

Analysis of Fundamental Metallicity Relation and Mass-metallicity Relation Evolution Based on IllustrisTNG

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Abstract. IllustrisTNG and the corresponding programming API function are used in this paper to analyze the relationship between different values and parameters (e.g., mass, density and SFR) and metallicity, FMR and visualize the essential relations such as relationship of metallicities and galaxies' star formation rates (SFRs), gas fraction in galaxies with different redshifts and the stellar mass versus gas fraction at a given redshift. Based on the analysis, a path to a deeper understanding of the MZR properties and evolution is now paved by various results and conclusions. Based on the IllustrisTNG simulation, a major test of galaxy feedback models is the MZR, which simulates metal distribution and evolution. Based on IllustrisTNG simulations, MZR at redshifts 0 - 2 is generally in agreement with observations. A fundamental metallicity relation is supported by the model used and the conclusions presented in this article. In addition, this paper also focuses on the analysis of star formation rate associated with different values and parameters like redshifts with suitable example galaxies. For the relationship between the gas fraction and stellar mass, different z was fitted according to the relationship that M_{gas}/M^* is proportional to $M^{*\gamma}$, and for $z=0$, $\gamma = -0.32$. The fitting results agrees with the conclusion drawn, which states that as redshift increases, the relationship of gas fraction and stellar mass steepens.

Keywords: IllustrisTNG, galaxy formation, fundamental metallicity relation, star formation rate, mass-metallicity relation.

1. Introduction

IllustrisTNG is an extremely large-scale, cosmological simulation that can be used to develop a comprehensive tool to understand numerous physical process and cosmic evolution by analyzing the simulation directly and interpreting observational data through the Arepo moving-mesh code. Among the most significant simulation examples are those related to galaxy populations, galaxies, and stellar populations, for instance, the MZR in the gas phase and the mergers of black holes [1, 2]. For cosmological volume hydrodynamical simulations, IllustrisTNG simulations provide the best galaxy formation physics model. It incorporates a number of core physical processes involved in stellar evolution, such as galaxy formation and star formation, stellar feedback and gas cooling [3, 4]. A common limitation of galaxy dynamical models and virtual observations is the value of volume versus resolution, which has been overcome by the TNG model that compares simulated galaxies with those observed in the real universe [4-7].

There are various physical mechanisms involved in how galaxy environments affect galaxies' physical properties. Consequently, morphology-density relations, star formation rate-density relationships, and color-density relations result from these environmental effects [8-10]. In addition to making accurate predictions about galaxies and halos, IllustrisTNG simulations produce accurate predictions about gas distributions, stellar masses, and ultimately, the distributions of matter in total. It is impossible to predict how baryonic effects will affect dark matter distribution with any degree of certainty by (semi-)analytical models [11, 12].

For the cosmological parameters and initialized parameters the simulations used, the initial redshift $z = 127$ and Planck 2015 results from Planck Collaboration were used [4, 13, 14]. A simulation based on the Illustris galaxy formation model and the code AREPO explores the development and evolution of stars, chemical enrichment, simulated star formation, cooling with metal-line, stellar feedback with

galaxy outflows, and multimode feedback using the Illustris galaxy formation model. It solves ideal magnetohydrodynamic equations using a quasi-Lagrangian, moving, unstructured mesh [4, 14]. The mass metallicity relationship (MZR) describes how galaxies and their metal content coevolve over time. As for the rate of galactic star formation or masses of gas and the MZR scatter, the relation between them has been found over the past few years. A fundamental metallicity relation has been proposed, describing how the SFR, gas mass, metallicity and stellar mass are related. As more systematic and comprehensive analyses are performed, an extensive number of mass ranges and significant portions of redshift have been demonstrated to be valid for the FMR. It has been shown that theoretical models explain why the FMR occurs naturally [15, 16]. Nevertheless, the fundamental metallicity relation is still not conclusively supported by observational evidence.

The rest sections of this article is organized as following: Sec. 2 states data utilizing, analytical models and research methods related to different relations and findings explored using IllustrisTNG; Sec. 3 demonstrates the results and the discussion of the results; and Sec. 4 gives a brief summary on the research and the limitation, as well as the future direction.

2. Methods

2.1. Data Access and Background

In this paper, all the results are obtained by python API offered by the IllustrisTNG project and website tutorials and the conclusions are reached by analysis using the python API and tools on the IllustrisTNG website. As part of TNG, Illustris's web-based interface has been enhanced with new features and advanced functionality, meeting the requests of a wide range of users. It allows users to navigate simulation data and plot the relationships between quantities within group catalogs [1].

FMR explains how a galaxy's stellar mass is related to its gas-phase metallicity of its gas and SFR. Using mass-metallicity relation offsets (MZR), stellar masses can be associated with metal-metallicity relationships (FMRs). For the purpose of quantifying oscillation of galaxies around average stellar mass, stellar fractions, and metallicities, a hydrodynamical simulation is used. As indicated by IllustrisTNG, galaxy offsets from main sequence and main zone star formation will also result in a very prominent FMR. The galaxy's SFR and metallicity offsets appear to oscillate around equilibrium values as the galaxy's stellar mass varies [16]. A change in metal retention efficiency not primarily takes responsibility for the development and evolution of redshift in the MZR normalization, but rather the increase in gas fractions of galaxies at high redshift. According to the FMR observed, the scatter in a simulated MZR is directly related to its star formation rate or gas mass, according to the observed correlation. During the accretion and enrichment periods, metallicity evolution in the MZR is distorted due to competition. In a stellar mass with a fixed metallicity, it is expected that the strength of the metallicity and gas mass relation will not be strongly influenced by redshift because of MZR normalization decreasing with redshift [15]. There is recent research showing that a FMR is naturally produced in hydrodynamical simulations, and its properties need to be explored to better understand how it emerges [15]. As this relationship emerges, it is argued that the galaxies and the SFR need to share similar dominant evolution timescales in order for galactic offsets from MZR and SFMS to remain anti-correlated as they evolve [16].

2.2. Data analysis

First, the mass evolution of different components is analyzed with z varying from 2 to 0. Fig. 1 demonstrates two example's mass evolution. A histogram of SFRs versus the metallicity is displayed in Fig. 2, and the stellar mass is also shown in the histogram. The median MZR is implied using black lines. According to the residual correlation about the MZR, SFRs are low in galaxies that have high metallicities, and high in galaxies that have low metallicities [17, 18].

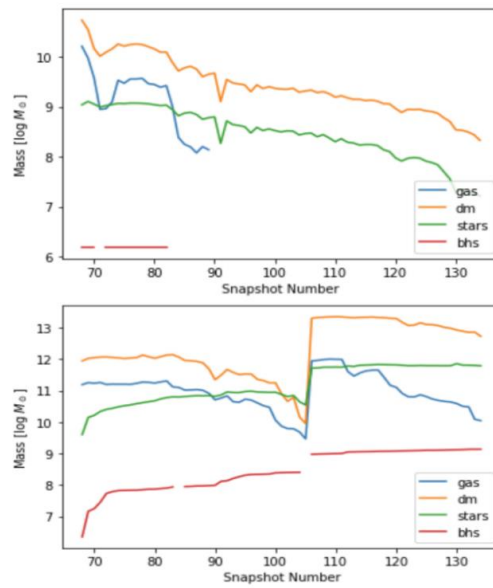


Fig. 1 The mass evolution of different components for Subfind ID 109975(upper) and 109974(lower) with Illustris-1, tracking from $z=2$ to $z=0$

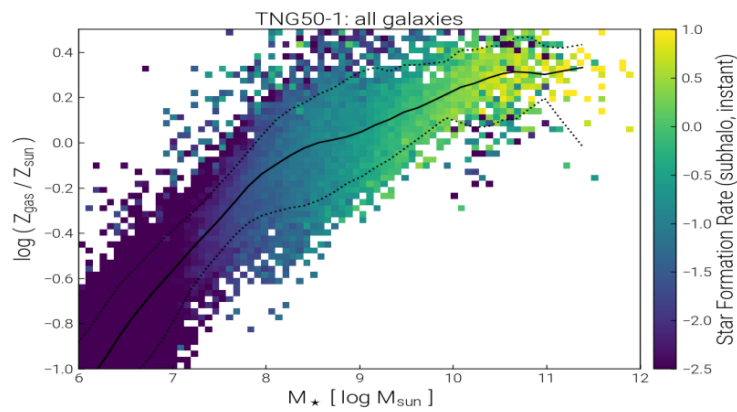


Fig. 2 metallicity versus stellar mass with SFR.

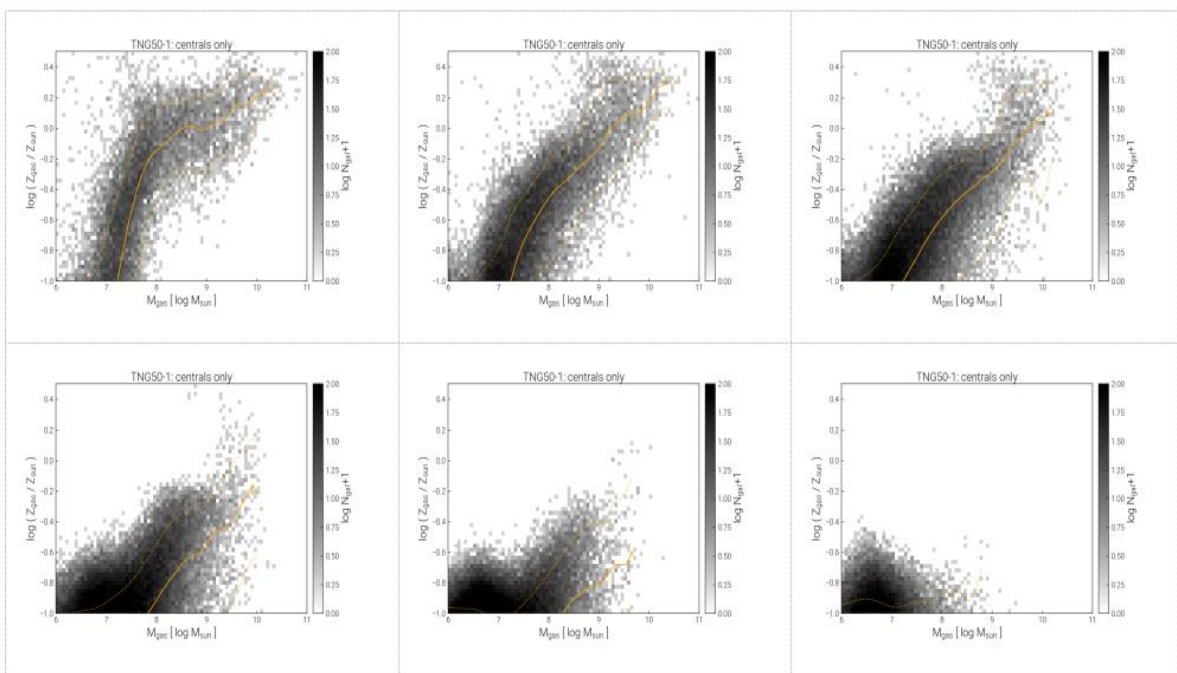


Fig. 3 The mass-metallicity relationship in the gas phase at different z values

Fig.3 demonstrates the relation with redshifts $z = 0$ (shown at upper left), $z=1$ (shown at upper middle), $z=2$ (shown at upper right), $z=4$ (shown at lower left), $z=6$ (shown at lower middle), $z=10$ (shown at lower right). As redshift increases, the normalization was found gradually declines, and the models are broadly in agreement with the MZR at low redshifts. It can be inferred that for high-mass galaxies, due to AGN feedback's dominated role, gas disks are not as well ordered and metallicity gradients are less clearly defined. Four gas fractions are plotted against stellar mass in Fig. 4. At higher redshifts, the gas fraction in galaxies increases significantly, which influences the evolution of MZR normalization. A comparison of MZR at higher redshifts with $z = 0$ shows that the normalization is continuously evolving, with lower normalizations at higher redshifts. After fitting each redshift and search for the best fitting independently, best fits was found to be a power law form: $M_{\text{gas}}/M^* \propto M^{*\gamma}$ and the best fit values is $\gamma = -0.3$ to -0.5 [15-19]. Generally, the relation steepens as redshift increases.

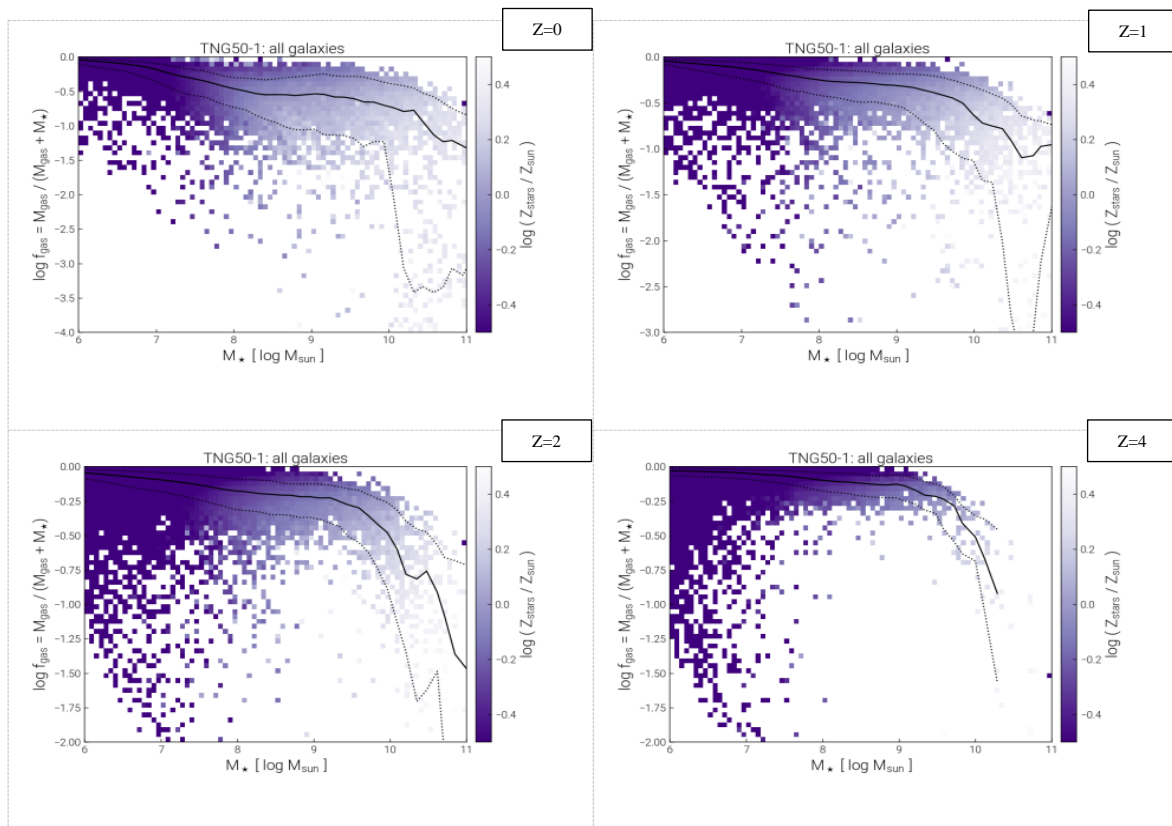


Fig. 4 Gas fractions versus stellar mass

3. Results and Discussion

As a result of the analysis, several results were obtained. Galaxy mass decayed with redshift when the redshift was fixed. For the same mass, galaxies with higher redshifts had larger gas fractions. The evolution of SFR and metallicity of higher redshift galaxies is shorter compared to their lower redshift companions. The evolution of MZR redshift is largely determined by the gas fractions of galaxies with high redshifts. High gas fractions lead to lower metallicities. It has been observed that high gas masses are associated with a rapid rate of star formation. MZR saturation metallicity is evolving with increasing redshift, indicating a decrease in the MZR normalization. At redshifts 0 - 2, the simulated MZR is generally consistent with observations, as evidenced by IllustrisTNG simulations.

When it comes to different best fits for different z in Fig. 4, for $z=0,1,2,4$, $\gamma = -0.32, 0.32, 0.41, 0.48$. And the fitting results keep consistent with the conclusion drawn, as redshift increases, the relationship of gas fraction and stellar mass steepens. There is still controversy over the existence or strength of the FMR although the model used in this paper and various research identify such a

relationship as plausible. Following a comprehensive discussion of the physical basis of fundamental metallicity and fraction calculations, the total gas mass, galaxies coevolution and halo size of the CGM should be studied further and future explorations need to consider these points in more detail. Accretion onto ISM by means of CGM can be significantly reduced in amplitude and frequency.

For identifying bursty from non-bursty galaxy formation feedback models, it is crucial to assess whether the FMR exists or is powerful at higher redshifts. There is a need to reconcile Illustris simulation results with observations in order to resolve the most significant tensions, further steps include seeking better models, improving resolution, and combining improved physics with ever more ambitious numerical realizations. In addition, examining the global metal budget more carefully may indicate areas where feedback modeling needs to be modified based on the IllustrisTNG results and observations.

For limitations and drawbacks, aside from the previous model's unresolved problem that need to be addressed quantitatively at sub-galaxy scales, there have been no satisfactory solutions to the problem of numerical resolution influencing hydrodynamical cosmological galaxy formation simulations.

4. Conclusion

In summary, analysis of the star formation rate, mass-metallicity relations, galaxy mass evolution and the fundamental metallicity relation based on IllustrisTNG was completed in this paper using python API and the IllustrisTNG website tools. A mass metallicity relation is analyzed within the TNG100 simulation, focusing on both its properties and evolution. The main outcomes and conclusions focused on Gas-phase mass-metallicity relation, relation of SFRs and metallicities and how they react with redshifts varying, gas fraction in galaxies at different redshifts, evolution of MZR normalization, how stellar mass decayed with gas fraction at a constant redshift and gas masses associated with star formation rates. Simulated MZR at redshifts 0 - 2 are generally in agreement with observations based on IllustrisTNG simulations. In addition, for the best fits for different z related to the association of gas fraction and stellar mass, the fitting results kept consistent with the conclusion drawn, a steepening relationship between gas fraction and mass is observed as redshift increases. This research offers a general insight into the MZR and how it evolved. There is still controversy over the existence or strength of the FMR although the model used in this paper and various research give evidence to support such a relation. Generally, this paper showed that a kilo-parsec spatial resolution hydrodynamic simulation model of structure formation can adequately analyze observed galaxies and reproduce their scaling relations.

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