IGM. In this paper, we have shown that such inflow and outflow processes concurrently govern the evolution of the metallicity and gas fraction within star-forming galaxies.

The central message of these two papers is that the evolution of the main constituents of star-forming galaxies can be broadly understood within the context of a cycle of inflow and outflow between galaxies and the IGM. An idea that features prominently in our models for the evolution of the gas and metal content is the notion of equilibrium. Galaxies prefer to live on specific equilibrium relations between the metal, gas and stellar content, whose forms are set by the cosmologically evolving inflow and outflow rates. The inflow rate into the ISM is tied to the accretion rate on to haloes, with notable departures at low masses and late epochs owing to preventive feedback. Meanwhile, the outflow rate appears to be most closely tied to stellar mass, since, for example, the metallicity of a galaxy is observed to have the tightest correlation with its stellar mass as compared to any other individual property. Inflow fuels SF, whereas outflows are the central governing agent that control how much of the inflowing material turns into stars. An key corollary of this scenario is that stochastic variations in the inflow rate tend to drive galaxies back towards the equilibrium relations, resulting in small scatter in metallicities and gas fractions that are correlated with the SFR. This equilibrium paradigm can therefore quantitatively explain the origin of the shape, slope and scatter of the relations between gas, metals and stars, as arising naturally from the hierarchical galaxy growth modulated by outflows.

With that framework in mind, we summarize the key conclusions of this paper:

(i) Galaxy metallicities are set by a balance between inflows that provides (relatively) pristine fuel and outflows that reduce the cosmological SF efficiency by ejecting fuel. This equilibrium can be expressed as a function of the outflow’s effective mass loading factor $\eta$ (equation 7), meaning that the stellar MZR mostly reflects the relationship between $\eta$ and stellar mass.

(ii) The evolution of the MZR in this scenario is expected to occur mostly along the relation, as confirmed by tracking simulated galaxies. In detail, there is a slow upward evolution in metallicity at a given stellar mass, that is, the MZR rises with time. We demonstrate that this is quantitatively understood as a result of accreted gas becoming more enriched with time.

(iii) Galaxy gas fractions reflect a competition between gas accretion, as quantified by the SF time-scale ($M_*/$SFR), and gas consumption, as quantified by the depletion time ($M_{\text{gas}}$/SFR) (equation 9). The depletion time in our models is set primarily by our assumed law for SF (based on the Kennicutt–Schmidt law), while the SF time is governed by cosmic inflow. Since both these time-scales are relatively insensitive to outflows, gas fractions are (in contrast to metallicities) likewise insensitive to outflows.

(iv) The stellar MGR drops slowly with time in all models. This arises because the gas supply rate, driven by cosmic accretion, drops faster than the gas consumption rate, which is tied to the galaxy’s dynamical time. Constant replenishment of ISM gas is a ubiquitous feature of these models, as appears to be required from observations. Galaxies individually evolve mostly along the MGR, but drop particularly at late epochs.

(v) Wind re-accretion plays an increasingly important role in the evolution of the MZR and MGR at late times, particularly at $z \lesssim 1$. Enriched inflow directly corresponds to the material that was ejected at an earlier epoch and alters the MZR (equation 11). In the MGR, all wind models develop a turnover at late epochs and low masses, likely reflecting the lack of the re-accretion of wind material in these systems.

(vi) The scatter in the MZR and MGR reflects how fast a galaxy can return to equilibrium, given a fluctuation in the accretion rate, as quantified by the dilution time given by $t_{\text{dep}}/(1 + \eta)$. The scaling of the MZR and MGR scatter with mass therefore provides an independent constraint on $\eta(M_*)$.

(vii) Departures from equilibrium naturally correlate with SF in all models, even without winds, as it is a consequence of equilibrium rather than feedback. Galaxies with high SFR for their $M_*$ are predicted to have low metallicity and high $f_{\text{gas}}$, consistent with observations. Galaxies in denser regions and satellites are also predicted to have higher metallicities as observed, since these systems are obtaining more enriched inflow and/or their inflow has been curtailed because they are not residing at the centre of the halo.

(viii) Comparing to observations of the $z = 0$ MZR, the equilibrium model with momentum-driven wind scalings predicts an unbroken power law of $Z \propto M_*/3$ with small scatter as broadly observed, while the constant-$\eta$ models predict a flattening of the MZR at low masses with a strongly increasing scatter. All models
qualitatively reproduce the observed slow evolution of the MZR upwards from $z = 3 \rightarrow 0$, but the momentum-driven wind scalings model comes closest to matching data at both $z = 2$ and $z = 0$.

(ix) Gas fractions at $z = 0$ in all wind models predict a falling $f_{\text{gas}}$ with $M_*$ at high masses and a turnover to lower $f_{\text{gas}}$ at the smallest masses. The former broadly agrees with data, while the latter is in clear disagreement with data. This turnover is related to a downturn in the sSFR and upturn in age in small systems (Paper I), and likewise may indicate that SF in dwarfs must be delayed on cosmic time-scales, perhaps owing to a different SF law or less efficient conversion of $\text{H}_1$ to $\text{H}_2$ in these systems.

Considering both metallicities and gas fractions in this paper along with stellar masses and SFRs from Paper I, our simulations with momentum-driven wind scalings provide the best ensemble match to available observations of the models considered here. Its general success hinges on having a higher mass loading factor in smaller systems, as well as not having a characteristic velocity scale picked out by the wind model that would translate into distinct features in relations such as the MZR that are clearly not observed. In both papers, however, we found that the model best matches at mass scales from $M^*$ down to moderately large dwarfs. At larger masses, it is clear that some form of quenching feedback is required, which is manifested here as overly high metallicities and a dearth of gas-free galaxies. At small masses, Paper I showed how small dwarfs have too low SFRs, which is accompanied here by too low gas fractions. Nevertheless, this is the first cosmological hydrodynamic simulation that provides a reasonable match to observed present-day galaxies around $M^*$ that contain the majority of cosmic SF.

Taking a broader view, the problem of galaxy evolution appears to be separable into three phases, predominantly divided by halo mass, which could somewhat fancifully be called the birth phase, the growth phase and the death phase. In the birth phase, haloes are small enough that photoionization plays a critical role in retarding accretion; these are galaxies below the so-called filtering mass (Oniedn 2000). In the growth phase, galaxy growth is regulated by baryon cycling, that is, by smooth, filamentary accretion and ubiquitous outflows that circulate mass, energy and metals between galaxies and the IGM. In the death phase, some mechanism (often associated with the feedback from the central black hole) quenches accretion into the ISM, thereby halting SF and creating a passive galaxy. Thus, the three phases are not only distinct in halo mass, but also have three separate dominant feedback mechanisms that govern galaxy growth, making galaxy evolution in each phase physically distinct from the others.

In this paper and Paper I, we have focused on galaxies in the growth phase. In this phase, the dark matter halo virial radius as a boundary between the galaxy and the IGM is of secondary importance: gas flows in and out unabated through the virial radius. Major mergers are a sub-dominant fuelling mechanism in such systems and are relatively unimportant in the overall SF history. Central black holes may be growing within these systems, but they play a minor role in the overall evolution. In contrast, the formation and evolution of passive ‘death-phase’ galaxies appears to be critically linked to major mergers, black holes with associated feedback and the presence of a stable hot gaseous halo (e.g. Keres et al. 2005) that demarcates the virialized region from the ambient IGM (e.g. Bower et al. 2006; Croton et al. 2006; Sijacki et al. 2007; Di Matteo et al. 2008; Hopkins et al. 2008; Somerville et al. 2008). The transition between the growth and death phases may be triggered by a major merger, such that bulge formation and black hole growth are linked (e.g. Hopkins et al. 2008), although it appears that maintaining a red and dead galaxy primarily relies on the existence of a hot gaseous halo (Croton et al. 2006; Gabor et al. 2011). While these phases are physically distinct, understanding the evolution of the galaxies in the death phase likely requires well-known ‘initial conditions’ provided by galaxies in the growth phase.

Many key aspects of the galaxy life cycle are far from being fully understood. It will be a transformative achievement in the galaxy formation community when even the basic framework is in place, and that work can begin towards a quantitative rather than qualitative understanding of the main physical processes (analogous to the era of precision cosmology). In these two papers, we have illustrated how simulations can be used to elucidate simple analytic relationships between physical processes of inflow and outflow and the observable properties of galaxies. We have shown that cosmic dark matter driven inflow combined with the mass loading factors, wind recycling properties and preventive effects of outflows govern the evolution of the basic constituents of galaxies. This provides a bridge between detailed studies of inflow and outflow, the latter being much more poorly understood, and large-scale surveys of galaxy properties across cosmic time. In other words, given a detailed model (e.g. from individual halo simulations) for outflow mass loading, wind recycling and preventive effects, we can now translate that with good fidelity into predictions for the evolutionary properties of galaxy populations. Alternatively, it allows observations of galaxy populations to be straightforwardly interpreted as constraints on the detailed properties of inflows and outflows. This scenario provides a first step towards understanding the much wider range of interesting observable galaxy properties, such as kinematics, radial gradients, morphologies and environmental dependences. Continuing to grow the synergy between multiscale models and mult wavelength observations of galaxies and their surrounding gas is the best way to advance our understanding of the life cycle of galaxies across cosmic time.

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