The relationship between galaxy features at redshift z=0,1,2,4,6, based on TNG100-1 database

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Abstract. Contemporarily, in the era of big data, astronomical research also requires a large number of database collection and simulation applications. The TNG project is one of the important database projects. Nowadays, the large-scale galaxy survey IllustrisTNG project has collected a huge number of databases, which makes it easier to understand the characteristics of galaxies, including the mass and size of galaxies, gas mass, star formation rate, circular velocity, black holes, etc. In the development process of the TNG project, a large number of open data packages have been collected. TNG50, TNG100, TNG300 and other data packages contain various data of galaxies, which enables scholars to intuitively study the relationship between various features and quickly generate relationship plots. In this essay, the relationship of the galaxy features (i.e., stellar mass, gas mass and star formation rate) will be discussed based on the TNG100-1 data package on the IllustrisTNG program platform to visualize the relationship under different redshift values. According to the analysis, at different redshift values (z=0,1,2,4,6), there is a close relationship between the three directly, the data distribution plots also show that there is linear-like relationship between their common logarithm values to a certain extent, and can be expressed by series of formula. These results reveal connections between the fundamental properties of galaxies and shed light on guiding further researches of the properties and formation of galaxies.

Keywords: Star formation rate, Galaxy stellar mass, Galaxy gas mass, IllustrisTNG program.

1. Introduction

Contemporarily, the formation and evolution of galaxies remains a hot topic for astrophysics and cosmology based on theorem provided by modern cosmology as the basic framework. On this basis, it is suitable for investigating the morphological structure, star population composition, gas accretion, stellar evolution, black hole growth, chemical elements of galaxies in various periods of the universe through observation and statistics. The currently accepted galaxy formation theory holds that galaxies form and evolve in dark matter halos. Hot gas falls into the center of the dark matter halo, through gravitational collapse and accretion, cools and condenses into dense molecular clouds, which break up to form stars and even galaxies [1]. In general, the evolution of galaxies involves extremely complex physical processes, and its research not only requires the support of a large number of observational data, but also relies on computer numerical simulations of cosmology, including the demonstration for interrelationship of the physical properties of galaxies, the changes in physical properties (e.g., the mass of galaxies).

Nowadays, the IllustrisTNG project is one of the main forces in the large database open-source project [2]. One of the goals of the IllustrisTNG project is to make it more convenient and effective for people to study the evolution and formation of galaxies. It contains a series of large-volume, cosmological, gravitational magneto-hydrodynamic simulations run using moving grid codes, which serves as a powerful tool for our understanding of the origin and evolution of galaxy formation within them based on cosmological simulations. The TNG project consists of three simulation systems: TNG50[3], TNG100 and TNG300, each TNG simulation contains a comprehensive physical model of galaxy formation and self-consistently addresses plenty of phenomena. TNG100 simulations are of moderate resolution and use the same initial conditions and the same phases as the original Illustris simulations. A robust comparison is made between them. This paper will focus on three fundamental and important characteristics of galaxies. The relationship between them is summarized and summarized. In addition, the TNG100-1 database is used to simulate and visualize the relationship between the three to further verify and help us better understand these relationships.

The rest part of the paper is organized as follows, which will summarize the relationship between the galaxy features accordingly. Specifically, the section 2 will analyze the correlation among masses of the stellar and gas. The section 3 will investigate the relationship between stellar mass and star formation rate. The section 4 will discuss the relationship between gas mass and star formation rate. At the same time, the TNG-100 database of Illustris is used in each Sec. to make a relationship diagram between the three to intuitively reflect and summarize these relationships.

2. Relationship between stellar and gas mass

The most basic property of a galaxy is its mass, which is divided into stellar mass and gas mass by the constituents of a galaxy. The current mainstream view is that most stars are born in molecular clouds, and gas and dust begin to collapse under their own gravitational force, gradually forming various stars[4]. After a galaxy is formed, it is expected that there should be some relationship between the gas mass and the star mass. The math and equation between stellar and gas mass is given as [5]:

$$\log M_{H1} = 0.35(\log M_{\star} - 10) + 9.45 \tag{1}$$

Here, M_{H1} is the mass of H1 gas and the $M_{\star}$ is the stellar mass, the log value is the common logarithm with base 10. In this formular, one can see that there is a linear relationship between the common logarithm of the mass of the H1 gas and the common logarithm of the mass of the star, and the H1 gas is the main component of the gas cloud and the main component of the star formed by collapse.

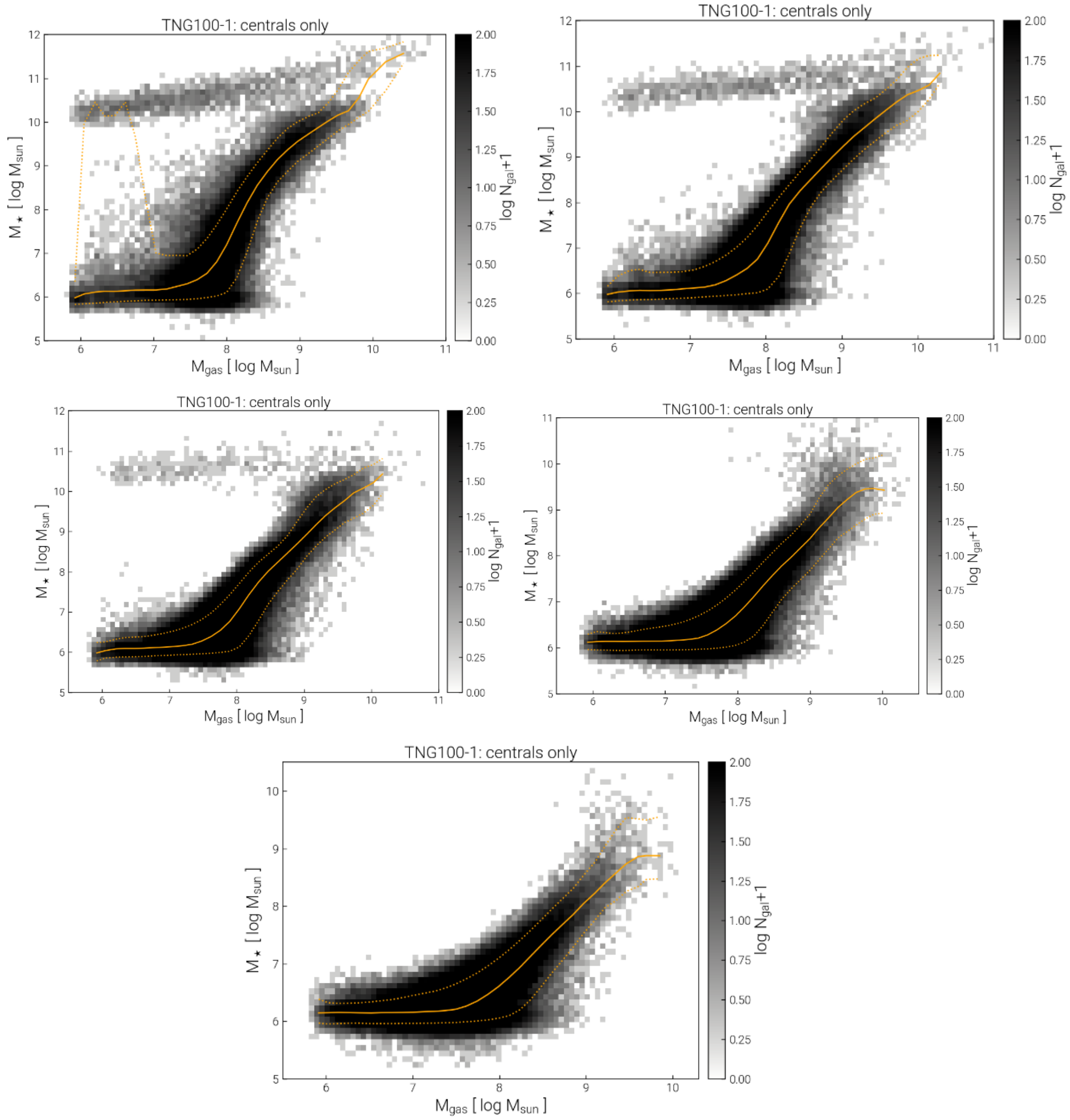

Figure 1 Plots of stellar mass vs gas mass in redshift z=0,1,2,4,6 based on TNG100-1 database.

Plots of stellar mass and gas mass made by TNG100-1 database are illustrated in Fig. 1. According to the figures, one can clearly see that there is an obvious proportional relationship between the two features. The relatively flat curve in the low stellar mass part (the slope of the relationship between log value of stellar mass and gas mass is close to 0) shows that for galaxies with smaller stellar mass, the proportional relationship between gas mass and stellar mass is not obvious. For galaxies with log value of stellar mass around 6 to 7, the log value of gas mass varies from 6 to 8. while for the larger stellar mass galaxy group, the log value of gas mass and stellar mass has an obvious proportional relationship with relatively stable ratio. With the redshift value increases the relationship ratio seems become more stable.

In addition, one can also find that at redshifts z=0, 1, 2, except to those galaxies which has ratio relationship between gas mass and stellar mass roughly distribute around the yellow median line, there are also a small number of galaxies distributed above. It is also clear that the stellar mass and gas mass of this part of galaxies are significantly proportionally distributed and have a stable slope that is less than 1. The slope of the relationship followed by this part of the galaxies is different from that of the most galaxies below. Moreover, as the redshift z value increases, the number of galaxies belonging to this part decreases. At redshifts z=4 and 6, there are no more galaxies in this category.

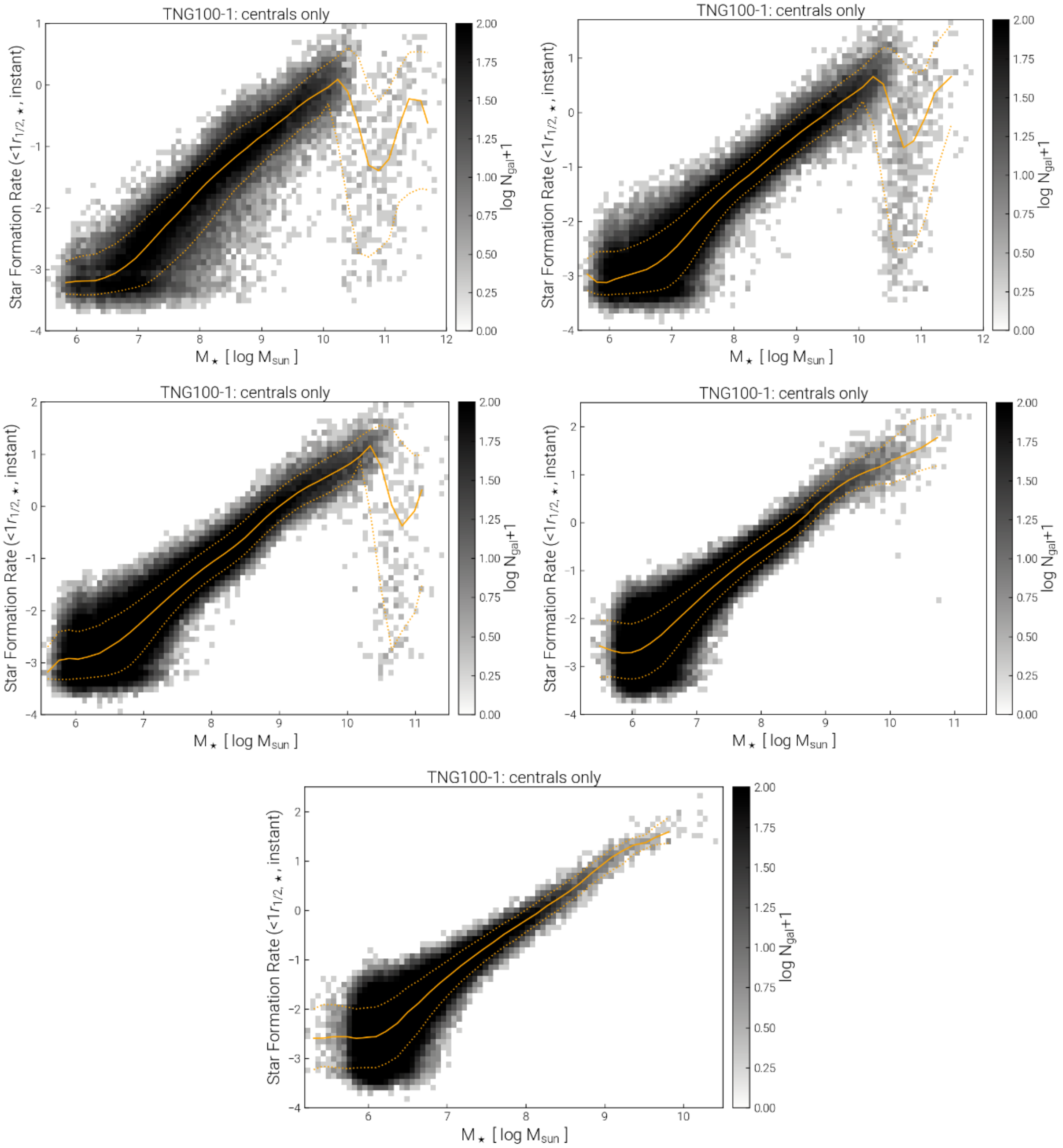

Figure 2 Plots of stellar mass as a function of star formation rate in redshift z=0,1,2,4,6 based on TNG100-1 database

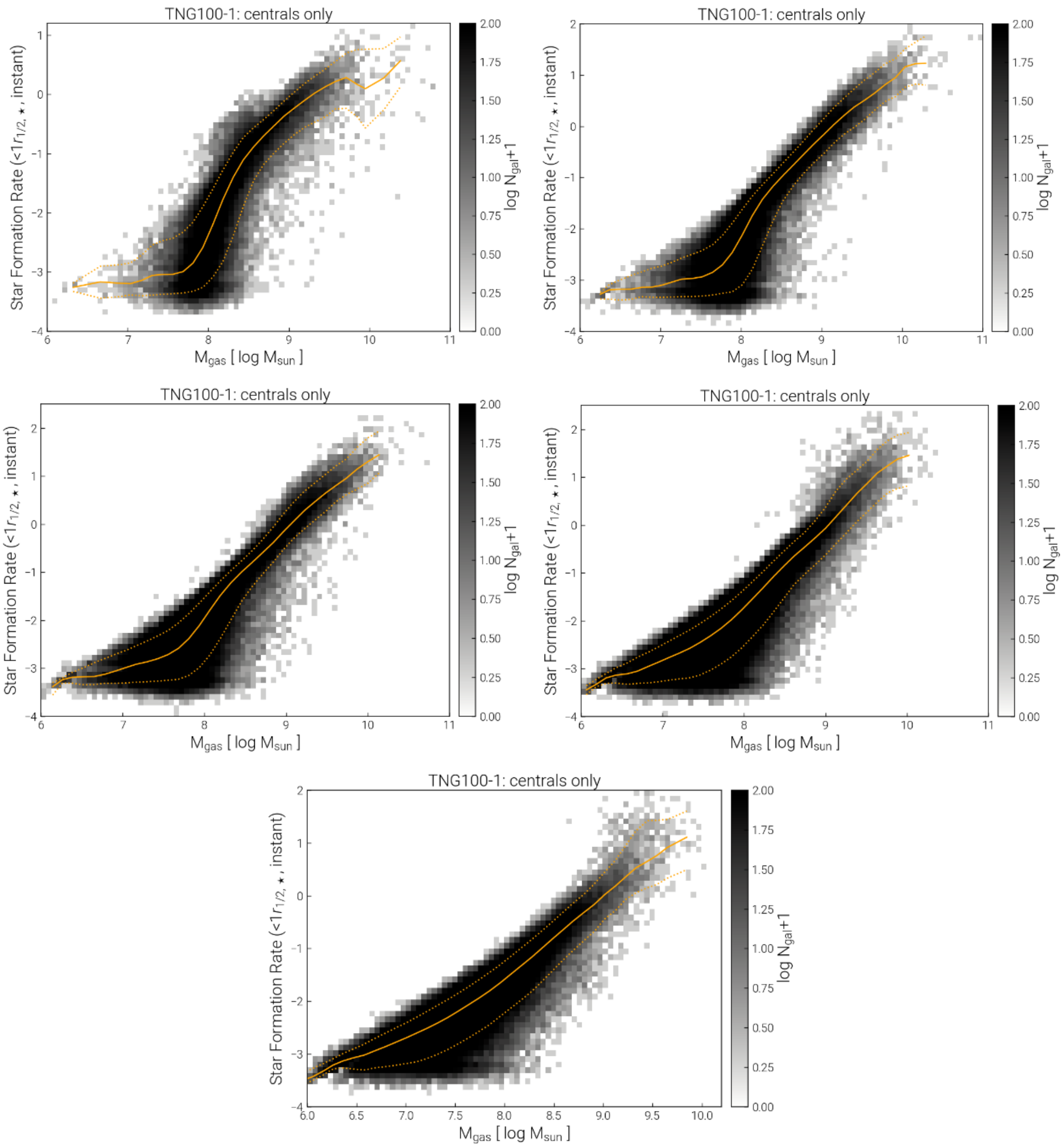

Figure 3 Plots of gas mass as a function of star formation rate in redshift z=0,1,2,4,6 based on TNG100-1 database

3. Relationship between star formation rate and stellar mass

The most basic property of galaxies is galaxy mass, which is divided into stellar mass and gas mass by the composition of galaxies. Star formation activity continuously converts gas into stars, so it is expected that some kind of relationship between the two characteristics here. The study of the law of star formation helps to understand the overall law of star formation, and can provide observational basis and constraints for constructing the theoretical models. For star formation research, the most critical issue is to measure the star formation rate. For the Milky Way, it can be obtained by counting young stars. Nevertheless, for extragalactic galaxies, it is basically difficult to distinguish individual stars, and it is necessary to measure the star formation rate by indirect means. Therefore, one can use data collection and simulation to aid research. Recently, researchers have found a linear relationship between dense molecular gas and SFR [6], a fundamental departure from the earlier nonlinear relationship between total gas (molecular gas + atomic gas) and SFR. In addition, great progress has been made in the study of local star formation laws, and the star formation laws obtained using different dense gas tracers are basically linear. The math and equation between stellar mass and star formation rate can be described as [7]:

$$\log\left(\frac{SFR}{M_{\odot}yr^{-1}}\right) = a\ \log(M_{\star}/M_{\odot}) +\ b \tag{2}$$

Here, SFR is the star formation rate, $M_{\star}$ is the stellar mass, the $M_{\odot}$ is the mass of the sun, the log value is the common logarithm with base 10, the a and b are constants which depend on redshift value. Many observations show that the stellar mass and the star formation rate usually conform to the relationship described by the above formula (Eq. (2)) [8]. Besides, it can be found that their common logarithmic values also satisfy a linear relationship.

The plots of stellar mass and star formation rate made by TNG100-1 database are illustrated in Fig. 2. The x-axis is log value of galaxy stellar mass measured within the stellar half mass radius. The y-axis is galaxy star formation rate in instantaneous, integrated within the stellar half mass radius. The solid yellow line represents the median line.

This series of plots show a very clear proportional relationship between stellar mass and star formation rate, and the distribution of galaxies becomes more concentrated to the midline as the redshift value increases. It can also be found that for groups of galaxies with very large stellar mass, some numbers of galaxies do not form a good proportional relationship between these two characteristics, which may be attributed to the fact that the formation of some massive stars is not in the traditional way, i.e., they are not form by molecular cloud collapse nor accretion by accretion disk.

4. Relationship between gas mass and star formation rate

The study by Kennicutt et al. shows that the gas mass and the SFR have the following relationship. For massive galaxies, the gas mass larger than $5 \times 10^{7} M_{\odot}$ has a star formation rate and neutral gas mass satisfying [9]:

$$\frac{SFR}{M_{\odot}yr^{-1}} = 3.91 \times 10^{-13} \left(\frac{M_{gas}}{M_{\odot}}\right)^{1.26} \tag{3}$$

For galaxies with less mass which is less than $5 \times 10^{7} M_{\odot}$, the relationship between the two satisfies the following equation:

$$\frac{SFR}{M_{\odot}yr^{-1}} = 7.96 \times 10^{-18} \left(\frac{M_{gas}}{M_{\odot}}\right)^{1.87} \tag{4}$$

In these two equations SFR is the star formation rate, $M_{\odot}$is the mass of the sun and M_{gas} is galaxy gas mass. It can be seen that the structure of these two relations is roughly the same.

The plots of gas mass and star formation rate made by TNG100-1 database are depicted in Fig. 3. Based on the TNG100-1 database, one can also make corresponding plots about the relationship between the gas mass of the galaxy and the star formation rate. Similarly, the x-axis becomes the log value of galaxy gas mass in all phase. From these plots it can be found that there is also an obvious positive proportional relationship between the galaxy gas mass and the SFR. Apparently, the ratio slope is presentively stable. To be specific, as the redshift value increases, the slope of the relationship between the gas mass and SFR becomes more stable and the distribution of galaxies becomes more concentrated to the midline.

5. Limitations & Future prospects

Nevertheless, it should be noted that the analysis and results discussed above have some shortcomings and defects. To be specific, this paper only explores the relationship at redshift z=0, 1, 2, 4, 6, and the database used only includes the galaxy data in TNG100-1. Data drawing, only a more general induction of the relationship between them. The data for the various types of galaxies has not been classified, nor has the situation been explored for the various types of special galaxies. Due to the different types of galaxies, the relationship must be different. Therefore, for further research, it is necessary for us to further classify the data in the database, and we need to classify different types of galaxies through different relational expressions, so as to better study the differences in the evolution process of different types of galaxies. As for gas mass, since different types of galaxies have different gas composition and content in the early stage of evolution, the relationship between gas mass and star formation rate should be more complicated [10]. In further research, a more specific examination of the effect of different gas contents on star formation is required. In addition, for further research in the future, we also need to cover a wider range of data, as well as compare and generalize more galaxies at different redshift values.

6. Conclusion

In conclusion, using the powerful database of the TNG project, one can realize the plot of various data, which makes it very convenient to study the relationship between different properties of galaxies. This project focused on the relationship between the mass of galactic stellar, the mass of galactic gas, and the star formation rate. By making series of relationship plots, one can found that there are proportional relationships between the features to a certain extent. At different redshift values, the ratio relationship plots are slightly different, but they all roughly have same slope. From these intuitive plots, one can gain a deeper understanding of the properties and formation processes of galaxies. Most small galaxies are formed by the accretion and collapse of gas, and galaxy clusters are formed slowly by the merger of various small galaxies. The stars in galaxies are mostly formed by the collapse of gas, so the mass of stellar and gas contained in the galaxy after formation is closely related, and the SFR is also proportional to the stellar mass and the gas mass of galaxies. In the future, through a more detailed classification study of these three characteristics of galaxies in a larger database to further understand the properties and evolution of various types of galaxies. Overall, the study of the basic characteristics of galaxies can support the evolution theory of galaxies to a certain extent, and the relationship between these three characteristics shown in this paper reflects the correctness of the current galaxy theory to a certain extent. These results offer a guideline for further research on galaxy evolution theory.

References

[1] I. A. Bonnell, and M. R. Bate, “Star Formation through Gravitational Collapse and Competitive Accretion.” Monthly Notices of the Royal Astronomical Society, vol. 370, no. 1, 2006, pp. 488–494. DOI: https://doi.org/10.1111/j.1365-2966.2006.10495.x.

[2] M. Donnari, et al. “The Star Formation Activity of Illustristng Galaxies: Main Sequence, UVJ Diagram, Quenched Fractions, and Systematics.” Monthly Notices of the Royal Astronomical Society, vol. 485, no. 4, 2019, pp. 4817–4840. DOI: https://doi.org/10.1093/mnras/stz712.

[3] A. Pillepich, et al. “First Results from the TNG50 Simulation: The Evolution of Stellar and Gaseous Discs across Cosmic Time.” Monthly Notices of the Royal Astronomical Society, vol. 490, no. 3, 2019, pp. 3196–3233. DOI: https://doi.org/10.1093/mnras/stz2338

[4] A. Katsianis, et al. “The Evolution of the Star Formation Rate Function in the Eagle Simulations: A Comparison with UV, IR and HA Observations from Z ~ 8 to Z ~ 0.” Monthly Notices of the Royal Astronomical Society, vol. 472, no. 1, 2017, pp. 919–939. DOI: https://doi.org/10.1093/mnras/stx2020

[5] V. Parkash, et al. “Relationships between Hi Gas Mass, Stellar Mass, and the Star Formation Rate of HICAT+Wise (H i-Wise) Galaxies.” The Astrophysical Journal, vol. 864, no. 1, 2018, p. 40. DOI: https://doi.org/10.3847/1538-4357/aad3b9.

[6] R. C. Kennicutt, et al. “Star Formation in NGC 5194 (M51A). II. the Spatially Resolved Star Formation Law.” The Astrophysical Journal, vol. 671, no. 1, 2007, pp. 333–348. DOI: https://doi.org/10.1086/522300.

[7] M. Donnari, et al. “The Star Formation Activity of Illustristng Galaxies: Main Sequence, UVJ Diagram, Quenched Fractions, and Systematics.” Monthly Notices of the Royal Astronomical Society, vol. 485, no. 4, 2019, pp. 4817–4840. DOI: https://doi.org/10.1093/mnras/stz712.

[8] B. Salmon, et al. "The Relation between Star Formation Rate and Stellar Mass for Galaxies at 3.5 ⩽z⩽6.5 in Candels." The Astrophysical Journal, vol. 799, no. 2, 2015, p. 183. DOI: https://doi.org/10.1088/0004-637x/799/2/183.

[9] J. P. Altenburg, and P. Kroupa. "The Fundamental Gas Depletion and Stellar-Mass Buildup Times of Star-Forming Galaxies." The Astrophysical Journal, vol. 706, no. 1, 2009, pp. 516–524. DOI: https://doi.org/10.1088/0004-637x/706/1/516.

[10] Y. Gao, and P. M. Solomon, "The Star Formation Rate and Dense Molecular Gas in Galaxies." The Astrophysical Journal, vol. 606, no. 1, 2004, pp. 271–290. DOI: https://doi.org/10.1086/382999.