EVOLUTION OF THE MASS–METALLICITY RELATIONS IN PASSIVE AND STAR-FORMING GALAXIES FROM SPH-COSMOLOGICAL SIMULATIONS

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ABSTRACT

We present results from SPH-cosmological simulations, including self-consistent modeling of supernova feedback and chemical evolution, of galaxies belonging to two clusters and 12 groups. We reproduce the mass–metallicity (ZM) relation of galaxies classified in two samples according to their star-forming (SF) activity, as parameterized by their specific star formation rate (sSFR), across a redshift range up to \( z = 2 \). The overall ZM relation for the composite population evolves according to a redshift-dependent quadratic functional form that is consistent with other empirical estimates, provided that the highest mass bin of the brightest central galaxies is excluded. Its slope shows irrelevant evolution in the passive sample, being steeper in groups than in clusters. However, the subsample of high-mass passive galaxies only is characterized by a steep increase of the slope with redshift, from which it can be inferred that the bulk of the slope evolution of the ZM relation is driven by the more massive passive objects. The scatter of the passive sample is dominated by low-mass galaxies at all redshifts and keeps constant over cosmic times. The mean metallicity is highest in cluster cores and lowest in normal groups, following the same environmental sequence as that previously found in the red sequence building. The ZM relation for the SF sample reveals an increasing scatter with redshift, indicating that it is still being built at early epochs. The SF galaxies make up a tight sequence in the SFR–\( M_\ast \) plane at high redshift, whose scatter increases with time alongside the consolidation of the passive sequence. We also confirm the anti-correlation between sSFR and stellar mass, pointing at a key role of the former in determining the galaxy downsizing, as the most significant means of diagnostics of the star formation efficiency. Likewise, an anti-correlation between sSFR and metallicity can be established for the SF galaxies, while on the contrary more active galaxies in terms of simple SFR are also metal-richer. Finally, the [O/Fe] abundance ratio is presented too: we report a strong increasing evolution with redshift at given mass, especially at \( z \gtrsim 1 \). The expected increasing trend with mass is recovered when only considering the more massive galaxies. We discuss these results in terms of the mechanisms driving the evolution within the high- and low-mass regimes at different epochs: mergers, feedback-driven outflows, and the intrinsic variation of the star formation efficiency.

Key words: galaxies: abundances – galaxies: clusters: general – galaxies: evolution – galaxies: fundamental parameters – galaxies: groups: general – galaxies: star formation – methods: numerical

Online-only material: color figures

1. INTRODUCTION

Nearby galaxy clusters are dominated by bright, massive early-type (ET) galaxies, which mostly consist of old stellar populations. Models of galaxy formation are strongly constrained by star formation histories of ET galaxies, which in turn have been probed by different observational means of diagnostics. One traditional test for galaxy formation theories is the color–magnitude relation (CMr)—and more specifically the building-up of the so-called red sequence (RS) of ET galaxies. Clusters of ellipticals form a tight RS, which is classically interpreted as a mass–metallicity (hereafter ZM) relation (see Bower et al. 1992; Gladders et al. 1998; Hogg et al. 2004; McIntosh et al. 2005).

A complete model of galaxy formation has to face the question of reproducing both the photometric and spectroscopic observables—for example, Pipino & Matteucci (2008) have shown that the bulk of star formation and the galaxy assembly should occur simultaneously in order to reproduce at the same time all the chemical properties of present-day massive ellipticals, like the observed relations of [Fe/H]–mass and [Mg/Fe]–mass (as in Thomas et al. 2005). The latter relation stems from a collateral manifestation of the downsizing (the so-called chemo-archaeological), in which more massive galaxies present higher [α/Fe] ratios (Thomas 1999)—a trend interpreted with shorter formation timescales in more luminous objects (Matteucci 1994).

More widespread, the local ZM relation holds for all galaxy types, with the more massive being the metal-richer. Several observational studies have extended the ZM relation up to \( z = 1 \), finding a flattening with redshift (Savaglio et al. 2005, hereafter S05; Lamareille et al. 2009) and also with mass at any given \( z \), in the sense that the relation forms a plateau at high masses and gets steeper at the faint end. Erb et al. (2006, hereafter Erb06), Maiolino et al. (2008, hereafter M08), and Mannucci et al. (2010) have found a strong and monotonic evolution of the ZM
relation, with metallicity decreasing with redshift at a given mass and interpreting this as a side effect of a metallicity–gas fraction relation holding at $z > 2$. In particular when going to even higher redshifts ($z \gtrsim 3$), M08 found evidences for a stronger evolution at all masses, but especially for less massive galaxies—what they attribute to a downsizing effect. Likewise, semi-analytical works such as Vale Asari et al. (2009, hereafter VA09) found that more massive galaxies show very little evolution since a lookback time of 9 Gyr, having evolved fastly in the past—which supports again the downsizing framework. On the other side, Pérez-Montero et al. (2009, hereafter PM09) found a flattening at $z = 0.9$–1.2 with respect to the local relation, with most of the evolution driven by most massive galaxies: they ascribe this as a result of lower effective yields in more massive galaxies at higher $z$, according to the hierarchical scenario.

Within the hierarchical model, hydrodynamical simulations with chemical enrichment (but without supernova (SN) winds) by Tissera et al. (2005, hereafter TDRS05) and De Rossi et al. (2007) confirmed a ZM relation well established already at $z \sim 3$ and weakly evolving thereafter; its slope changes at a characteristic galaxy mass of $3 \times 10^{10} M_\odot$, below which the evolution is ruled by wet mergers affecting the resulting metallicity. Other cosmological simulations, including winds, by Dvè et al. (2011) explained the slow dropping of gas fractions and slow rise of metallicity with time (at given mass) as a result of an increasing metallicity in the accreted gas, infalling at a rate that decreases faster than the gas depletion rate.

In general, the origin of a ZM sequence has been linked to the higher efficiency of SN outflows at expelling metal-enriched gas in lower-mass galaxies (see Arimoto & Yoshii 1987; Gallazzi et al. 2005; Kobayashi et al. 2007). On the other side, the connection between star formation efficiency and ZM relation was evidenced, for example, by Tremonti et al. (2004), who found that star-forming (SF) galaxies at $z = 0.1$ exhibit a strong ZM relation. Brooks et al. (2007) and Finlator & Davé (2008) also concluded that SF efficiency is the primary driver of the ZM relation. In particular, Calura et al. (2009) demonstrated that it can arise as a natural by-product of the increasing efficiency of star formation (parameterized as star formation rate (SFR) per unit mass of gas) with galaxy mass, without need to invoke gas outflows producing metal losses in less massive galaxies. Similar conclusion was reached by VA09, while Gallazzi et al. (2005) argued that neglecting winds does not correctly reproduce the observations.

In any case, toy models without SN feedback or winds (the so-called closed box) have proven to result in early metal overproduction in low-mass galaxies and hence a too flat ZM relation (see Brooks et al. 2007), or in a general overestimated metallicity at all masses at high redshift (De Rossi et al. 2007; Finlator & Davé 2008). After all, outflows are to be considered as a natural and necessary mechanism to expel metals from the galaxy, yet their effects on the slope of the ZM relation are still not clear. In general, the latter depends on the effective metal yield (in turn depending on the cold gas fraction available to star formation) and the combination of inflows and outflows; under this scenario, S05 found that a closed-box model results in a steeper relation, and Erb06 concluded as well that their $z \sim 2$ data are better described by a shallower slope than the one deriving from significant outflows.

Ellison et al. (2008, hereafter E08) and Mannucci et al. (2010) have pointed at a relation between specific SFR (sSFR) and metallicity as a more general scaling relation in a threefold space including mass, SFR, and metallicity. Romeo et al. (2008, hereafter R08) have extended this dependency to the CMr itself, of which the ZM relation can be considered as an degenerate projection: therein the sSFR was proposed as a third variable to describe its evolution. Pérez-Montero et al. (2013, hereafter PM13) recently corrected the ZM relation to take into account the natural evolution of the SFR with redshift, consistently using for the first time a composite sample of galaxies spanning over a redshift range up to $z = 1.3$.

Indeed discrepancies arise in the available data about the dependence of the ZM relation on the SFR: relatively to local Sloan Digital Sky Survey (SDSS) samples, E08 had deduced a dependence of the ZM relation on sSFR at lower masses ($M_* < 10^{10} M_\odot$), according to which galaxies with higher sSFR have lower gas-phase metallicities for a given stellar mass by a factor $\sim 0.1$ dex with respect to the less SF; they impute this to different star formation efficiencies, in the sense that more intense past SF activity would yield higher present gas metallicity but lower current sSFR, inasmuch as more gas had been previously depleted. In sharp contrast to them, Lara-López et al. (2010) found instead a shallow yet positive correlation between SFR and metallicity at low redshift, by virtue of which high SFR galaxies tend to have higher metallicities. Yates et al. (2012) explain this result with a semi-analytical model (SAM) by which passive and massive galaxies have exhausted their gas reservoirs during a recent major merger that inhibited further star formation.

All in all, there remain still open two compelling questions about the evolution of the ZM relation: (1) whether it is mainly driven by galactic winds or just by the natural trend of the galaxy star formation history, and (2) whether the variation of its slope with redshift is more compatible with downsizing or with hierarchical assembling of stellar mass in galaxies. In this paper, we aim at studying both the absolute variation of metallicity with mass at different redshifts (the evolution of the ZM relation) and the evolution of its slope as well. The latter gives more precise indications about how the almost monotonic increase of metallicity with time at given mass depends in turn on the galaxy mass itself, hence representing an optimal diagnostic tool to shed light on both questions aforementioned.

In this work, we will consider two galaxy classes, according to their sSFR: SF and passive galaxies, separated by redshift-dependent thresholds mimicking the observed RS evolution (see Section 3). Caution has to be warned about coping with passive and SF objects within the same framework, since metallicity is measured by different methods in either of these: most of the observational data we are going to compare with refer to interstellar galactic metallicity that is commonly expressed in terms of oxygen abundance and derived from nebular emission lines in gas-rich or SF galaxies. For local ellipticals instead a luminosity-weighted stellar ZM is rather employed by aid of single stellar population (SSP) synthesis models (see Thomas et al. 2007). Current semi-analytical studies can employ either the stellar metallicity Z$_*$ (e.g., Pipino et al. 2009a; VA09) or the gaseous one (Sakstein et al. 2011). In general, besides being less prone to spectroscopic bias, as an intrinsic parameter the stellar metallicity allows us to probe metallicities at different epochs of galaxy evolution, which is this paper’s main scope.

Moreover, Gallazzi et al. (2005) have demonstrated a ZM relation holding with stellar metallicities, even though with an offset to lower values than nebular ones. Finlator & Davé (2008) confirmed that the metallicity of the parent gas cloud is mostly tracked by younger galaxies, whose UV-only luminosity-weighted metallicity overestimates by 50% the mean values in
SSPs. The main difference is that bolometric stellar metallicity traces all the past metal enrichment as a result of an extended star formation history, whereas nebular metallicity (or UV-only luminosity-weighted metallicity) rather only mirrors the more recent SF episodes (see also Sommariva et al. 2012). As a consequence, we prefer to rely on stellar metallicities as a more suitable parameter to combine with the other relevant one: the sSFR, defined as the aggregate SFR over the final stellar mass of the galaxy at that redshift, i.e., calculated at the same time as the galaxy age.

2. SIMULATIONS

In the simulations presented here we consider as standard recipe the “superwind” scheme, which has proven successful in reproducing many of the chemical and thermal properties of the intergalactic medium (IGM; Romeo et al. 2006; Figures 13, 14, 16, 18, and 19 therein demonstrate that models with weak stellar feedback are inadequate to account for the abundance levels of the IGM in clusters or groups). In particular, the star-to-IGM iron mass ratio in the models without outflows is strongly skewed toward a five times higher metal content locked up in stars than in the outer gas (at \( z = 0 \)); this means that a closed-box model tends by its nature to heavily overestimate stellar metallicity, as well as the interstellar medium (ISM) gaseous one (see below).

Our scheme works as follows: gas and metal galactic outflows are triggered by starburst episodes, their strength being proportional to the fraction of stars partaking in each starburst. Each star particle hosts an SSP of total mass corresponding to the stellar mass resolution of the simulation, which in this work is \( 4.43 \times 10^7 \, \text{M}_\odot \). The individual stellar masses are distributed according to an Arimoto–Yoshi initial mass function (IMF). Each of these SSPs represents a coeval and chemically homogeneous stellar population, characterized by its age and metallicity. The newborn stars evolve according to the IMF chosen and feed energy back to the ISM mostly by means of SN II: the energy from SN II is transferred to the ISM as thermal, whence a fraction is converted into kinetic energy of the expanding fronts.

At the same time, stars return to the surrounding gas also chemically processed material, leading to an increase in its cooling rate. The resulting stellar feedback is then the combination of energy (given by SN rate) and metal release. During the SSP lifetime, energy and metals are thus injected into the gas, according to a stochastic return model. The whole cycle of gas stars consistently follows the birth and evolution of the SSPs and their final “decay” again into gas particles through feedback mechanism; the latter will in turn regulate further episodes of star formation, and so forth. All the chemical yields are calculated within a non-instantaneous recycling model, taking into account the stellar timescales.

More details about the cosmological and SPH simulation are available in Romeo et al. (2006, 2008). New galaxy-finding algorithms have been implemented on top of the original simulations. It is worth stressing that most theoretical works on the subject, as well as many observational extrapolations at higher redshifts, have been developed under significant approximations: either the closed box (e.g., VA09; TDRS05; De Rossi et al. 2007; S05) or the instantaneous recycling chemical evolution (VA09). Remarkable exceptions are, for example, Davé et al. (2011), who ran N-body + SPH simulations within the same rezooming paradigm as ours and adopted similar physical modules; they however focused on field galaxies and in addition experimented with variable winds.

The individual galaxies selected are then assigned a luminosity as the sum of the luminosities of its constituent star particles, in the classical broad bands \( UBVRIJHK \). For each SSP, luminosities are computed by mass-weighted integration of the Padova isochrones (Girardi et al. 2002). Thus, the physically meaningful quantities of our data are age and metallicity, from which colors are derived. All results are here presented for (total, O, and Fe) mass-weighted metallicities, but data are also available for Si and Mg and for luminosity-weighted metallicity as well.

3. SAMPLES AND METHODS

The targets selected from the cosmological simulation were one cluster of \( T \approx 3 \) keV, one of \( T \approx 6 \) keV, and 12 groups (\( T \approx 1.5 \) keV), four of which are fossil. The two clusters are in different dynamical stages of their evolution, the larger being less relaxed and hence dynamically younger (undergoing the last major merger at \( z \approx 0.8 \)) than the smaller (for which the last major merger occurred at \( z \approx 1.5 \)); notwithstanding, we have stacked their galaxies together, aiming at reproducing the natural cosmic variance observed at any epoch.

All simulated galaxies belong to a class of environment, which in the clusters is a function of radial cluster-centric distance, corresponding to regions inside and outside a threshold radius of \( 1/3 \, R_{\text{vir}} \) (with \( R_{\text{vir}} = R_{\text{R08}} \)). All in all, there are four classes of galaxies: the two cluster cores (IN), the two cluster outskirts (OUT), the eight normal groups (NG), and the four fossil groups (FGs).

The issue of defining a consistent selection of RS members to be compared with observations at different redshifts is a crucial one. To this purpose, we have considered two different galaxy samples:

1. The dead sequence (DS) sample, which belongs to all and only those galaxies having sSFR below a threshold that has been defined as slowly progressive with redshift: from \( 10^{-2} \) (at \( z = 0 \)) to \( 10^{-1} \) (at \( z = 2 \)) \( M_\odot \, \text{Gyr}^{-1} \, \text{M}_\odot^{-1} \). By virtue of its color-independent definition, the DS may be considered as the model equivalent of the observed RS (see R08).

2. The star-forming sample, comprising galaxies having sSFR higher than the above threshold value. These objects correspond to the blue cloud in the color–magnitude (CM) plane (see R08).

We are using a separation in sSFR (=sSFR/\( M_* \)), rather than SFR simply, because the former is a parameter closer to the star formation efficiency, defined as proportional to SFR/\( M_{\text{cold}} \) (see, e.g., Sakstein et al. 2011). As such, sSFR allows a more direct analysis of the SFR–Z–M* plane as introduced by Mannoni et al. (2010). In fact, if one defines the efficiency such that \( SFR = \epsilon M_{\text{gas}} \) (from a Schmidt–Kennicutt unit power law), then \( sSFR = \epsilon (M_{\text{gas}}/M_*) \), that is, sSFR and star formation efficiency are linked by a factor which is a function of the gas fraction only (see Lilly et al. 2013).

The redshift dependence of the threshold is empirically mimicking the decreasing SFR with time (see, e.g., Lilly et al. 1996) and is quantitatively equivalent to common parameterizations used in SAMs (see again Sakstein et al. 2011). It is also compatible with observationally established divisions of the CM plane in order to define the RS on a color base (see Bell et al. 2004).

As a general matter, any comparison with and between data is affected by both aperture effects and different metallicity indicators used: this is true up to the extent that it is seldom possible to place different samples on the same metallicity scale, due to the lack of conversion factors between the indicators (see...
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Figure 1. Relation between SFR and stellar mass at different redshifts for the four galaxy classes considered: cluster IN (diamonds), cluster OUT (circles), normal groups (squares), and fossil groups (triangles), all classified by their mass-weighted total metallicity $Z_*/Z_\odot$: blue ($<0.5$), cyan (0.5–1), green (1–1.5), magenta (1.5–2), and red ($>2$). Data (long-dashed lines) at $z = 0$ are from SDSS, at $z = 1$ (Elbaz et al. 2007) and $z = 2$ (Daddi et al. 2007) from GOODS—all for star-forming galaxies; all are compared with the Millennium simulation (Kitzbichler & White 2007; dashed). The dotted curve gives the threshold in sSFR considered to select the active and passive samples (see Section 3).

(A color version of this figure is available in the online journal.)

Erb06; Foster et al. 2012; PM13). The estimation of the global trend of the ZM relation at different cosmological epochs is possible only through the analysis of statistically significant samples, provided that we are consistently adopting the same calibrations: in particular PM09 warn against a selection bias toward galaxies with bright emission lines and hence lower metallicities, while Andrews & Martini (2013) claim that the commonly used method of strong line ratios needs a complicated empirical calibration resulting in an indirect approximation to real metallicities.

Due to internal metallicity gradients in galaxies (see Tortora et al., 2011), also the choice of aperture is critical in order to compare with observational results; Kewley & Ellison (2008) calculated that different apertures in the SDSS can account for a $\sim 0.15$ dex offset between nuclear and integrated metallicities. This may lead to an uncertainty in the metallicity which is approximately of a factor two, that is, about the same as the observed difference between the amplitudes of the ZM relation for $z \sim 2$ and local galaxies (Erb06). However, Ellison et al. (2009, hereafter E09) have demonstrated that the ZM relation with stellar metallicity is much less affected by aperture cuts in terms of half light radii than that with nebular gas metallicity.

Throughout this work, the colors of our brightest central galaxies (BCGs or CD) were corrected using fractional apertures in terms of the virial radius (that is, $0.003 – 0.008 R_{\text{vir}}$, with $R_{\text{vir}}$ decreasing with redshift: the resulting value is approximately equivalent to $R_{\text{eff}}$ for the CD), in order to cut the diffuse envelope out; thus, we excluded the intra-cluster stellar component, whose profile can often be superposed to the extended BCG one (see Sommer-Larsen et al. 2005 for more details). Moreover, we cut the innermost 10 kpc out of the BCGs, since in many cases the presence of excess young stellar populations therein affects the galaxy color, resulting in a bluer position within the CM plane (see R08). Consequently, the whole CDs were accounted for their magnitude and the aperture-corrected ones for their color.

Finally, as anticipated in Section 1, we can choose to model our results in terms of the gaseous or the stellar metallicities that are more suitable to describe, respectively, the SF or the passive galaxies. However, in order to attain a more consistent description that is valid for both samples, and also due to the larger uncertainties met in binding the gas particles to the galaxy stellar component within a self-consistent radius, in the following we will limit our analysis to the stellar metallicities only— with the exception of Section 4.3, where results for the gas abundances are presented as well for reference.

4. RESULTS

4.1. Evolution of the SF Efficiency

It is noteworthy to remind here that all our galaxies follow on average an SFR evolution such that the SF activity is steeply declining since $z = 2$ (see Romeo et al. 2005), consistently with Madau plots for both cluster and field galaxies. To this respect, Figures 1 and 2 show the SFR and sSFR as a function of stellar mass, respectively, at different redshifts, where the threshold introduced in Section 3 is evidenced (dotted lines). First of all, both the SFR–mass correlation and the sSFR–mass anti-correlation are fairly reproduced. Our galaxies are compared with the well-established relations observed at $z = 0$, 1, and 2, from SDSS and GOODS data for SF galaxies: good concordance can be evidenced, except at $z = 2$, where the simulated active galaxies lie below the observed average. Apart from the
normalization, the evolution of the two galaxy populations can be followed across time: a passive sequence of low-metallicity galaxies starts being built at least from $z = 2$ and from the low-mass side; higher-metallicity and higher-mass objects begin to fall down onto this passive sequence just after $z = 2$, filling the mass gaps until completing the horizontal sequence at around $z = 0.7$. At the same time, the active galaxies that have not yet fallen onto the passive sequence tend to form a tighter, although lesser populated, relation in the sSFR–mass plane; in the SFR–mass plot instead their scatter increases steadily with time, until the complete destruction of the original tight sequence. The next step to understanding this insight would be to extend such analysis to epochs beyond $z = 2$, in order to better discriminate the birth epoch of the SFR–mass sequence.

From the combined analysis of Figures 1 and 2 one can confirm the conclusions of R08, that is, the RS follows the same consolidating evolution of the sSFR, while parallelly the SFR–mass sequence breaks down with time. In general, our results are compatible with the SAM described in Lilly et al. (2013), where the sSFR of the “main sequence” of SF galaxies declines weakly with stellar mass as $sSFR \propto M_*^{-1}$, maintaining a tight dispersion at around 0.3 dex, and at the same time strongly evolving with redshift as $sSFR \propto (1 + z)^3$ at least up to $z \simeq 2$.

4.2. The Global ZM Relation

In Figure 5, the ZM relation is plotted for both classes of galaxies, colored according to their sSFR: at any epoch the galaxies with higher sSFR are those at intermediate mass around $10^{10} M_\odot$, but a definite trend is established at high redshift only above this mass, recovering that mass bimodality in the ZM slope is already reported in several works (see below). The SF galaxies (here all but the red-colored ones) smooth their slope with time, until merging with the DS at low $z$. The latter is well established at $z \simeq 0.7$ and presents a high scatter at low masses, probably due to an excess of overmetallic dwarfs. At high masses instead, the ZM relation is definitely shaped as a sequence in sSFR, namely, in star formation efficiency.

In Figure 6, we plot the stellar (mass-weighted) total metallicity as a function of mass, calculated as an average value in trend increasing with $\mu_{\min}$, with a scatter initially high at low-mass end and eventually, after a turnpoint of maximum scatter at $z \simeq 0.5$, increased at high masses. Not shown in the figure are the completely passive galaxies that occupy the bottom right corner in each plot, without any evolution besides the growing number of members with time. The metallicity generally increases with $\mu_{\min}$, but interestingly the nature of such a trend varies with whether the galaxies are further classified according to their SFR or sSFR: in the first case (Figure 3) the more active are also metal-richer, whereas in the second case (Figure 4) the metal-richer are those with lower sSFR, that is, lower efficiency in gas-to-stars conversion. Again this is in agreement with the simple analytical model developed by Lilly et al. (2013), where metallicity decreases as sSFR increases.
Figure 3. Relation between stellar metallicity and the parameter $\mu_{\text{min}} = \log M_* - 0.32 \log(\text{SFR})$ as defined in Mannucci et al. (2010); the polynomial fit proposed therein is plotted as a dashed curve. Galaxies considered here are only the star-forming ones, belonging to the four environmental classes (same symbols as previous figures) and colored according to their SFR: red (SFR < 2), magenta (2 < SFR < 5), orange (5 < SFR < 10), green (10 < SFR < 20), cyan (20 < SFR < 30), and blue (SFR > 30), in units of $M_\odot \, \text{yr}^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 4. Same as previous figure, with galaxies colored according to their sSFR: red (sSFR < 0.1), magenta (0.1 < sSFR < 0.4), orange (0.4 < sSFR < 0.8), green (0.8 < sSFR < 1.2), cyan (1.2 < sSFR < 1.5), and blue (sSFR > 1.5), in units of Gyr$^{-1}$.

(A color version of this figure is available in the online journal.)
each mass bin, at different redshifts, for both cluster and group galaxies, including DS+SF. The overall trend is approximately linear in the space ($\log Z$, $\log M_*$). However, we note that the relation gets steeper with redshift at the bright end in clusters, whereas at the faint end in groups: the higher-mass galaxies in clusters and conversely the lower-mass ones in groups are mostly responsible for steepening the relation since redshift 1, blending it toward either metallicity extreme, respectively.
VA09 have estimated the lookback evolution of local galaxies by applying a spectral synthesis code on SDSS data at $z = 0.1$ (within the closed-box approximation): a good overall agreement can be found with their points, except at the faint end ($M \lesssim 10^{10} M_{\odot}$) when they report a very steep relation that goes out of scale in both our Figures 1 and 9(b) (see below). Simulations from TDRS05, also without outflows, are plotted too: their mean metallicity decreases with $z$, but the trend with mass is shallower than ours and also than that by VA09, especially at the faint end at high redshift, where the absence of galactic winds overestimates metallicity in low-mass galaxies.

As for observational data, our results fairly match those by PM09 at $z \simeq 0.7$ and 1 over two orders of magnitude in mass, while they lie well below data from E09 at $z = 0.07$ from SDSS. The ZM relation from S05 at $z \simeq 0.7$, calculated as a linear best fit over a mean redshift, has a quite steep slope, leaving lower all other data (including ours) at the high-mass end; moreover, they do not find any significant evolution with respect to the two redshift halves of the whole sample. At $z \simeq 2$, our ZM relation finds good accordance with VA09 at high masses and with Erb06 and M08 at the low end. As to the slope at high redshift, VA09 and M08 present a much steeper relation with respect to Erb06 and TDRS05. In particular, the curvature of our ZM relation would be flattening at the high-mass end if excluding the highest mass bin (corresponding to the CDs), which is compatible with the quadratic best fit proposed by M08 (see panel at $z = 0.7$) and E08 (at $z = 0$).

However, the comparison with observational data and even among them is not straightforward: the slope evolution of the ZM relation is modeled in observational works as an extrapolation of redshift-limited samples, under some strong assumptions such as the closed-box model (S05), or by assuming an unchanged shape along with a joint shift in mass and metallicity (M08). In particular, the latter authors adopt the same empirical function of the local ZM relation by simply changing a few parameters in it, in order to provide the best fit to the observed data at other redshifts. In any case, it is worth noticing that there is no observational counterpart to our BCG mass bin that stands as outlier with respect to the extrapolated best-fitted quadratic curve at epochs $z \gtrsim 1$.

**4.3. Gas Abundances and $\alpha$/Fe**

In Figure 7, we have also plotted the gas-phase oxygen and total abundances, for the lesser cluster as reference, excluding the BCG. Here, our model attains two main results: first, the total gas abundance is at all epochs steeper than the oxygen one; and second, both show inappreciable evolution in either their slope or normalization.

In Figure 8, the $\alpha$/Fe relative abundance is plotted as a function of stellar mass for the same cluster at various epochs. Here, we get a flatter ratio than observed at low $z$. The overall trend is slightly increasing, and with virtually no change in slope, up to $z = 1$. On the other hand, the [O/Fe] inverts to decreasing at $z = 1.5$ and 2, when it also gets on average higher by a factor of two and three, respectively. As a general feature, a decreasing of the relative abundance with time at given mass is expected as long as star formation keeps converting iron-enriched ISM into stars, which in turn makes the initially high abundance ratio lower (see de la Rosa et al. 2011).

An increasing [$\alpha$/Fe] ratio with stellar mass in ET galaxies generally implies that more massive ellipticals formed earlier and faster than less massive ones and can be derived within a model with either star formation efficiency as an increasing
Figure 6. Logarithmic relation between stellar (mass-weighted) global metallicity and stellar mass at different redshifts, for clusters (purple triangles) and groups (green squares). Here, all galaxies are included. Error bars give the scatter around the average metallicity within each mass bin. Observational points are E09 from SDSS at $z \approx 0.07$ as dot-dashed curve (polynomial best fit), S05 at $z \approx 0.7$ (linear fit over a redshift range 0.5–0.9) as cyan dot-dashed curve, PM09 at $z \approx 0.7$ and 1 as blue open diamonds, Erb06 at $z = 2.2$ as dotted curve, and M08 at $z = 0.7, 2.2$ as dot-long-dashed curves (quadratic best fit). Also shown are simulations from TDRS05 at $z = 0, 1, 2$ (as dashed lines) and SAM by VA09 (as orange asterisks; including all environments). All data (except VA09) have been converted to mean metallicities by means of the approximation $12 + \log(O/H) = \log(Z/Z_\odot) + 8.69$, with $Z_\odot = 0.0134$ (Asplund et al. 2009). Testing with luminosity-weighted metallicities has yielded very similar results.

(A color version of this figure is available in the online journal.)

Figure 7. Mass-weighted oxygen (blue) and total (red) gas metallicity–stellar mass relation, as linear best fit for one cluster, excluding the CD. A minimum threshold of gas particles has been applied. Data symbols as in previous figure.

(A color version of this figure is available in the online journal.)

function of galaxy mass or a mass-dependent IMF, top heavier in more massive galaxies (Matteucci 1994). Calura & Menci (2011) ascertain that it is active galactic nucleus (AGN) late quenching of the starburst activity that can effectively account for the observed $\alpha/\text{Fe}$ ratio in ellipticals.

Yet, it is a meaningful indicator itself about the contribution of SN feedback to the total $\alpha$-enhancement of the ISM; under this scenario the increasing trend with galaxy mass at low redshift means that simple stellar aging prevails in more massive galaxies upon the SN channel in releasing $\alpha$-elements, while in less massive ones the latter is still the predominant mechanism in enriching the surrounding gas: from this comes the higher iron abundance relative to oxygen in smaller local galaxies. This picture is consistent with less massive galaxies being the site of enduring SF activity, hence of SN II episodes bringing forth starbursts, than more massive ones—provided that the SN Ia rate is of the same order across the two regimes. Arrigoni et al. (2010) support that a correct $\alpha$/Fe–mass relation can only be reproduced if a top-heavy IMF and a low fraction of binaries that explode as an SN Ia are assumed, which are both prescriptions adopted in our model.

At high redshift ($z > 1$) the trend overturns, consistently with a significant population of massive galaxies still in the course of active star formation at that epoch.
massive galaxies (\(z\) = 0) in the previous figure, excluding the CD. The stellar \(z\) = 0 (dotted line) is split for the passive and massive galaxies only (\(M_*>2 \times 10^{10}M_\odot\), green) and compared with data from Thomas et al. (2007) for an SDSS luminous-limited sample of nearby non-star-forming ellipticals (green solid). The stellar fits are calculated over a mass-limited sample at \(M_*>2.5 \times 10^{10}M_\odot\), below which the scatter is too high for a relation to exist. Bottom: the ratio between O/Fe in stars and in the ISM is plotted.

(A color version of this figure is available in the online journal.)

Figure 8. Linear best fits to the gaseous (upper) and stellar (middle) \([\alpha/Fe]\)-stellar mass relation at different redshifts, for the same cluster as in the previous figure, with redshift for all classes.

In the second panel, the stellar \([O/Fe]\) is plotted too: here a tight relation can be established only from \(M_*>2.5 \times 10^{10}M_\odot\), below which the scatter is too high to be compatible with a mass functionality. Under these limitations, the reported trend is here decreasing, with a smooth flattening with redshift. The stellar \([O/Fe]\) is lower than the ISM one at almost any mass for \(z<0.2\), that is, the distribution of \(\alpha\)-elements with respect to iron is skewed toward the gaseous phase. At \(z=2\), the ratio between the two is basically independent of the galaxy mass and is also fairly equiparted; since then, progressively lower-mass galaxies present higher metal content in stars than in the ISM, with the opposite for high-mass ones—\(log M_*>10.3\) being the turnover mass at \(z=1–1.5\) (bottom panel).

The \(z=0\) best fit is also presented considering the more massive galaxies (\(M>3 \times 10^{10}M_\odot\)) only, to be compared with data synthesized from an SDSS luminous sample of passive ellipticals (Thomas et al. 2007): both converge in giving a much steeper relation, which is also concordant with a semi-analytical model by Pipino et al. (2009a). In particular, our fit reproduces the same slope as observed in that mass regime, although at considerably lower values of \([O/Fe]\): the reason for this may be an excess of \(\alpha\)-enhanced satellites, as previously pointed out by, again, Pipino et al. (2009a).

4.4. Slope Evolution: The Passive Sample

We derive the slope of the ZM relation from the logarithmic relation plotted in Figure 6, as \(\alpha_{ZM} = \delta(log Z)/\delta(log M_*)\), which is equivalent to a power law \(Z \propto M_*^{\alpha_{ZM}}\). Its evolution with redshift is plotted in Figures 9 and 11, along with the scatter and zero point (or intercept at \(log M_* = 10.5\)) of the ZM relations calculated in the different samples. These plots further confirm the previous results outlined above for the overall galaxy population in Figure 6.

As a general feature, we first note that in all the cases studied the amplitude of the ZM relation (bottom panels) smoothly increases with time, confirming that earlier (less evolved) galaxies, presumably with higher gas fractions, have also lower gas-phase metallicities (cf. S05; Erb06), which translates into lower stellar ones as well. Moreover, cluster core galaxies have a higher metallicity than in groups and than cluster outer galaxies, irrespectively to their SF activity, and at all redshifts: this is in accordance with E09, who find an offset of \(-0.03\) dex between inner and outer galaxies in clusters.

The results of DS are displayed in Figure 9: we find that the slope of the ZM relation remains roughly constant with redshift, at average values between \(-0.2\) for clusters and \(-0.3\) for groups, with fluctuations more evident at higher redshift compatible with the Poissonian errors (which for passive galaxies increase with redshift). Its scatter maintains around \(-0.2\) almost constantly with time, and the mean metallicity decreases with redshift for all classes.

In particular, cluster cores stay at super-solar level throughout up to \(z \sim 1.5\), with an offset with respect to cluster outskirts comparable to that by E09. Although not explicitly separated in the plot, higher mean metallicity is presented by the larger, less dynamically relaxed of the two clusters, both in the core and in the outskirts. Moreover, a sequence can be drawn in the characteristic metallicity (third panel), going from cluster IN through OUT, FG, and NG, that is, the same environmental sequence found in R08 for galaxies to complete their approach to the RS.

When looking at DS massive galaxies only (\(M_*>2 \times 10^{10}M_\odot\), Figure 9(b)), the main result is that the ZM slope increases steeply with redshift (with the exception of cluster outskirts), indicating that the bulk of its evolution is mostly driven by more massive galaxies.

Comparing Figures 9(a) and (b) (with the aid of Figure 10, showing the slope and scatter ratios between the two samples), shows that the contribution to the slope is mainly given by the massive systems at \(z \gtrsim 1\), when it starts to deviate from that of the overall DS sample. Only in the outer cluster galaxies is the massive subsample contribution to the total slope overwhelming at all epochs, following a quasi-constant pattern: that is, massive outer cluster galaxies have a steep distribution in the ZM plane with little evolution in time. Opposite behavior is observed in massive group galaxies, which have a flat low-\(z\) ZM relation (especially FGs), but with a strong redshift evolution of the slope thenceforth.

In Figure 9(b), we also compare ours with the slope data points from VA09, limited to the massive end (\(M>1.5 \times 10^{10}\)) and averaged over all environments: they closely follow those of our cluster cores up to \(z \sim 1\). These authors indeed found a slight increase of the ZM slope up to \(z \sim 1.9\), when only considering the massive subsample; on the less massive side instead, the reported slope was much steeper, reaching extreme values of \(1.2\) at \(z = 0.7\), up to \(1.5\) at \(z = 1.9\)—which leads to a very strong mass bimodality quite at odds with any other data.

In both Figures 9(a) and (b), no significative evolution of scatter is reported; for massive galaxies, it remains almost constant again, yet at a value between 0.1 and 0.15, which is more than 0.05 dex lower with respect to the whole DS sample—namely, the scatter of the ZM relation for passive galaxies is dominated by low-mass systems.
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Figure 9. (a) Slope, scatter, and characteristic mass (calculated at log $M_\ast = 10.5$) of the ZM relation for DS galaxies: filled diamonds for cluster cores, open circles for cluster outskirts, blue triangles for normal groups, red squares for fossil groups. In the upper and bottom panels, we compare with simulations from TDRS05 (magenta open stars) and data from S05 (cyan solid circles). Error bars indicate the Poissonian error at each redshift and are only drawn for the slope for simplicity. Pairwise, overlapping data points are slightly offset in redshift for clarity’s sake. Here, a completeness limit of $M_\ast > 10^9 M_\odot$ has been adopted (see R08 for details). (b) Same as above for galaxies more massive than $2 \times 10^{10} M_\odot$ (same symbols). Data points for the slope are from VA 0 9 (orange asterisks, averaged over all environments) and S05 (cyan solid circles).

(A color version of this figure is available in the online journal.)

Figure 10. Ratios of the slope and scatter of the ZM relation for the massive DS to overall DS sample.

(A color version of this figure is available in the online journal.)

4.5. The Star-forming Sample

In Figure 11(a), we analyze the SF sample, with the caveat that only results from $z \sim 0.3$ onward can be considered significant, given the low number of SF galaxies found at lower redshift. Here, we compare with some of the many observational data available for SF samples at different epochs: their slopes at $z = 0.1, 0.7, 1,$ and 2 are consistent with our points for clusters, although they draw a quasi-constant evolution altogether. Indeed, our slope here evolves more rapidly than in DS galaxies up to $z \sim 1$, after which it gets almost constant too, and again higher in groups (first panel).

As for the scatter, it is increasing with redshift up to beyond a value of 0.2 (second panel). This is expected, since this is the same galaxy population of the blue cloud, reducing its scatter throughout their approach toward the RS (see R08).

As for the characteristic metallicity at given mass (third panel), in the galaxy cores it reaches a maximum at $z = 0.5$, thence decreasing along a hump-shaped curve: this reproduces to a very good extent the trend found by PM13, who pointed out a strong acceleration at increasing the oxygen abundance before $z \sim 0.5$, somewhat braked thereafter. Moreover, the metal abundance was around half the present value at $z \sim 1$ (average over all classes), which is consistent again with findings by these same authors.

In Figure 11(b), the contribution to the slope, scatter, and normalization by SF $M > 2 \times 10^{10} M_\odot$ galaxies only is analyzed. As in the DS, the slope evolution is dominated by more massive systems for $z \gtrsim 0.5$–0.7, except in outer cluster regions where the ZM relation steepens very slightly with redshift. Also the scatter keeps basically constant and at lower level than in the whole sample, indicating that it is mostly driven by smaller galaxies of the blue cloud at earlier epochs.

Finally, we compare in Figure 12 the respective ZM properties of both the DS and SF samples. For the slope (first panel), the ZM relation keeps slightly steeper in SF than in DS until $z = 1$ (IN), 0.8 (FG), and 0.6 (NG): this is consistent with the epoch when the SF galaxies complete their migration toward the RS, i.e., $z \sim 1, 0.7,$ and 0.5 for IN, FG, and NG, respectively, as from R08. A similar trend is followed by the scatter that is mostly
proceeding by the SF population at higher redshift than about 1, while in cluster cores and FG at low $z$ that of the DS sample is prevailing (second panel); SF galaxies in NG present higher scatter at almost all epochs. Such a trend simply follows that of $N_{\text{pas}}/N_{\text{act}}$ as outlined in R08.

Regarding the ratio of mean metallicities between the SF and DS samples (third panel), it maintains about unity until $z \sim 0.7$. Afterward, it undergoes an uprise, especially marked when calculated at $\log M = 9.5$, bringing it to values higher than unity within a redshift range from 0.7 to 0.2. Such a trend is explained by the slope’s behavior in the first panel: at nearer epochs than $\sim 0.7$, DS galaxies have a higher slope than SF ones, yet lower absolute metallicity; this results in a reduced difference between the mean abundance at $\log M = 10.5$ and that at $\log M = 9.5$. Conversely, for $z \geq 0.7$ the SF galaxies acquire a steeper ZM relation, while DS ones keep their almost constant slope: this gives rise to a positive $Z_{\text{DS}} - Z_{\text{SF}}$ at the lower-mass bin, while negative at higher mass.

These results are in partial accordance with Yates et al. (2012), who observed and modeled at $z = 0$ a low-mass galaxy population supporting an anti-correlation between mean (oxygen) abundance and SFR, whereas in the high-mass regime less active galaxies are metal-poorer, though their threshold in mass is $\log M = 10.5$, which gives little room for our high-mass end systems in the ZM plane. They explain this trend by massive local metal-poorer galaxies having undergone a gas-rich merger in the past, triggering a starburst that exhausted most of the cold gas, leaving little room for further star formation: in this scenario the turnover in the ZM relation would then be due to the dilution of the gas-phase metallicities in these systems. The inversion in the ratio we find at $z \sim 0.7$ can be due to similar mechanisms acting in our cluster galaxies as a delayed response to the major merger they experienced at $z \sim 0.8$–1.5, when bearing in mind that the SFR parameter as here defined traces the past SF activity over approximately the last Gyr. Pairwise, Lara-López et al. (2010) reported an SF population in SDSS galaxies, mostly composed of late-type, blue cloud galaxies, whose abundance is positively correlated with SFR, corroborating our findings at $z \lesssim 0.7$. In any case, it is worth stressing that we are here comparing two classes of galaxies whose chemical properties are observable by means of different diagnostic tools. In particular in this subsection, we are not focusing on the dependence of metallicity on SFR or sSFR that has been previously shown in Figures 3 and 4 for the SF only sample; rather we are here looking at the
average metallicity within each sample and at its variation with stellar mass.

### 4.6. The Role of Galactic Winds

In order to assess the effect of our superwind scheme on the outflow contribution to the variation of galaxy metallicities, we selected the largest ($M_\star \simeq 10^{11} M_\odot$) galaxy in the Virgo simulation at $z = 3.1$ that displays a clear asymmetric starburst driven outflow. Figure 13 plots $[\text{O}/\text{H}]$ for the (mostly hot) gas particles within 15 kpc galactocentric distance versus their radial velocity relative to the galaxy’s center. From this, one can infer the following:

1. Most SPH particles are outflowing in this frame.
2. The wind is highly metal-enriched with median $[\text{O}/\text{H}] \sim 0.7$–0.8 and mean $[\text{O}/\text{H}]$ even higher.

Identifying the gas particles belonging to the winds is not straightforward, since some of the particles with positive radial velocities may not be part of the outflow itself, but just have dynamical motions. We tried with different thresholds that could yield reasonable definitions of outflowing particle: in particular, if one defines the superwind as particles of $\log T > 4.5$ and $v_{\text{rad}} > +500$ km s$^{-1}$, then for these particles we found that the median $[\text{O}/\text{H}] = 0.65$ and the mean oxygen abundance is 6.76 times solar. Changing these values to looser ones of $\log T > 4.5$ and $v_{\text{rad}} > +300$ km s$^{-1}$ gives for their median $[\text{O}/\text{H}] = 0.53$ and a mean oxygen abundance of 5.25 times solar.

Besides this, we verified that in the same galaxy the cold gas ($\log T < 4.5$) with $v_{\text{rad}} < 0$, that is, potentially SF gas not affected by the asymmetric outflow, has a median $[\text{O}/\text{H}] = 0.15$ (mean $[\text{O}/\text{H}] = 0.45$). The young stars (age < 34 Myr) responsible for producing the outflow have a median $[\text{O}/\text{H}] = 0.12$ (mean $[\text{O}/\text{H}] = 0.48$), whereas the entire galaxy (all stellar ages) has an average $[\text{O}/\text{H}]$ about 50% lower than this.

We can conclude that the outflow is clearly significantly metal-enriched compared to the SF cold gas left behind in the galaxy, and also compared to the stellar component. We also extended such analysis to other galaxies at lower redshifts, confirming these main findings.

### 5. DISCUSSION AND CONCLUSIONS

Our cosmological-SPH simulations aimed at modeling in a self-consistent way the chemical enrichment of the IGM in reply to the stellar feedback (SN and galactic winds). The physical processes at work in the codes include metal-dependent radiative cooling, star formation, SN feedback generating galactic superwinds, and chemical evolution with no instantaneous recycling into the IGM. The combination of these modules allows us to reproduce most of the phenomena involved in the galaxy formation—namely, galaxy mergers, infalling of extragalactic gas, and outflows of enriched ISM, along with internal physics driven by stellar feedback.

We extracted galaxies belonging to different environments from simulated clusters and groups and analyzed their ZM relation and $\alpha$/Fe dependence on $z$ and mass. These were further classified as SF or passive (DS) according to their sSFR, in order to assess the contribution of star formation efficiency in shaping the ZM relations and their variation. We also studied how the SFR and sSFR vary with stellar mass, and besides this dependence of metallicity on each of these parameters, we attempted to classify different models of galaxy downsizing. Likewise, we compared different environments to evaluate relations between the three parameters ($Z$, mass, and SFR) and the ZM relation itself is shown to be dependent on setup choices such as the stellar (rather than gaseous) metallicity, the strength of galactic winds, or the IMF (top-heavy rather than Salpeter) in our models:

1. The SF galaxies make up a tight sequence in the SFR–$M_\star$ plane at high redshift, whose scatter increases with time as well as the consolidation of the passive sequence (Figure 1). At the same time, an anti-correlation between sSFR and stellar mass can be deduced (Figure 2), according to the paradigm of galaxy downsizing. Likewise, and relatively to the SF sample only, an anti-correlation between sSFR and metallicity can be established (Figure 4), while on the contrary more active galaxies in terms of simple SF are also metal-richer (Figure 3). These findings confirm the role of the sSFR as the most reliable tracer of the star formation efficiency. Moreover, the ZM relation itself is shown to be built as a sequence in sSFR, at least at high masses, while at low mass a high scatter prevails (Figure 5).
2. The overall stellar ZM relation gets steeper at $z \gtrsim 1$, due to low-mass galaxies in groups and high-mass ones (BCGs) in clusters. Yet when excluding the highest mass bin corresponding to the BCGs, its shape is compatible with quadratic functional forms estimated in particular by M08 at different redshifts (Figure 6).
3. The gaseous oxygen abundance presents very scarce evolution with redshift (Figure 7); its dependence on mass emerges however as shallower than observed at $z = 0$, perhaps due to an insufficient non-stellar feedback in our modeling of late massive galaxies (see Pipino et al. 2009).
4. The (both gaseous and stellar) [$\text{O}/\text{Fe}$] abundance ratio supports a clear trend to growing with redshift at given mass, following the natural iron enrichment of the ISM that occurs on longer timescales with respect to the SN II ejected $\alpha$-elements associated with early starbursts. Its expected increasing slope with mass is recovered provided...
that only more massive (than \(3 \times 10^9 M_\odot\)) galaxies are considered, though at lower level of stellar [O/Fe] than observed (Figure 8).

5. In the DS sample, groups present on average \(\sim 0.1\) dex higher slope than clusters. The summed up slope in groups is the result of a combined effect by high-mass galaxies at \(z \gtrsim 0.7\), and by low mass at nearer epochs. For cluster cores, the global slope is dominated by more massive galaxies from the same epoch \(z \sim 0.7\) onward. In cluster outskirts instead the whole contribution to the slope is given by high-mass galaxies at all redshifts, meaning that low-mass outer galaxies keep a quasi-flat ZM relation (Figures 9 and 10).

6. In the whole DS sample, little redshift evolution is observed for the slope in all environments. On the contrary, the slope of the ZM relation is increasing with \(z\) for high-mass only galaxies. This does not hold for cluster outskirts, where no slope evolution is reported even in the high-mass subsample (Figures 9 and 10).

7. The scatter of the ZM relation in the DS sample keeps fairly constant and tight over time. It is mainly dominated by low-mass galaxies, which lie on a \(\sim 0.05\) dex higher value with respect to higher-mass ones (Figures 9 and 10). The scatter in the SF sample instead is increasing with redshift and is higher than that of the DS at \(z \gtrsim 1\), indicating that the relation is still under construction at earlier epochs (Figures 11 and 12).

8. The slope of the ZM relation presents stronger overall evolution in the SF sample than in the DS, being higher at \(z \gtrsim 1\) and lower at closer epochs (Figure 12).

9. The characteristic metallicity (at log \(M^* = 10.5\)) decreases steadily with increasing redshift, in both DS and SF, clearly following the accumulation of metals with the cosmic time. This is confirmed as a universal behavior, as much well established as the corresponding decline in SFR in all galaxies, since a peak at some epoch slightly earlier than \(z = 2\) that is our farther redshift considered in the present analysis (see Romeo et al. 2005).

At all redshifts, it is highest in cluster cores (concordant with results by E09) and lowest in NGs: this may be correlated with the later lasting star formation activity in the latter systems, as found in R08. Moreover, SF galaxies in clusters follow an accelerating pace up to \(z \sim 0.5\), slowed down at nearer epochs. The difference in metallicity between massive and faint galaxies is more marked in the DS sample, where it amounts to twice at almost all epochs (Figure 9).

From the comparison between our two classes (Figure 12), we can evince that the characteristic metallicity in SF galaxies taken at log \(M^* = 10.5\) is slightly higher than that of DS at all epochs; when estimated at log \(M^* = 9.5\) instead, it is slightly lower for \(z \gtrsim 0.7\) for SF galaxies than in passive ones, but with an inversion at around that epoch, after which it gets considerably higher until recent times. Such a trend for \(z \lesssim 0.7\) is imputable to low-mass metal-rich galaxies contributing to flattening the slope of the ZM relation in the SF sample.

10. The effect of galactic winds triggered by SN events is to eject from the galaxy gas particles having higher metallicity than those of the SF gas and than the star particles as well (Figure 13). This translates into a lowered galaxy abundance and is presumably enhanced in lower-mass systems, where the outflows attain higher radial velocities—ultimately contributing to differentially changing the ZM slope.

To summarize, we find a ZM relation that is basically determined in its shape and evolution by its parameterization in terms of sSFR, that is, ultimately a function of star-forming efficiency (SFE). Moreover, a stronger evolution is reported for the metallicity of more massive and passive galaxies in cluster cores. Among the SF galaxies, the SFE is higher at lower mass at any epoch, while the DS galaxies present both SFR and sSFR independent of mass.

In addition to the natural variations of SFE, the role of galactic outflows is also shown as contributing to the global evolution of the ZM relation, even though its statistical effect is hard to assess on a global (rather than sub-grid) scale. Thus, the effect of mechanisms helping to recycle metals more efficiently in the IGM, at the same time hampering the star formation, cannot be neglected: processes in our simulations working toward this direction are either post-starburst strong winds triggering shocks or dynamical heating due to the hierarchical growth, e.g., (dry) merging and galaxy encounters. The latter mechanisms have been shown in R08 to be rather relevant above \(z \sim 1\) (see BCG mass growth in their Figure 9) and in dense environments, and this could actually explain the steeper slope profiles of cluster cores and groups with respect to the cluster outskirts earlier than that epoch (Figure 9(b)).

In fact, massive DS systems in cluster outskirts show steep ZM at all epochs (Figure 9(b)): such non-evolving ZM slope is a feature from our simulations for which we have no direct observational counterpart as currently evidences generally come from mixed environments. Moreover, they reach their maximum metallicity only at \(z \sim 0\), which suggests that here outflows acting to dissipate the metal accumulation are less efficient than in cluster cores.

These results indicate that during the dynamical phase of cluster pre-virialization some form of internal heating is relevant. Our simulations do not explicitly model AGN feedback: nevertheless, the role of AGN energy feedback in our simulations can be mimicked by the enhanced winds originating from post-(gas-rich)-merger starbursts associated with simultaneous SN II events. Although these continuous winds are unrestricted in time by construction, Antonuccio-Delogu & Silk (2008) demonstrated that AGN feedback is able to suppress star formation in circumnuclear clouds during timescales much longer than that of the AGN cycle itself. Moreover, our superwind scheme is likely as much effective as quasar-driven outflows in propagating metals at galactic scale, even though not yet sufficient to quench innermost star formation by direct energy injection. Then, the need for AGN feedback in reproducing the ZM relation would be less compelling than that demanded by the CM relation, where the lack of a proper AGN modeling hinders correct age and SFR (hence color) estimations at the center of massive galaxies (see R08).

The combined effect of outflows of processed gas and internal heating would act thus to shape the later stages of the DS building by shutting down star formation in more massive cluster galaxies, at the same time halting the metallicity uplift. This evolution proceeds starting from the inner galaxies following through the outer ones, with the latter not attaining yet the abundance peak till present time; instead, massive galaxies in groups and cluster cores progressively saturate up to their maximum metal content, at around \(z \simeq 0.5\)–0.2, while at the same time keep flattening their ZM relation (Figure 9(b)). Conversely, in the low-mass regime, which begins to dominate the slope in groups and cluster cores since \(z < 1\), the major feedback mechanisms acting on the ZM must rather be attributed
to SNe, whose rate depends only and directly on the SFR at any epoch (see Scannapieco et al. 2006).

Regarding the SF galaxies, they start migrating toward the DS as soon as a change in their SFE takes place, whether induced by shock-like events or by intrinsic nature; there they will grow their metallicity by internal shock heating, while low-mass ones keep metal-poor gas inflows regulating the metal balance in less active galaxies, resulting in a shallower ZM slope. Conversely, at $z \lesssim 1$, massive DS galaxies quench their residual star formation by internal shock heating, while low-mass ones keep metallicity as well as the relative flattening of their ZM slope, along with the positive correlation between metallicity and SFR. We expect to further corroborate such interpretation by applying different feedback recipes in our simulations, as to better evaluate their effect on the SFE.

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