The Effect of colliding galaxies on star formation rates based on IllustrisTNG

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Abstract. Galaxy collisions are a complex and common cosmic phenomenon that attracts attention of plenty of scholars. In this paper, the effect of colliding galaxies on the star formation rates will be investigated based on IllustrisTNG, considering three properties of colliding galaxies: distance, velocity and mass. According to the analysis, the deeper the galaxies collide, the larger the SFR values they have. Besides, the effect of collisional and tidal forces on the SFR is continuous. In collisions, galaxies with high relative velocity have higher SFR values compared to galaxies with low velocity; the lighter galaxies have higher SFR values and are more pronounced as the mass ratio of the two galaxies becomes larger. When the colliding galaxies are close in mass, the collision does not have a significant effect on the SFR of both sides. In connection with these results, the possible reasons are discussed for the changing of the SFR by galaxy collisions, i.e., galaxy collisions lead to structural instability of gas clouds in galaxies, causing star formation. These results shed light on guiding further exploration of star formation.

Keywords: method: numerical - galaxies: collision - galaxies: star formation rates.

1. Introduction

The existence of extragalactic galaxies was discovered in the early 20th century by Hubble's ranging of the Andromeda galaxy, and subsequent observations of numerous galaxies spread throughout the universe confirmed the island universe hypothesis. Galaxies are gravitationally bound systems of stars, gas, dark matter, and other cosmic material, and are the place where most astronomical phenomena happens, including star formation. 20th century studies of galaxy rotation curves have demonstrated the existence of dark matter from one perspective [1]. Under the modern, widely accepted Lambda-CDM model, the dark matter halo is treated as the fundamental unit of the structure of the universe, usually consisting of a galaxy and the dark matter that envelops it [2].

The cold gas present in galaxies is the raw material for star production, the unstable collapse of gas clouds induces star formation [3]. It has been demonstrated that collisions of galaxies can induce star formation [4], possibly due to the strong external forces brought about by galaxy collisions that alter the original stable state of the gas in galaxies. In addition, the effect of galaxy collision velocities on the dynamics and star formation rates of the gas in galaxies has also been discussed [5].

The detection of the star formation rates of a galaxy is usually observed by analyzing the spectral features and luminosity of the galaxy. A quantitative description is provided by the Kennicutt-Schmidt law [6]. In this paper we use The Next Generation Illustris Simulations (TNG) to study the universe in numerical simulations. The instantaneous star formation rates is defined in the TNG as the rate of stellar mass growth (the rate of gas conversion to stellar mass) in $M_\odot$/yr. In this paper, we do not study the star formation rates (SFR) as a function of time, so the SFR refers specifically to the instantaneous star formation rates. SFR exists for every gas cell in the TNG, and the SFR of a subhalo (dark matter halo) is the average of the SFR of all the gas cells.

The intention of this paper is to use IllustrisTNG to further investigate the effect of different properties (distance, velocity, mass) of colliding galaxies on the SFR. The rest part of the paper is organized as follows. The second section describes the sources and processing of the data, as well as the main terms mentioned in the paper. The third section shows the results obtained, including the interpretation and discussion of the results. The fourth section is a summary of the work.

2. Methodology

2.1. Definition of terms

Generally, there are 4 terms that are used high frequently in this paper. The definitions will be given in the following:

Subhalo: Subhalo is the basic unit in the TNG simulation universe, a halo (the superstructure of subhalos) may exist from zero to more than one subhalo, where the most massive subhalo is called primary subhalo, and the other subhalos are called secondary subhalo, the part of the subhalo composed of baryonic matter is the nebula or galaxy. In the following text galaxies and subhalos are equivalent.

Collision Coefficient (CC): A collision-related factor that defines collision occurrence: CC = the distance between the centers of mass of two subhalos / the sum of two subhalos' radius. The smaller the CC, the closer the two galaxies are to each other and the more they are affected by each other (either by tidal forces or direct collisions). Compared to the direct use of metric units, using CC as a distance unit takes into account the size of galaxies and makes more sense when measuring intergalactic effects. Depending on the definition of the radius, the CC changes.

Star Formation Rates (local) (SFRl): The SFR of a collection of subhalos satisfying a specified CC interval, velocity interval or mass interval.

Star Formation Promotion Rates: SFRl/SFR (background SFR). When the value is greater than 1, it means that the selected galaxies promote star formation (compared to the average value for the whole universe), and vice versa when the value is less than 1.

2.2. Data

The IllustrisTNG Simulations is an ongoing series of large, cosmological magnetohydrodynamical simulations of galaxy formation [7]. It is a successor to the original Illustris simulation. IllustrisTNG retains the basic approach of Illustris, but adapts it to the latest cosmology and brings it more in line with observations. TNG follows the coupled dynamics of DM and gas with the quasi-Lagrangian code AREPO [8]. TNG uses the friends-of-friends (FOF) algorithm [9] and the Subfind algorithm [10] to identify halos and subhalos, respectively. There are three types of TNGs, TNG50, TNG100 and TNG300, which have different simulation volumes and resolutions. The details are in Tab. 1.

Table. 1. Important data about TNG simulation [11].

	Unit	TNG50	TNG100	TNG300
Volume	$[\mathrm{Mpc}^3]$	51.7^3	110.7^3	302.6^3
L_{box}	$[\mathrm{Mpc}/h]$	35	75	205
N_{GAS}	-	2160^3	1820^3	2500^3
N_{DM}	-	2160^3	1820^3	2500^3
m_{baryon}	$[M_\odot]$	8.5×10^4	1.4×10^6	1.1×10^7
m_{DM}	$[M_\odot]$	4.5×10^5	7.5×10^6	5.9×10^7
N_{snap}	-	100	100	100
N_{Subfind} (z=0)	-	5688113	4371211	14485709

To obtain a sufficient sample size, TNG300 is used for this study. This work reads #99 (z=0) groupcat data of TNG300. Groupcat data stores a lot of properties about subhalos, the properties used in this paper is shown in Table. 2.

Table. 2. The data used in the paper. Note that the c in ckpc refers to "comoving" [11].

Field	DataType	Dimensions	Units	Description
SubhaloFlag	int16	N	-	Used to select galaxies without cosmological origin.
SubhaloCM	float32	N,3	$ckpc/h$	Comoving center of mass of the Subhalo, computed as the sum of the mass weighted relative coordinates of all particles/cells in the Subhalo, of all types.
SubhaloMass	float32	N	$10^{10}M_{\odot}/h$	Total mass of all member particle/cells which are bound to this Subhalo, of all types.
SubhaloSFR	float32	N	$M_{\odot}/yr$	Sum of the individual star formation rates of all gas cells in this subhalo.
SubhaloSFRinHalfRad	float32	N	$M_{\odot}/yr$	Same as SubhaloSFR, but restricted to cells within the stellar half mass radius.
SubhaloSFRinMaxRad	float32	N	$M_{\odot}/yr$	Same as SubhaloSFR, but restricted to cells within the radius of V_{max}.
SubhaloVel	float32	N,3	km/s	Peculiar velocity of the group, computed as the sum of the mass weighted velocities of all particles/cells in this group, of all types.
SubhaloHalfmassRad	float32	N	$ckpc/h$	Comoving radius containing half of the total mass (SubhaloMass) of this Subhalo.
SubhaloVmaxRad	float32	N	$ckpc/h$	Comoving radius of rotation curve maximum (where V_{max} is achieved).

2.3. Processing

Each slice of TNG300 has about 1.5e+07 subhalos. In this paper, only subhalos with masses above 1 (unit see Tab. 2) are considered in order to filter out the low-resolution subhalos, this process also filters out many subhalos with a large fraction of dark matter (their masses are usually small). Also, galaxies of non-cosmological origin, i.e. SubhaloFlag=0, are filtered out. Because they were split from other haloes and are often too close to their parent haloes. The final amount screened galaxies is 2114618 (2.1e+06).

The boundary condition set by the algorithm for the collision is CC=2. If CC<2, they are considered to have collided, and their distance, velocity, mass and SFR information are statistically analyzed. There is a possibility that the detected pair of galaxies has other galaxies that are closer to one or both of them. But this case is rare when CC<2, so it is ignored in this paper. The sample of galaxies with CC<2 in #99 has 52161 pairs.

3. Results & Discussion

3.1. SFPR-CC diagram

Fig. 1 divides the CC distance [0,2] into ten parts, each of length is 0.2 (as presented in Table. 3). The SFPR value is the mean value of all pairs of galaxies in the corresponding CC interval. One can see that there is a significant negative linear correlation between distance and SFPR, indicating that the star formation rates increase gradually as the collision between galaxies deepens. When the CC interval is converging to 2, the SFPR is also converging to the background SFR value.

Table. 3. Basic settings of all diagrams.

Number of CC intervals	10
Length of a CC interval	0.2
CC range	(0,2)
Number of velocity intervals	10
Length of a velocity interval (km/s)	60
Velocity range (km/s)	(0,600)
Number of mass ratio intervals	10
Length of a mass ratio intervals	0.2
Mass ratio range	(0,20)

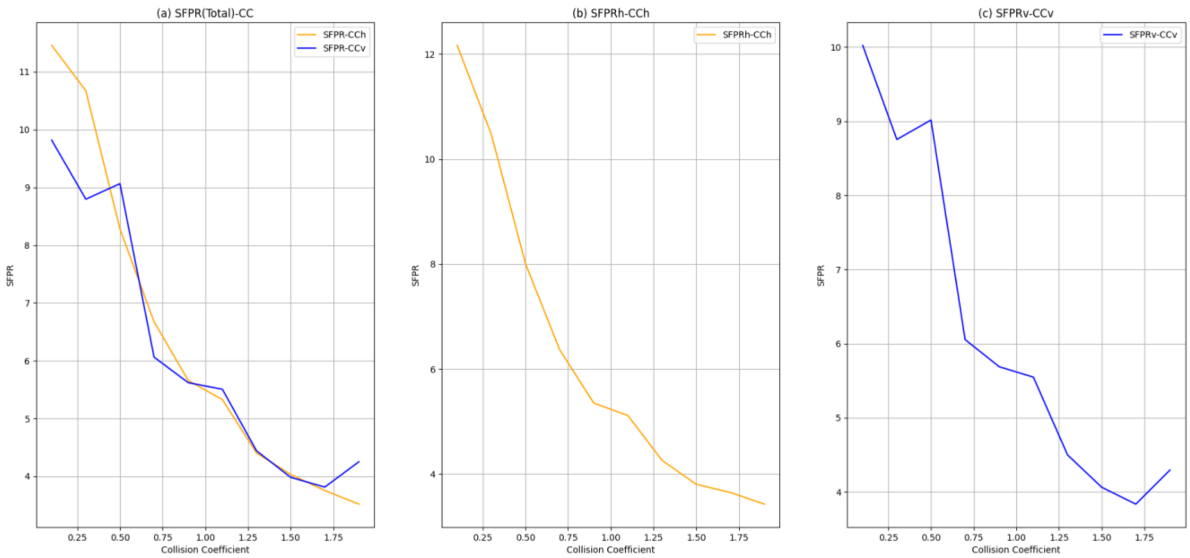

Figure. 1. SFPR-CC diagram with groupcat number #99. "CCh" refers to CC of half mass radius and "CCv" refers to CC of V_max radius. SFPRh and SFPRv refer to the SFPR values calculated with SubhaloSFRinHalfRad and SubhaloSFRinMaxRad, respectively, while the default SubhaloSFR is used in (a).

3.2. SFPR heat map on CC and velocity

For reference, the average velocity of the #99 screened subhalos is 441.7±255.2km/s (one standard deviation). Both Figs. 2(a) and Figs. 2(b) show a positive correlation between galaxy collision velocity and SFR, while the SFR of the slower colliding galaxies (0-120km/s) is close to the background value. This paper also plots the heat map of the sample size (Fig. 3) and finds an interesting phenomenon. That is, the majority of colliding galaxies have velocities in the interval 60 to 180, but this is well below the average velocity of galaxies, indicating that colliding galaxies are generally slow.

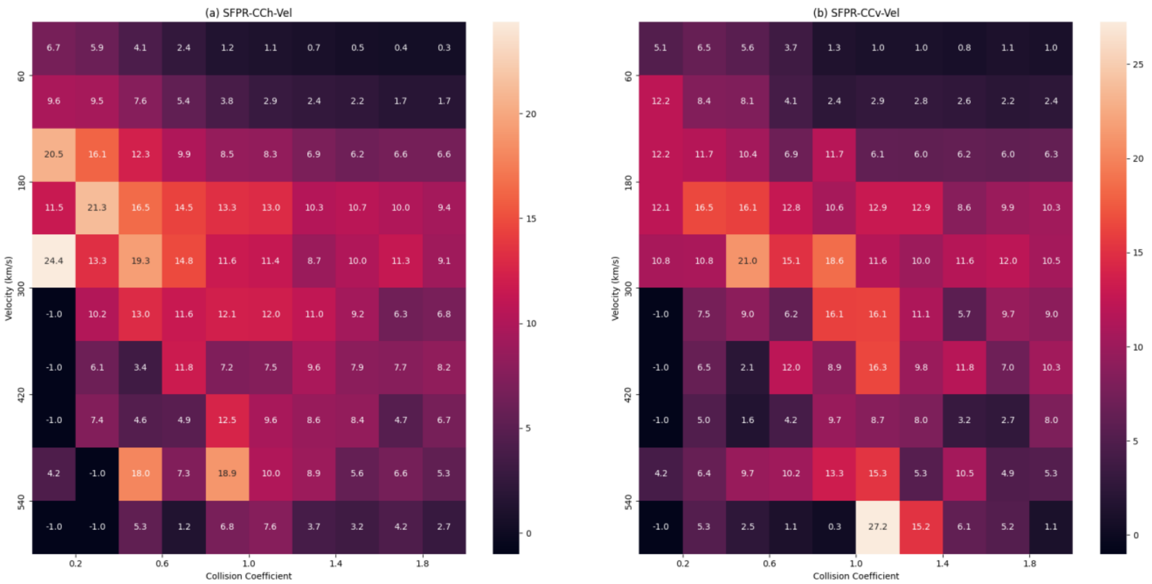

Figure. 2. SFPR heat map on CC and velocity with groupcat number #99. Velocity is the relative velocity of the two galaxies. Note that the area with SFPR value of -1 in the figure has no data collected.

3.3. SFPR heat map on CC and mass ratio

As illustrated in Fig. 4 it can be seen that the heavier galaxies generally have smaller SFPR values, while the lighter galaxies have larger SFPR values, even reaching a value of 163.4 in the lower left corner of the Figs. 4(b). In the upper part of Figs. 4(a) and Figs. 4(b), the value of SFPR is close to 1, indicating that the closer the masses of the two colliding parties are, the closer the SFR values of both are to the background value, and vice versa for the larger mass ratio of the colliding parties. It is also noted that the more distant (less colliding) galaxies are, the less significant the SFPR variation with mass ratio. The extremes of Figs. 4(b) are concentrated in the region with small distances and large mass ratios, while the SFPR values of Figs. 4(a) are more uniform.

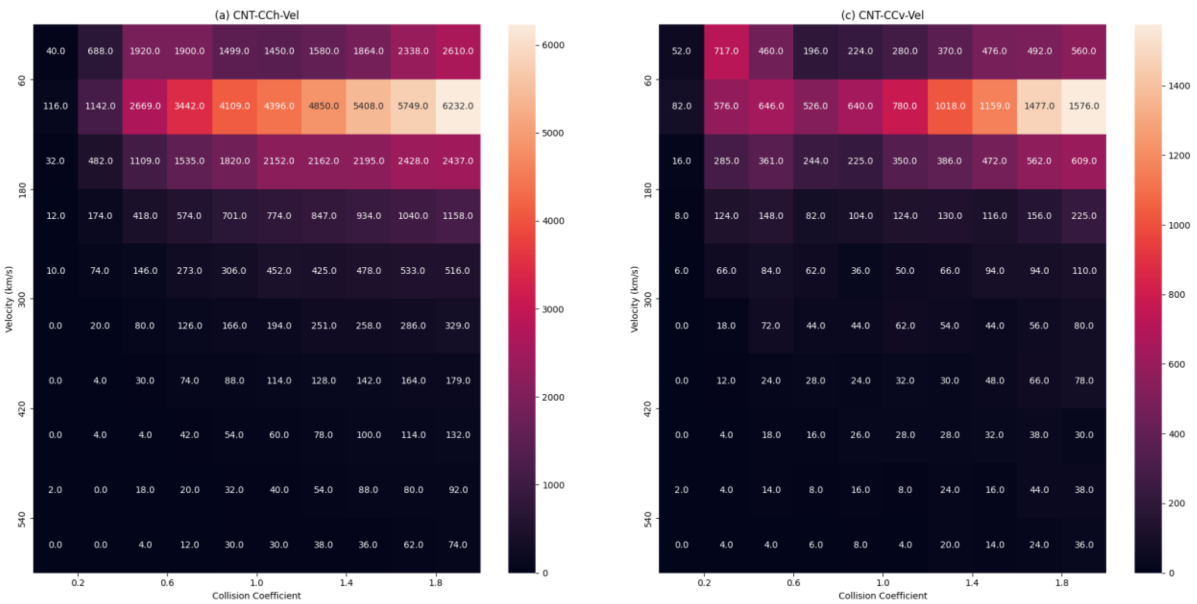

Figure. 3. Sample size heat map on CC and velocity with groupcat number #99. The values in the figure represent the collected sample size.

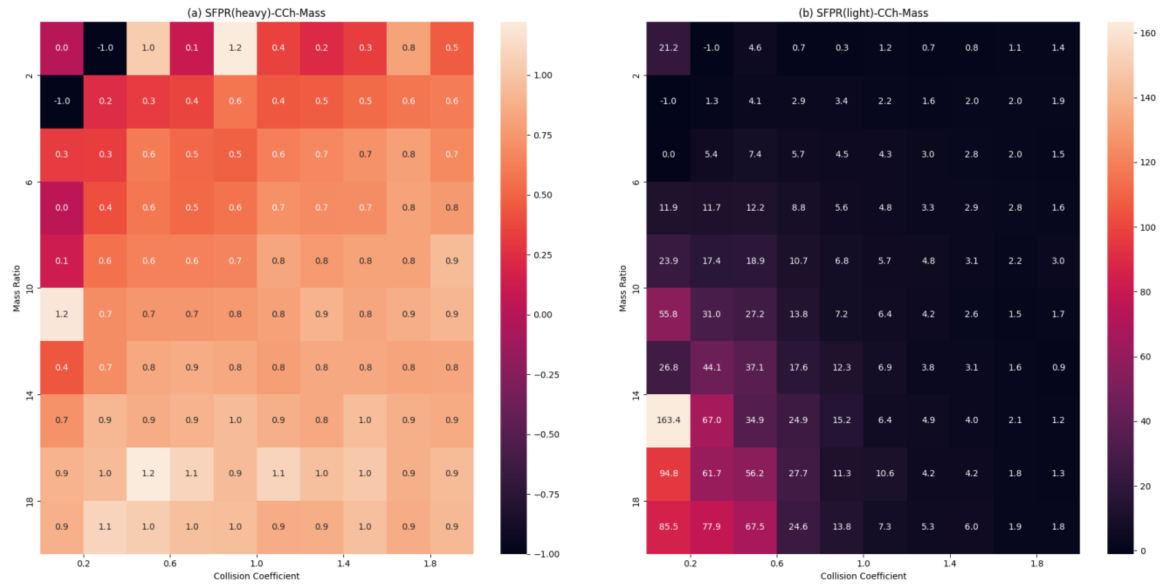

Figure. 4. SFPR heat map on CC and mass ratio with groupcat number #99. “heavy” is the heat map composed of galaxies with heavier mass in the collision, and “light” is composed of galaxies with lighter mass. For example, the mass ratio interval [10,12] in the heavy diagram means that the galaxies in this region are all 10-12 times heavier than the other one in the collision, light diagram is vice versa. Also, for heavy/light, the mass ratio interval [0,2] means that the galaxies are 1-2 times heavier/lighter than the other, [0,1] has no data.

3.4. Explanation

The results in Sec. 3.1 indicate that the deeper the collision of two galaxies, the more efficient the star formation is induced. It is presumed that the deeper the collision, the greater the perturbation of the gas in the galaxy, and the easier it is to break the Jeans instability and generate stars. In addition, the definition of CC shows that 1 should be the watershed between "collision" and "tidal". When CCv is less than 1, the edges of the two galaxies start to overlap and physical collisions occur, while when CCv is greater than 1, there are strong tidal forces on the two galaxies, but they are not in direct contact with each other. The smooth fold line of Fig. 1 does not show this feature, presumably because the galaxies still exert their influence on each other with gravitational force after the collision, and the actual physical collision of the objects is rare due to the low density. In Sec. 3.2, a positive correlation between galaxy collision velocity and SFR is found, presumably because the larger kinetic energy is more likely to disrupt the equilibrium structure of the gas cloud at impact and induce its collapse to form stars. As for the phenomenon that colliding galaxies have generally slow velocity, the reason for this remains to be explored. The Sec. 3.3 demonstrates the unsurprising result that the lighter one in the collision is more affected, probably because the structure of the lighter galaxy in the collision is more unstable under the massive gravity. The SFPR value of the heavier party in the collision is lower than 1 probably because the SFR background value is averaging both the lighter and heavier galaxies. At the same distance, the collision has little effect on the SFR of the two galaxies when the masses of the colliding parties are not too different. The deeper the collision, the larger the SFR value of the lighter galaxy, which is consistent with the results in former sections.

3.5. Limitation

Limited by the computing power, this study doesn’t investigate the case where CC exceeds 2. In fact, the tidal forces of close galaxies can also influence each other when CC exceeds 2. Also, this paper only considers the galaxy closest to a galaxy, didn’t consider the effects of multi-galaxy collisions and tides. In addition, the sample size in this paper is also not large enough, so the data in some areas of the figure are not statistically significant. For example, in Fig.3 the sample size of many regions doesn't even reach 50.

4. Conclusion

In summary, this paper investigates the effect of colliding galaxies on the star formation rates using IllustrisTNG, considering three properties of colliding galaxies: distance, velocity and mass. According to the analysis, the closer the galaxies collide have the larger the SFR value, and the effect of collision and tidal forces on the SFR is continuous. The study of galaxy collision velocity reveals a positive correlation between collision velocity and galaxy SFR. The last result is the effect of mass on galaxies. In galaxy collisions, the lighter galaxies have higher SFR values and are more pronounced as the mass ratio of the two galaxies becomes larger. When the colliding galaxies are close in mass, the collision does not have a significant effect on the SFR of both sides. It is often assumed that in galaxy collisions, the objects within the galaxy rarely actually collide. However, this does not mean that galaxy collisions don't have an effect on the matter in the galaxy, as evidenced by this paper. In the future, the ultimate goal is to increase the sample size and to study the rate of galaxy collisions on changes in other properties of galaxies, such as metal abundance and spin. Overall, these results offer a perspective for investigating the star formation rates based on simulations.

References

[1] V. Rubin, W. K. Ford, Jr. Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions. Astrophysical Journal, 1970, 159: 379

[2] Wechsler Risa, Tinker Jeremy. The Connection between Galaxies and their Dark Matter Halos. Annual Review of Astronomy and Astrophysics, 2018, 56: 435–487

[3] S. W. Stahler, F. Palla. The Formation of Stars. Germany: Weinheim: Wiley-VCH, 2004

[4] Reinhard Genzel, et al. Star formation triggered by galaxy collisions. Nature, 1998, 395: 859-862

[5] A.V. Tutukov, et al. Gas dynamics of a central collision of two galaxies: Merger, disruption, passage, and the formation of a new galaxy. Astron. Rep, 2011, 55: 770

[6] Schmidt Maarten. The Rate of Star Formation. The Astrophysical Journal, 1959, 129: 243

[7] Pillepich A, et al. First results from the IllustrisTNG simulations: the stellar mass content of groups and clusters of galaxies. Monthly Notices of the Royal Astronomical Society, 2018, 475(1): 648-675.

[8] V Springel. E pur si muove: Galilean-invariant cosmological hydrodynamical simulations on a moving mesh. Monthly Notices of the Royal Astronomical Society, 2010, 401(2): 791-851.

[9] M Davis, et al. The evolution of large-scale structure in a universe dominated by cold dark matter. The Astrophysical Journal, 1985, 292: 371-394.

[10] K Dolag, et al. Substructures in hydrodynamical cluster simulations. Monthly Notices of the Royal Astronomical Society, 2009, 399(2): 497-514.

[11] Nelson D. IllustrisTNG. Retreived from: https://www.tng-project.org/