Chemical pre-processing of cluster galaxies over the past 10 billion years in the IllustrisTNG simulations

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Accepted 2018 February 17. Received 2018 February 16; in original form 2018 January 9

ABSTRACT

We use the IllustrisTNG simulations to investigate the evolution of the mass–metallicity relation (MZR) for star-forming cluster galaxies as a function of the formation history of their cluster host. The simulations predict an enhancement in the gas-phase metallicities of star-forming cluster galaxies (10^9 < M_\star < 10^{10} M_\odot h^{-1}) at z ≤ 1.0 in comparisons to field galaxies. This is qualitatively consistent with observations. We find that the metallicity enhancement of cluster galaxies appears prior to their infall into the central cluster potential, indicating for the first time a systematic ‘chemical pre-processing’ signature for infalling cluster galaxies. Namely, galaxies that will fall into a cluster by z = 0 show a ∼0.05 dex enhancement in the MZR compared to field galaxies at z ≤ 0.5. Based on the inflow rate of gas into cluster galaxies and its metallicity, we identify that the accretion of pre-enriched gas is the key driver of the chemical evolution of such galaxies, particularly in the stellar mass range (10^9 < M_\star < 10^{10} M_\odot h^{-1}). We see signatures of an environmental dependence of the ambient/inflowing gas metallicity that extends well outside the nominal virial radius of clusters. Our results motivate future observations looking for pre-enrichment signatures in dense environments.

Key words: methods: numerical – galaxies: abundances – galaxies: clusters: general – galaxies: evolution – galaxies: groups: general.

1 INTRODUCTION

The chemical abundance of galaxies encodes the cumulative history of baryonic processes such as star formation and gas inflow/outflow. Observations clearly show that the cluster environment causes morphological and colour transformations of galaxies (e.g. Dressler 1980). However, the impact of cluster-scale overdensities on the
chemical evolution of galaxies remains controversial. Observations at $z \sim 0$ find a minimal difference (at most 0.05 dex) in the mass-metallicity relation (MZR) of cluster and field star-forming galaxies (Ellison et al. 2009; Pasquali, Gallazzi & van den Bosch 2012; Pilyugin et al. 2017). On the other hand, significant dependencies of the gas-phase metallicity on the cluster-centric distance and the cluster dynamic state are observed (Petropoulou, Vilchez & Iglesias-Páramo 2012; Gupta et al. 2016). Observations of the MZR at $z > 1.0$ are reported for only a handful of clusters with conflicting results (Kacprzak et al. 2015; Tran et al. 2015; Valentino et al. 2015).

In a hierarchical Λ cold dark matter (ΛCDM) Universe, massive clusters form through the merger of smaller galaxy groups. Physical properties of group galaxies may be modified prior to accretion on to the main cluster, a process referred to as ‘pre-processing’ (e.g. Zabludoff & Mulchaey 1998; Hou, Parker & Harris 2014). The most recent observational evidence of pre-processing includes H I deficiency and quenching of star formation in galaxy groups (Brown et al. 2017; Bianconi et al. 2018), though the significance of group pre-processing is debatable (e.g. Berrier et al. 2009). Darvish et al. (2015) find ∼0.10 dex higher metallicity for galaxies in a filamentary structure at $z \sim 0.5$ than the counterpart field galaxies, suggesting a pre-processing role of galaxy filament on the metallicity. Whether, when and how the chemical abundance of galaxies is altered in the cluster formation history remains an open question.

Current observations are plagued by poorly understood systematic errors such as projection effects, interlopers, selection biases, and metallicity diagnostics. These errors can easily overwhelm the chemical enrichment signal as a function of environment, particularly at high redshifts. In addition, the diverse definition of environment makes comparisons across different studies ambiguous (Ellison et al. 2009; Peng & Maiolino 2014). Cosmological simulations with a full three-dimensional formation history of cluster galaxies are a powerful tool to overcome observational biases and understand the physics of the environmental dependence of the chemical evolution (Davé et al. 2011; Bahé et al. 2016; Genel 2016).

In this Letter, we explore the MZR evolution as a function of the formation history of galaxy groups and clusters in IllustrisTNG, a large-scale cosmological simulation. Using a novel method of separating progenitor cluster galaxies into accreted and infalling categories, we report for the first time a clear systematic signature of ‘chemical pre-processing’ in cluster galaxies over the past 10 Gyr. We show the effectiveness of pre-enriched gas inflows in driving the chemical evolution of cluster galaxies out to twice the virial radius.

2 METHODS

Our results are based on the IllustrisTNG simulations (Marinacci et al. 2017; Naiman et al. 2018; Nelson et al. 2018; Pillepich et al. 2018a; Springel et al. 2018). The galaxy formation model is an updated and extended version of the Illustris model (Vogelsberger et al. 2013; Torrey et al. 2014). Details of the model modifications are described in Weinberger et al. (2017) and Pillepich et al. (2018b).

We use the TNG100 simulation that has a volume of (∼100 Mpc)³ and $m_b = 9.4 \times 10^9$ M⊙ h⁻¹, where $m_b$ is the baryonic mass per particle.

From the TNG100 simulation, we select all haloes with $M_{200} \geq 10^{14.0}$ M⊙ h⁻¹, where $M_{200}$ is total mass enclosed within $R_{200}$ (the radius within which the mean density is 200 times the critical density of the Universe at the halo redshift). This leads to a selection of 127 galaxy clusters and groups at $z = 0$. The mean cluster halo mass of our sample is $10^{13.4}$ M⊙ h⁻¹. We define the boundary of a cluster as twice the $R_{200}$ of the cluster halo, which is similar to the splashback radius (Diemer et al. 2017). Out of all friends-of-friends (FOF) subhaloes associated with the cluster at $z = 0$, all galaxies whether centrals or satellites residing within twice the $R_{200}$ make up our cluster member galaxy sample. Note that we exclude flybys and satellite galaxies in the process of splashing back at $z = 0$ from our analysis.

We restrict this analysis to a stellar mass range of $10^9$–$10^{10.5}$ M⊙ h⁻¹. The lower stellar mass cut is to minimize numerical uncertainties such that there are at least 1000 stellar particles per galaxy (a single star particle in TNG100 has a mass of about $10^5$ M⊙ h⁻¹). We impose the upper mass cut of $<10^{10.5}$ M⊙ h⁻¹ to reduce contaminations from active galactic nuclei (AGN) activities (Pillepich et al. 2018a). The removal of high-mass star-forming ($M_* > 10^{10.5}$ M⊙ h⁻¹) galaxies does not change our results significantly because environmental effects are more efficient for low-mass galaxies. We select 3567 cluster member galaxies with stellar mass $10^9$–$10^{10.5}$ M⊙ h⁻¹, without any star formation rates (SFRs) cut at $z = 0$. Most cluster galaxies at $z = 0$ are not forming stars.

Our field galaxy sample consists of 8900 galaxies at $z = 0$ that reside in host haloes of mass $M_{200} < 10^{12.0}$ M⊙ h⁻¹, have SFR > 0, and $10^3 < M_* < 10^{10.5}$ M⊙ h⁻¹. We focus on the SFR-weighted gas-phase metallicity represented in terms of fractional oxygen abundance (12 + log(O/H)) to facilitate a direct comparison with the nebular metallicity observations. Throughout this Letter the stellar mass and SFR are measured within twice the stellar half-mass radius. Our SFR-weighted gas metallicity is independent of aperture and has been found to provide a good approximation of the global metallicity from observations (Davé et al. 2011; Bahé et al. 2016; Torrey et al. 2017).

We track all $z = 0$ cluster and field galaxies back in time, but galaxies with stellar mass in the range $10^9$–$10^{10.5}$ M⊙ h⁻¹ and SFR > 0 at a given redshift, will only be shown in Figs 2–4. We use merger tree catalogue based on the technique of Rodriguez-Gomez et al. (2015) to track progenitors of the cluster and field galaxy samples at $z = 0$. At each redshift slice, we use the host halo of the progenitor central cluster galaxy to identify the cluster centre and the cluster boundary based on its $R_{200}$. We estimate $z_{\text{infall}}$ for each progenitor of the present-day cluster member galaxy as the earliest time (highest redshift) at which the galaxy crosses the cluster boundary ($R < 2 \times R_{200}$ of the central cluster halo) for the first time. Using $z_{\text{infall}}$, we separate progenitor cluster galaxies into two subgroups at each redshift slice: accreted ($z_{\text{infall}} > z$) and infalling ($z_{\text{infall}} < z$) galaxies.

This technique can unambiguously separate the infalling galaxies from the accreted cluster galaxies that are on their second passage into the cluster potential. At each redshift, the progenitors of the field galaxy sample form our comparison sample. Fig. 1 shows the assembly history of the most massive cluster in TNG100 ($M_{200} = 10^{14.4}$ M⊙ h⁻¹) through the projected spatial distribution of progenitors at a few redshift snapshots. At high redshift ($z \sim 1.5$), progenitor cluster galaxies have a comoving spatial extent of $\sim 10$–20 Mpc h⁻¹, consistent with the recent work by Chiang et al. (2017).

3 RESULTS

3.1 Cosmic evolution of the mass–metallicity relation with environment

Fig. 2 shows the stellar mass versus SFR-weighted gas-phase metallicity for our three galaxy samples (accreted cluster, infalling cluster, and field) at six different redshifts. We restrict our gas metallicity analysis only to galaxies with SFR > 0 at any given redshift. We bin the data by stellar mass such that each stellar mass bin has nearly the
same number of galaxies at $z = 0$. At any given redshift, we use the same stellar mass bins defined at $z = 0$ and only plot bins that have at least 10 galaxies. The MZR of accreted and infalling galaxies is consistent with the MZR of the field galaxy sample at $z = 2.0$. Signs of the environmental dependence of metallicity emerge around $z = 1.5$, in particular the low-mass accreted galaxies ($<10^{10.5} M_\odot h^{-1}$) are $\sim 0.05$ dex more metal rich compared to counterpart field galaxies. At $z \leq 1.0$, the gas-phase metallicity of accreted cluster galaxies shows a consistent metallicity enhancement of $0.15–0.20$ dex with respect to field galaxies.

The MRZ evolution of cluster and field shows a qualitative agreement with observations (Ellison et al. 2009; Pilyugin et al. 2017), though a detailed quantitative comparison with observations is not feasible because of discrepancies in emission line diagnostics (Kewley & Ellison 2008), the choice of nucleosynthesis yields in the simulations, diverse definition of environments, and selection effects. Most observations find a maximum of $0.05$ dex metallicity enhancement for cluster galaxies (Pilyugin et al. 2017), significantly lower than the one predicted by simulations. Contamination by interlopers or infalling galaxies due to projection effects and the lack of dynamic time estimates can easily wash out the metallicity enhancement in observations. Also, a higher SFR cut in observations specifically removes cluster galaxies undergoing change due to the environment. We test different SFR cuts and find a maximum SFR cut of $0.1 M_\odot h^{-1} yr^{-1}$ is required to observe the environment-driven changes in the metallicity, any higher SFR cut will dilute the observed metallicity enhancement.

The simulation shows a $1\sigma$ scatter of $\sim 0.20$ dex in the MRZ. The large scatter underlines the cluster-to-cluster variation and shows the challenge of detecting the metallicity enhancement with relatively small cluster samples in observations. Meanwhile, we notice that the scatter of the simulated MRZ at $z \sim 0$ seems to be large in comparison with observations (e.g. Pilyugin et al. 2017). We plan to investigate the origin of the scatter in more detail in a future work. Simulations predict no significant evolution in the average
metallicity of the highest mass bin ($10^{10}$–$10^{10.5}$ $M_{\odot}$) between $z = 2.0$ and $z = 0.0$ for any galaxy sample. The average metallicity in the highest mass bin is biased towards galaxies with either extremely low SFRs and/or significant AGN contribution.

3.2 Properties of gas accretion in high-density environment

To understand the origin of the environmental dependence of the MZR and the chemical pre-processing, we investigate the gas accretion history of our three samples using Monte Carlo tracer particles (Genel et al. 2013). At any given redshift, we measure the tracer flux associated with baryons entering the galaxy for the first time over a time interval of 1 Gyr. We then multiply the tracer count with an effective tracer mass to estimate a ‘raw gas mass inflow rate’ (Nelson et al. 2015). The median number of tracer particles associated with the gas mass inflow rate is about 800–15 000.

Fig. 3 shows the average gas mass inflow rate for the three samples (accreted, infalling, and field) in six redshift slices. We find that the gas mass inflow rate is consistently lower by 0.4–1.0 dex for accreted and infalling cluster galaxies compared to field galaxies across all redshift slices. The difference in the average gas mass inflow rate between cluster (accreted and infalling) and field galaxies increases slightly with cosmic time, i.e. increases from ~0.4 dex at $z = 2.0$ to ~1.0 dex at $z < 0.5$. Almost 50 per cent of accreted cluster galaxies with non-zero gas mass inflow rate and SFRs have been accreted on to the main cluster in the past 2 Gyr. In TNG100, cluster galaxies have on average 0.5 dex lower SFRs than field galaxies at all epochs. Torrey et al. (2017) show that the MZR of field galaxies evolves through either the accretion-dominant or enrichment-dominant phase.

Fig. 4 shows the redshift evolution of the mean metallicity of the inflowing gas. The average metallicity of the baryons associated with the raw gas mass inflow rate is defined as the mean metallicity of inflowing gas. The mass abundance of all metals used in Fig. 4 relates to the oxygen number abundance by a simple multiplicative factor (~0.03). The average metallicity of the inflowing gas increases with cosmic time, irrespective of the galaxy sample or the stellar mass bin. However, galaxies in the cluster environment (accreted or infalling) receive more metal-rich inflowing gas than galaxies in the field, and relatively more so at lower redshifts (Fig. 4). Even at $z = 1.5$, accreted cluster galaxies are receiving almost 1.3 times more metal-rich gas than field galaxies; at $z < 0.5$, the difference in metal content can be as large as a factor of 3. Yet, the inflowing mass gas rate is ~1.0 dex lower for cluster galaxies than field galaxies. We also find a secondary positive correlation in the metallicity of inflowing gas and the stellar mass, consistent with previous suggestions (Kacprzak et al. 2016; Fraternali 2017).

The average metallicity of the inflowing gas for infalling galaxies continues to lie in-between accreted cluster and field galaxies at all epochs (Fig. 4). In fact, at $z < 0.5$, infalling galaxies are accreting 1.5–2 times more metal-rich gas compared to field galaxies. The infalling galaxies have never crossed the boundary of the central cluster potential ($2 \times R_{200}$) and are receiving metal-rich gas compared to field galaxies, suggesting that enriched gas inflows can be significant at distances larger than $2 \times R_{200}$. Figs 3 and 4 suggest that the enriched gas inflows contribute significantly to the chemical enrichment of galaxies in overdense environments.

4 DISCUSSION AND CONCLUSION

Using the IllustrisTNG cosmological simulation, we demonstrate the first systematic signature of ‘chemical pre-processing’ of infalling cluster galaxies, namely galaxies that will be accreted by $z = 0$ into a massive host. Before infall, these galaxies exhibit a ~0.05 dex enhancement in the MZR in comparison to field galaxies, a difference observable at low redshifts ($z < 0.5$, Fig. 2). The simulation also predicts a systematic pre-enrichment of the gas that
is available for inflow into cluster galaxies (Fig. 4). At \( z < 1.0 \), cluster galaxies (both already accreted and infalling) accrete gas that is 2–3 times more metal rich compared to field galaxies.

We suggest that infalling galaxies exhibiting pre-processing signatures may or may not belong to smaller infalling groups, a distinction that will be clarified in a follow-up paper. The underlying pre-processing physical mechanisms do not act necessarily on the cluster galaxies themselves, but rather on the gas around them that is available for accretion. Gas removal via gravitational or hydrodynamic interactions in infalling groups has instead previously been suspected as the cause of pre-processing of infalling galaxies (Cortese et al. 2006; Scott et al. 2015). Our definition of cluster boundary to separate infalling and accreted cluster galaxies is similar to the splashback radius (Diemer et al. 2017). The signature of chemical pre-processing can be used as an observational identification for the splashback radius.

The metallicity enhancement of cluster galaxies on the MZR is qualitatively consistent with observations and recent investigations of cosmological simulations (Davé et al. 2011; Bahe et al. 2016; Genel 2016). Genel (2016) attribute the metallicity enhancement to either the reduced inflow of metal-poor gas or SFR concentration towards the inner, more metal-rich parts for galaxies with stellar mass \( \sim 10^{10.3} M_\odot h^{-1} \). Observations show that environmental processes are mostly effective for galaxies with \( M_\star < 10^{10} M_\odot h^{-1} \) (Peng et al. 2010). Gupta et al. (2017) show that star formation suppression in the galactic outskirts due to ram pressure stripping (RPS) cannot directly produce a significant enhancement in the SFR-weighted metallicity. However, a relative increase in the metallicity of cluster galaxies compared to field galaxies due to suppression of pristine gas inflow by RPS cannot be ruled out. We also consistently find lower gas mass inflow rates for both infalling and accreted galaxies compared to field galaxies in the simulation.

The pre-enrichment of the inflowing gas in clusters follows the cosmic evolution of intracluster medium (ICM) enrichment (Vogelsberger et al. 2018). Peng & Maiolino (2014) also suggested that the mixing of the inflowing gas with the metal-rich ICM can be responsible for the pre-enrichment of inflowing gas in the cluster environment. We speculate that the inflow of pre-enriched gas in combination with the suppression of gas inflows drives the chemical pre-processing of infalling galaxies and the metallicity enhancement of star-forming cluster galaxies. Carefully designed observations are needed to confirm the chemical pre-processing of infalling galaxies and the pre-enrichment signal in overdense environment.

ACKNOWLEDGEMENTS

PT was supported by NASA through Hubble Fellowship grant HST-HF-51384.001-A. MV acknowledges support from a MIT RSC award, the Alfred P. Sloan Foundation, and by NASA ATP grant NNX17AG29G. LJK gratefully acknowledges support from an Australian Research Council (ARC) Laureate Fellowship (FL150100113). TY acknowledges support from an ASTRO 3D fellowship. K-VHT acknowledges support by the National Science Foundation under Grant Number 1410728. Parts of this research were conducted by the Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), through project number CE170100013. The IllustrisTNG simulations and the ancillary runs were run on the HazelHep Cray XC40-system (project GCS-ILLU), Stampede supercomputer at TACC/XSEDE (allocation AST140663), at the Hydra, Draco supercomputers at the Max Planck Computing and Data Facility, and on the MIT/Harvard computing facilities supported by FAS and MIT MKI.

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