ENVIRONMENTAL DEPENDENCE OF THE GALAXY MERGER RATE IN A ΛCDM UNIVERSE

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ABSTRACT

We make use of four galaxy catalogs based on four different semi-analytical models (SAMs) implemented in the Millennium Simulation to study the environmental effects and the model dependence of the galaxy merger rate. We begin the analyses by finding that the galaxy merger rate in SAMs has a mild redshift evolution with luminosity-selected samples in the evolution-corrected B-band magnitude range, $-21 \leq M_B \leq -19$, consistent with the results of previous works. To study the environmental dependence of the galaxy merger rate, we adopt two estimators, the local overdensity $(1 + \delta_n)$, defined as the surface density from the $n$th nearest neighbor ($n = 6$ is chosen in this study), and the host halo mass $M_h$. We find that the galaxy merger rate $F_{mg}$ shows a strong dependence on the local overdensity $(1 + \delta_n)$ and the dependence is similar at all redshifts. For the overdensity estimator, the merger rate $F_{mg}$ is found to be about twenty times larger in the densest regions than in underdense ones in two of the four SAMs, while it is roughly four times higher in the other two. In other words, the discrepancies of the merger rate difference between the two extremes can differ by a factor of $\sim 5$ depending on the SAMs adopted. On the other hand, for the halo mass estimator, $F_{mg}$ does not monotonically increase with the host halo mass $M_h$, but peaks in the $M_h$ range between $10^{12}$ and $10^{13} h^{-1} M_\odot$, which corresponds to group environments. The high merger rate in high local density regions corresponds primarily to the high merger rate in group environments. In addition, we also study the merger probability of “close pairs” identified using the projected separation and the line-of-sight velocity difference $C_{mg}$ and the merger timescale $T_{mg}$; these are two important quantities for observations to convert the pair fraction $N_c$ into the galaxy merger rate. We discover that $T_{mg}$ has a weak dependence on environment and different SAMs, and is about 2 Gyr old at $z \sim 1$. In contrast, $C_{mg}$ depends on both environment (declining with density) and different SAMs; its environmental dependence is primarily due to the projection effect. At $z \sim 1$, it is found that only $\sim 31\%$ of projected close pairs will eventually merge by $z = 0$. We find that the projection effect is the dominant factor in accounting for the low merger probability of projected close pairs.

Key words: cosmology: theory – galaxies: evolution – galaxies: interactions – methods: numerical

1. INTRODUCTION

In a standard ΛCDM model, the major framework is the hierarchical structure formation within which dark matter (DM) halos and galaxies are assembled from the successive accretion of smaller objects (Peebles 1982; Blumenthal et al. 1984; Davis et al. 1985). Merging is thus an inevitable process and plays an essential role in galaxy formation and evolution. The potential impacts of mergers on galaxy evolution have been intensely discussed. In addition to being responsible for mass growth in the assembly history of galaxies, they are, for example, expected to trigger quasar activities (Carlberg 1990) and starbursts (Barnes & Hernquist 1991), and thought to shape many important observational properties of galaxies, such as star formation rate, color, and morphology transformation (Toomre & Toomre 1972). Galaxy mergers continue to be an important component of galaxy evolution in recent works on star formation history and remnant properties (e.g., Cox et al. 2006), starbursts, quasars, black hole growth (e.g., Hopkins et al. 2006), bulge growth and morphology (e.g., Hopkins et al. 2010a), baryonic content of galaxies (e.g., Stewart et al. 2009b), and formation of diffuse intrahalo light components (e.g., Purcell et al. 2007).

Many studies have explored the galaxy merger rate as a function of cosmic time in order to understand the assembly history of galaxies observationally (Patton et al. 2002; Patton & Atfield 2008; Conselice at al. 2003; Lin et al. 2004, 2008; Lotz et al. 2008a, 2011; Kampczyk et al. 2007; Kartaltepe et al. 2007; Hsieh et al. 2008; Bundy et al. 2009; de Ravel et al. 2009, 2011; Chou et al. 2011; Xu et al. 2012) and theoretically (e.g., Berrier et al. 2006; Guo & White 2008; Mateus 2008; Genel et al. 2009; Stewart et al. 2009a; Bonoli et al. 2010; Hopkins et al. 2010b). Since galaxy merging assembles two or more galaxies into one, it is expected to be more common in dense regions, i.e., having a strong dependence on environments. To what degree this is so is an issue of great concern. Studies have looked for environmental dependence of merging, and found locally that the highest fractions of mergers are in intermediate to high-density regions (e.g., Darg et al. 2010; Ellison et al. 2010). Lin et al. (2010) also addressed this issue by probing the environments of wet, dry, and mixed galaxy mergers at $0.75 < z < 1.2$ using close pairs in the DEEP2 Galaxy Redshift Survey, and found that the environmental dependence of the galaxy merger rate for wet mergers is marginal while the dry and mixed merger rates increase rapidly with local density. A similar conclusion that the merger rate has a strong environmental dependence was also obtained by de Ravel et al. (2011) and Kampczyk et al. (2011). However, the galaxy merger rate in observation is actually an indirect physical quantity and can only be obtained by combining the fraction of galaxies that reveal signatures of merger activity from observations, and the merger timescale and merger probability estimated from theoretical models. The environmental dependence of the merger...
probability and the merger timescale in theoretical models is addressed especially less frequently. Hence, to interpret the observational results more precisely, a theoretical determination of how the merger time varies with environment is essential. Only a few theoretical studies have addressed the environmental dependence associated with mergers (Fakhouri & Ma 2009; Hester & Tastisiomi 2010; Tonnesen & Cen 2011). Fakhouri & Ma (2009) utilized the Millennium Simulation to derive the merger rate of the friends-of-friends (FOF) DM halos as a function of the local mass density within a sphere of 7h⁻¹ Mpc, and demonstrated that mergers occur about 2.5 times more frequently in the densest regions than in voids at both z = 0 and higher redshifts. However, their study focused on mergers of distinct FOF halos, whereas galaxy mergers do not necessarily follow their scenario. Hester & Tastisiomi (2010) alternatively adopted the merger tree of subhalos from the Millennium database to explore the same issues. The local halo environment in their study is defined as the count of all distinct halos and subhalos, with V_{\text{max}} \leq 120 \text{ km s}^{-1} \text{ within a sphere of a comoving radius of } 2h^{-1} \text{ Mpc centered on each halo. They found that the merger rate is roughly independent of environment. However, the evolutionary history of subhalos may not be exactly that of galaxies, due to different treatments of orphan galaxies when subhalos are disrupted, which may lead to different conclusions. The requirements for a relation between the histories of a given DM halo and of a galaxy inside that halo make the conversion from DM (halo/subhalo) merger rates to galaxy merger rates non-trivial (Hopkins et al. 2010b).

In this study, we make use of the publicly available galaxy catalogs based on four different semi-analytical models (SAMs) implemented in the Millennium database. In addition to exploring the environmental dependence of the galaxy merger rate, we also investigate the merger probability of close pairs (C_{mg}), which provides a correction due to the projected selection criterion and the merger timescale (T_{mg}), which provides the mean merger time for a close pair to merge, as a function of environment. These two quantities are important for observations to convert the pair fraction into the galaxy merger rate. A similar analysis for merger time and merger fraction was done by Kampczyk et al. (2011). In addition, our analyses on the merger timescale are similar to Kitzbichler & White (2008) and are extended to discuss the environmental dependence of merger rate and merger timescale. Moreover, it is illuminating to understand how different SAMs affect the galaxy merger rate as well as these two quantities. In fact, Hopkins et al. (2010b) have already pointed out that different theoretical methodologies lead to order-of-magnitude variations in the predicted galaxy–galaxy merger rates. Whether such variations among different SAMs propagate into the environmental dependence requires careful scrutiny.

The paper is structured as follows. We briefly describe the Millennium Simulation and the four galaxy catalogs from the SAMs in use in Section 2. Section 3 is divided into five subsections. Environmental estimators are introduced in Section 3.1. In Section 3.2, the galaxy merger rate is defined, where the redshift evolution of the pair fraction N_c and the galaxy merger rate between the models and the observations are compared. The environmental dependence of N_c and the galaxy merger rate is presented in Section 3.3. Our results for C_{mg} and T_{mg} as a function of environment are shown in Section 3.4. In Section 3.5, the impact of the mass ratio of merging galaxies on the merger rate in different environments is discussed. Finally, a discussion and the conclusions are given in Sections 4 and 5, respectively.

2. MODELS

2.1. Simulations

We make use of the Millennium Simulation, provided by the Virgo Consortium, in this study. The Millennium Simulation follows the hierarchical growth of DM structures with N = 2160³ particles of mass 8.6 \times 10^{10} h^{-1} M_\odot in a comoving periodic box 500 h^{-1} \text{ Mpc on a side from redshift } z = 127 to the present (Springel et al. 2005), where the Hubble constant is parameterized as H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}. The concordance ΛCDM cosmology is assumed in the Millennium Simulation with parameters Ω_m = 0.25, Ω_L = 0.045, h = 0.73, Ω_k = 0.75, n = 1, and σ_8 = 0.9, consistent with a combined analysis of the 2dF Galaxy Redshift Survey and the first-year Wilkinson Microwave Anisotropy Probe data. The GADGET-2 code (Springel 2005), a variant of the TreePM method, is adopted for evaluating gravitational forces, allowing for a very large dynamic range and a high computational speed even in situations where the clustering becomes strong. With a softened length of 5 h⁻¹ kpc on a comoving scale, taken as the spatial resolution limit of the computation, the effective dynamic range thus reaches 10³ in spatial scale. In addition, halos hosting all luminous galaxies brighter than 0.1 L_*, (where L_*) is the characteristic luminosity of galaxies) can be resolved with a mass resolution of ~100 particles. There are 64 epochs of output data spaced approximately logarithmically in time at early epochs and approximately linearly in time at late epochs (with Δt ~ 300 Myr).

An FOF group finder (Davis et al. 1985) with a linking length of b = 0.2 in units of the mean particle separation is used to identify halos in the simulation. Each FOF-identified halo is broken into constituent subhalos (each with at least 20 particles or 2.35 \times 10^{10} h^{-1} M_\odot) by the SUBFIND algorithm (Springel et al. 2001), which identifies gravitationally bound substructures within the host FOF halo; SUBFIND typically finds a large background host subhalo and a number of smaller satellite subhalos. With all halos and subhalos determined, the hierarchical merging trees containing the details of how structures build up over cosmic time can then be constructed. These trees are the key information needed to compute the physical properties of the associated galaxy population for SAMs. It is known that the merger tree construction is to basically connect subhalos across all snapshot outputs and is established through the determination of a unique descendant from any given halo. In the Millennium Simulation, each potential descendant is scored based on a weighted count, giving higher weight to particles that are more tightly bound in the halo under consideration, and the unique descendant is the one with the highest score. In this way, the merger trees are defined and constitute the basic input needed by SAMs.

The other simulation, ΛCDM_{100}, adopted in this work is evolved in the flat ΛCDM model: Ω_0 = 0.3, Ω_L = 0.7. Ω_m = 0.05, h = 0.7, and σ_8 = 0.94, using 512³ DM particles in a comoving periodic box 100 h^{-1} \text{ Mpc on a side from redshift } z = 100 to the present (Jian et al. 2008). This simulation also employs the GADGET-2 code, and the softening length ε is set to 10 h^{-1} kpc (comoving) before redshift z = 2.3 and modified to 3 h^{-1} kpc (physical) thereafter. Additionally, the outputs are at 67 epochs spaced equally in a 100 h^{-1} \text{ Mpc comoving length, and therefore, the time difference for the two adjacent snapshots increases slightly. For example, Δt ~ 0.24 Gyrs at } z ~ 1 \text{ and } Δt ~ 0.4 Gyrs at } z ~ 0\).
In simulation $\Lambda$CDM, a subhalo finder called Hierarchical Friends-of-Friends (HiFOF; Jian et al. 2008) is hired to identify bound substructures. HiFOF first finds halos with a linking length of $b = 0.2$ in units of the mean particle separation (the lowest level), and starts to shorten the linking length linearly like a zoom-in process and performs a virial condition check on those newly found substructures satisfying a criterion that the minimum particle number for subhalos has to be greater than 30, corresponding to $1.9 \times 10^{10} h^{-1} M_\odot$. The process will continue for both bound or unbound structures until it reaches a certain level or finds no further bound structures. The merger tree in this simulation is defined differently from the Millennium one in how the unique descendant is determined. The criterion is that the potential descendants are subhalos with at least 30 percent of members overlapped with their progenitor members. The descendant with the most particles is the unique descendant. We also test the same tree definition as the one in Millennium and the result turns out to be similar. For example, the merger rate derived from these two trees differs by less than 4% for any redshift. Moreover, the galaxy model applied to simulation $\Lambda$CDM is a simplified one (see Jian et al. 2008, for detail), where subhalos residing in host halos more massive than a certain mass $\sim 4 \times 10^{13} h^{-1} M_\odot$ at $z = 0$ are galaxy samples, and others are dark halos. This threshold is not based on galaxy luminosity but on the mass of the host halo in which galaxies reside. Due to the simple treatment of the galaxy properties, no orphan galaxies are considered, and the result from this simulation is included in this analysis in order to provide an extreme reference case relative to SAMs. The result allows us to understand whether the merger rate derived from subhalo mergers (without orphan galaxies) may be significantly different from the merger rate derived from galaxy mergers.

2.2. Semi-analytic Models

Semi-analytic modeling on galaxy formation and evolution was initially proposed by White & Frenk (1991), and since then variations of the original SAM have been proposed and verified to be successful (Croton et al. 2006; Bower et al. 2006; de Lucia & Blaizot 2007; Bertone et al. 2007; Font et al. 2008). In this study, we focus on the galaxy catalogs produced by four different SAMs implemented in the Millennium simulation including Bower06 (Bower et al. 2006), Font08 (Font et al. 2008), DeLucia06 (de Lucia & Blaizot 2007), and Bertone07 (Bertone et al. 2007). We investigate how much the results converge for the galaxy merger rate as a function of environment among different models. In addition, these galaxy catalogs are utilized to obtain information such as the merger probability of close pairs and the merger time, which are essential in determining the galaxy merger rate from observations. These catalogs are publicly available on the Millennium download site.\footnote{http://galaxy-catalogue.dur.ac.uk:8080/Millennium/} In the following, brief descriptions of different SAMs are given. For more detail, readers should refer to these papers.

Bower06 is based on the Durham semi-analytic model of galaxy formation, GALFORM, and implements a new treatment for the active galactic nucleus (AGN) energy injection, determined by a self-regulating feedback loop that is assumed to quench cooling flows in massive halos. They found that the feedback mechanism naturally produces a break at the bright end of the local luminosity function. In addition, satellite galaxies are assumed to lose all of their hot gases to the new parent halo upon being sufficiently close to the parent halos.

DeLucia06 is a slightly modified version of the one used in Springel et al. (2005), Croton et al. (2006), and de Lucia & Blaizot (2007). It includes the AGN feedback model from Croton et al. (2006) to suppress the cooling flows, and the model seems to be extremely efficient in switching off cooling in relatively massive halos even at high redshifts. Additionally, they also employed the supernova feedback model from Croton et al. (2006) to drive strong winds that blow out all gases away from galaxies on short timescales.

Bertone07 presents a new feedback scheme, which replaces empirical prescriptions on the supernova feedback of the Munich semi-analytic model with a dynamical treatment of the galactic wind evolution, where ejection and recycling of gases and metals are treated self-consistently. It was shown that the observed mass–stellar-metallicity and luminosity–gas-metallicity relationships are able to be reproduced by their model. However, two drawbacks exist in this model. The number of bright galaxies in the luminosity functions tends to be overestimated, and the color distribution of galaxies does not display the sharp color bimodality observed for galaxies in the local universe.

Finally, in Font08, which is one of the Durham SAMs, the major change is that they merge a model of stripping processes based on detailed hydrodynamic simulations into the GALFORM semi-analytical model for galaxy formation in an attempt to fix the problem that satellite galaxies in groups and clusters are redder than observed. They found that the effect of the ram pressure stripping on the colors of the satellite galaxies is significant. With assumptions of the gradual stripping as opposed to the sudden stripping in Bower06, a considerable fraction of hot gases in satellite galaxies is preserve for several Gyr, and satellite galaxies remain blue for a relatively long period of time as a result.

Kitzbichler & White (2008) noticed that different treatments in SAM influence the merger rate indirectly when identifying the merging systems as the observed merging galaxies. The galaxy formation modeling does not alter the dynamics of the underlying distribution of DM halos and subhalos, but when a galactic subhalo is tidally disrupted near the center of a more massive halo and is eligible to merge into that halo, the model estimates the merger time based on a dynamical friction time argument rather than assuming instant merging. In other words, once the subhalo is disrupted, the galaxy evolution model waits for one dynamical friction time before the associated galaxy of this halo completes merging into the central galaxy of the main halo. After subhalo disruption, the associated satellite galaxy is assumed to be attached to some particles, which are the most strongly bound particles of its last identified subhalo. The condition to obtain realistic close pairs is demonstrated in Kitzbichler & White (2008) via comparisons on the two-point correlations between simulated galaxies and real galaxies. However, we notice that different treatments of orphan galaxies affect not only the timescales when a close pair completes merging, but also the fraction of close pairs that will actually merge (see Section 3.4).

3. GALAXY MERGER RATE AS A FUNCTION OF ENVIRONMENT

3.1. Environmental Estimators: $M_h$ and $(1 + \delta_n)$

To study the environmental effect, we adopt two different environmental estimators. One is the host halo mass $M_h$ for the merging galaxies, which is a clear physical variable to represent the environmental effect and can be obtained easily.
that (1 + δ_n) is also studied in conjunction with M_h. The local galaxy density (1 + δ_n) is estimated using the projected nth nearest neighbor surface density, Σ_n ≡ n/π D_{p,n}^2, where D_{p,n} is the projected distance to the nth nearest neighbor that is within the line-of-sight velocity interval of 1000 km s^{-1}. In addition, each density value is divided by the median (Σ_n/median(Σ_n)), to reduce the influence of variations in redshift sampling in the survey (Cooper et al. 2005). Note that (1 + δ_n) is a relative but not an absolute quantity, and direct comparison for the same (1 + δ_n) at two different redshifts is, thus, not appropriate. In order to make a direct comparison with DEEP2 results from Lin et al. (2010), n = 6 is chosen to account for using the 3rd nearest neighbor in the DEEP2 sample with an average redshift completeness of ~50%. In the rest of this paper, we refer to 1 + δ_n as the overdensity measured up to the 6th nearest neighbor for galaxies. Furthermore, the applied galaxy selection cuts are different in simulation ΛCDM_{1000} and in the SAMs. For the SAMs, galaxy samples are selected with a flux-limit cut of R < 24.1, which is the same cut as in DEEP galaxies. For simulation ΛCDM_{1000}, the median distance to the nth nearest neighbor above a certain mass cut M_{cut} is computed so as to match the median distance to the 3rd nearest neighbor in the DEEP2 sample. The resulting (1 + δ_n) distribution of halos for ΛCDM_{1000} displays a very similar profile with the (1 + δ) distribution of observed DEEP2 galaxies (see Figure 4 of Lin et al. 2010). The corresponding M_{cut} for n = 6 are (1) 2.23, (2) 2.48, (3) 5.75, and (4) 8.35 × 10^{10} h^{-1} M_⊙ for four different redshifts, i.e., z = (1) ~1.1, (2) ~0.9, (3) ~0.7, and (4) ~0.5.

With these two estimators, M_h and (1 + δ_n), it is interesting to understand how they are correlated and how their correlation evolves. Therefore, the local density (1 + δ_n) distributions for galaxies residing in hosts of different masses denoted in color-coded lines from Font08 are plotted in Figure 1 as an example. We split a total sample of N galaxies at a certain redshift into four bins based on the host halo mass of galaxies. These M_h bins are 11 ≤ log_{10}(M_h/(h^{-1} M_⊙)) ≤ 12 (red), 12 ≤ log_{10}(M_h/(h^{-1} M_⊙)) ≤ 13 (green), 13 ≤ log_{10}(M_h/(h^{-1} M_⊙)) ≤ 14 (blue), and 14 ≤ log_{10}(M_h/(h^{-1} M_⊙)) ≤ 15 (black). In each of these four M_h bins, we further divide galaxies into different (1 + δ_n) bins. That is, the total sum of galaxy counts from all (1 + δ_n) bins and from the four M_h bins should be equal to N. We subsequently use N as a normalization factor so that the sum of the normalized count from all (1 + δ_n) bins for the light blue line is equal to one. It is noted that for a given range of the local density (1 + δ_n), its total strength is a collective result combining different contributions from various hosting environments. In other words, a galaxy with the highest (1 + δ_n) is not necessarily from the most massive hosting environment. Nevertheless, as seen in Figure 1, for those galaxies in a more massive host halo, their local density (1 + δ_n) tends to be distributed in a denser region. In addition, it is observed that when comparing the local density distributions at two different redshifts, the relative contribution from different M_h bins evolves with redshift. The contribution from the two most massive M_h bins increases with decreasing z and that from the two least massive bins decreases with decreasing z, implying that in time field galaxies gradually merge with galaxy clusters. Therefore, we conclude that the two estimators are well correlated, the local density indicator (1 + δ_n) has a

![Figure 1](image-url)
real physical meaning for the environment, and the dominant contribution for large \((1 + \delta_n)\) is from groups or small clusters.

### 3.2. Pair Fraction \(N_c\) and Galaxy Merger Rate

There are two observational approaches used to probe the evolution of mergers. One is related to the close-pair count (e.g., Patton et al. 2002; Lin et al. 2004, 2008), and the other is to count galaxy mergers through morphological signatures of galaxy interaction (e.g., Conselice at al. 2003; Lotz et al. 2008a). In this study, we follow the close-pair count approach to study the galaxy merger and explore its environmental dependence. In this approach, the direct observable is the average number of companions per galaxy, defined as

\[
N_c \equiv \frac{2N_{\text{pair}}}{N_g},
\]

where \(N_{\text{pair}}\) is the number of galaxy pairs and \(N_g\) is the number of galaxies in the sample. Through studying \(N_c\) from different models, a direct comparison between theories and observations can be made. Normally, the pair fraction is not equal to the average number of companions per galaxy, \(N_c\), but in this study, we liberally refer to the term “pair fraction” as “the average number of companions per galaxy.” Following the observational criterion in Patton et al. (2002), projected close pairs are so defined that the projected separation satisfies \(10 h^{-1} \text{kpc} \leq \Delta r \leq r_{\text{max}}\), where \(r_{\text{max}} = 50 h^{-1} \text{kpc}\) is assumed in this study, and the rest-frame relative velocity \(\Delta v\) is less than \(500 \text{ km s}^{-1}\). Additionally, galaxy samples are selected in the evolution-corrected B-band magnitude range, \(-21 \leq M_B \leq -19\), where \(M_B\) is defined as \(M_B(z = 0) + Q z\), with \(Q = 1.3\) adopted from Faber et al. (2007).

Our results on the evolution of the pair fraction \(N_c\) are shown in the left panel in Figure 2. This figure contains observation results (red error bars) taken from Lin et al. (2004) and Lin et al. (2008) that include DEEP2 (Davis et al. 2003, 2007) and some low-redshift data and simulation results from four SAMs, Bower06, Font08, DeLucia06, and Bertone07, along with results from Jian et al. (2008) (\(\Lambda\)CDM100b) and Berrier et al. (2006). Berrier et al. (2006) adopted two simple models for associating subhalos with galaxies: \(V_{\text{in}}\), the maximum circular velocity that the subhalo has when it was first accreted into the host halo, and \(V_{\text{low}}\), the maximum circular velocity that the subhalo has at the current epoch. Two models of Berrier et al. (2006) give a reasonable range compared with observations, as shown in Figure 2. It appears that the theoretical \(N_c(z)\) vary with models by a factor as large as \(\sim 3\) and overall deviate slightly from the observations. However, the flat evolutionary trends in the models are consistent with the observations. The flat trend of \(N_c(z)\) was first theoretically obtained by Berrier et al. (2006) and our results
The normalized merger rate is defined and estimated as follows:

\[ f_{mg} = 1 + G \frac{C_{mg} N_c}{T_{mg}}, \]  

where \( N_{mg} \) is the number of mergers, and \( T_i \) is the time to form the \( i \)th merger when the merger was still an identified close pair. In Equation (2), the factor of two is introduced to turn the number of merger pairs into the number of merging galaxies. From the definition, \( F_{mg} \) appear to depend on the distribution of \( T \) for the merger pairs. To understand the distribution of \( T \), we follow the identified close pairs at four starting redshifts until they merge and record its distribution. The results are presented in Figure 3. The distributions among different models are nearly flat and agree with each other. The flat distribution results in a longer medium or mean merging time of about 3–4 Gyr. On the contrary, the distribution from simulation \( \Lambda CDM_{100b} \) shows a peak at a short merging time. The main reason for the deviation is correlated with the lack of orphan galaxies in \( \Lambda CDM_{100b} \) and the merging time turns out to be much shorter than in the SAMs.

From an observational point of view, the galaxy merger rate is not an observable but an indirect quantity converted from the pair fraction \( N_c \). On the contrary, the theoretical merger rate is a direct measurable in simulation. By taking this advantage, we connect the theoretical merger rate to the merger rate in observational form to derive \( T_{mg} \) and to know the real meaning of \( T_{mg} \) defined in observation. We start by giving a clear definition of how the merger rate is measured in this work. There are two definitions considered for the galaxy merger rate. The first one is the normalized merger rate, and it is defined and estimated as follows:

\[ F_{mg} \equiv 2 \times \frac{1}{N_g} \sum_{i=1}^{N_{mg}} \frac{1}{T_i}, \]  

where \( N_{mg} \) is the number of mergers, and \( T_i \) is the time to form the \( i \)th merger when the merger was still an identified close pair. In Equation (2), the factor of two is introduced to turn the number of merger pairs into the number of merging galaxies. From the definition, \( F_{mg} \) appear to depend on the distribution of \( T \) for the merger pairs. To understand the distribution of \( T \), we follow the identified close pairs at four starting redshifts until they merge and record its distribution. The results are presented in Figure 3. The distributions among different models are nearly flat and agree with each other. The flat distribution results in a longer medium or mean merging time of about 3–4 Gyr. On the contrary, the distribution from simulation \( \Lambda CDM_{100b} \) shows a peak at a short merging time. The main reason for the deviation is correlated with the lack of orphan galaxies in \( \Lambda CDM_{100b} \) and the merging time turns out to be much shorter than in the SAMs.

In contrast, the definition from Lin et al. (2010) for the normalized merger rate is

\[ f_{mg} = 1 + G \frac{C_{mg} N_c}{T_{mg}}, \]  

where \( G \) is the correction factor that accounts for the selection effect of companions due to the restricted luminosity range, and \( C_{mg} \) represents the probability of galaxies in projected close pairs that will merge before the present. In mathematical expression,

\[ C_{mg} = N_{mg}/N_{pair}. \]  

Because not all projected pairs are merging systems, \( C_{mg} \) is introduced to account for the contamination from interlopers due to the difficulty in disentangling the Hubble expansion and
the galaxy peculiar velocity. To obtain \( f_{mg} \), \( C_{mg} \) is therefore as important as \( T_{mg} \), and these two essential quantities are not direct observables but can be evaluated through simulations. Apart from the factor of \((1 + G)\), \( F_{mg} \) and \( f_{mg} \) should be the same. The normalized merger rate \( F_{mg} \) can then be expressed in terms of \( N_c \), \( C_{mg} \), and \( T_{mg} \). Substituting \( C_{mg} \) with Equation (4) and \( N_c \) with Equation (1), we then obtain

\[
F_{mg} = \frac{C_{mg} N_c}{T_{mg}} = \frac{2N_{mg}}{N_g T_{mg}}.
\] (5)

Rewriting Equation (5), \( T_{mg} \) can then be expressed as a function of \( F_{mg}, N_g, \) and \( N_{mg} \) such that

\[
T_{mg} = \frac{2N_{mg}}{N_g F_{mg}} = \frac{N_{mg}}{\sum_{i=1}^{N_{mg}} \frac{1}{T_i}} = \frac{1}{\langle T^{-1} \rangle}.
\] (6)

The determination of \( T_{mg} \) is based on this formula in our work. There is an innate difference between the true merger timescale and the timescale over which the merger would be observable, i.e., the “observability timescale,” see, for example, Lotz et al. (2011). \( T_{mg} \) is also an average observability timescale, but defined differently from Equation (8) in Lotz et al. (2011). Our \( T_{mg} \) definition is close to Equation (8) in Kitzbichler & White (2008), and the main difference is that they absorb \( C_{mg} \) into the merger time but we do not, making their merger timescale longer than ours.

The other definition is the volumetric merger rate, which has the form

\[
R_{mg} = \frac{1}{L^3} = \frac{1}{2} F_{mg} \times n_g(z),
\] (7)

where \( L \) is the length of the simulation box on a side in units of \( h^{-1} \) Mpc and \( n_g(z) \) is the comoving number density of galaxies, i.e., \( n_g(z) = N_g / L^3 \) in this study. Comparatively, Lin et al. (2004) gives

\[
\Gamma_{mg} = (0.5 + G) \times \frac{n_g C_{mg} N_c}{T_{mg}}.
\] (8)

where \( G \) is the correction factor previously described and the factor of 0.5 in \((0.5 + G)\) converts the number of merging galaxies into the number of merger events. Except for the factor of \((0.5 + G), R_{mg} \) is the same as \( F_{mg} \).

In Figure 4, the normalized merger rate \( F_{mg} \) (top) and the volumetric merger rate \( R_{mg} \) (bottom left) for the models and observations are plotted as a function of \( z \), plus the evolution of the number density of the selected galaxies \( n_g \) (bottom

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**Figure 4.** Normalized galaxy merger rate \( F_{mg} \) (top), the volumetric merger rate \( R_{mg} \) (bottom left), and the number density of the galaxy sample in the magnitude range (bottom right) are plotted as a function of redshift \( z \). Top: the observational results (red) are taken from literatures including those from Patton et al. (2002) (diamond), Lin et al. (2004) (cross), Bell et al. (2006) (star), De Propris et al. (2007) (filled square), and de Ravel et al. (2011) (filled reverse triangle) adopting the approach of galaxy pair counts, and from Conselice et al. at al. (2003) (filled circle) and Lotz et al. (2008a) (filled triangle) using a morphological analysis of galaxies. Bottom left: the observational data points are taken from literatures including Lin et al. (2008) (DEEP2, TKRS, MGC, and CNOC2) and de Ravel et al. (2011) (zCOSMOS). The large deviation is observed between the observational merger rate and the theoretical values in the models. This is mainly due to the normalization factor \( C_{mg} / T_{mg} \) adopted by the observables to convert \( N_c \) into a merger rate much larger than those found in the models. However, the flat evolutionary trend is seen among the models. In addition, it is also evident that the merger rates vary with the models, and at a high redshift the variation is as large as an order of magnitude. Bottom right: the plot is to illustrate how the number density of galaxies varies with the redshift \( z \). At high redshift, the deviation among different models is as large as a factor of 10. \( R_{mg} \) basically is \( F_{mg} \times n_g(z) \).
right). Deviations in the merger rates among the models are seen, but the flat evolutionary trends in the merger rate for the models are consistent in the figures of $\Lambda_{\text{CDM}100}$ and $N_c$. Consequently, the merging history turns out to be very different, yielding a higher merger rate in $\Lambda_{\text{CDM}100}$. However, it was demonstrated by Kitzbichler & White (2008) that with the orphan galaxy treatment, clustering at a small scale at $z = 0$ produces a similar correlation strength as in the Sloan Digital Sky Survey, whereas there will be a deficit in the correlation strength without the treatment. The consistency of $\Lambda_{\text{CDM}100}$ may therefore seem to be a coincidence, and subhalo–subhalo mergers may present only a partial picture of real galaxy mergers. Our inclusion of the results from $\Lambda_{\text{CDM}100}$ in this study is simply to provide a reference.

On the bottom-right panel in Figure 4, the evolution of $n_c$ with galaxies selected in a two magnitude range is plotted for the models. The densities among the models can differ by an order of a magnitude at a high redshift and converge at a low redshift. This plot is to demonstrate that under the same selection criteria, density variations exist among different models.

### 3.3 $N_c$ and $F_{mg}$ as a Function of Environment

In the previous section, the redshift evolution of the pair fraction and the merger rate was discussed without considering the environmental effect. To assess the effect of the environmental dependence of the pair fraction, $N_c$ is plotted as a function of local density $(1 + \delta_n)$ (left) and $M_b$ (right) in four redshift ranges (1) $1.0 < z < 1.4$, (2) $0.8 < z < 1.0$, (3) $0.5 < z < 0.8$, and (4) $0.2 < z < 0.5$ in Figure 5. When we bin galaxy close pairs into different environments, we exclude pairs whose pair galaxies are in different $(1 + \delta_n)$ or $M_b$ bins, and we find that the

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**Figure 5.** Pair fraction $N_c$ is expressed as a function of local density $(1 + \delta_n)$ (left) and $M_b$ (right) in four redshift ranges. Because the correspondence between two estimators is not one to one, the profiles of $N_c$ from the models reveal the same linear growth with $(1 + \delta_n)$, and $N_c$ is in good agreement with DEEP2 observation (Lin et al. 2010), while those of $N_c$ show a turnover in $M_b$. The result is a higher $N_c$ found in high-density regions than in underdense regions and is consistent with the expectation that galaxies are more clustered in dense regions. It is also seen that $N_c$ varies with the models by a factor of ~1.5 in high-density regions and by a factor of ~4 in high $M_b$ bins.
that the pair fraction is small and unlikely to affect the result. In the left panel, it is seen that \( \alpha \) increases with \( 1 + \delta_n \), and different models are in good agreement with the DEEP2 observation (Lin et al. 2008), except for the densest bin. This increasing tendency is understandable simply because the galaxies in an overdense environment are more clustered, and thus easily appear in pairs. By contrast, in the right panel, \( N_c \) appears to grow at low \( M_h \) bins, but gradually becomes flat and displays large deviations among the models at high \( M_h \) bins. The explanation for this is that any given bin of \( 1 + \delta_n \) is contributed from various \( M_h \) bins, as discussed in Section 3.1 (see Figure 1), and due to the least contribution from the most massive cluster scale in overdense regions (the bins with high \( 1 + \delta_n \)), the total effect leads to the result where \( N_c \) continues to grow as the local density \( 1 + \delta_n \) increases. Additionally, the evolution of \( N_c \) appears to evolve weakly with redshift \( z \) in any case. However, different SAMs differ considerably by a factor of \(~1.5\) in \( N_c \) in the high-density region and by a factor of \(~4\) in the highest \( M_h \) bin.

The normalized galaxy merger rate \( F_{mg} \) is also evaluated in terms of \((1 + \delta_n)\) (left) and \( M_h \) (right) in Figure 6. In the left panel, the observational results from Lin et al. (2010) are included for comparisons. It is evident that \( F_{mg} \) has a strong dependence on the surrounding environment, demonstrating that mergers occur more frequently in a more dense region than in an underdense region. In addition, \( F_{mg} \) appears to be nearly redshift independent but model dependent. In the left panel, the galaxy merger rate is parameterized as \( F_{mg} \propto (1 + \delta_n)^\alpha \), then it is seen that \( F_{mg} \) is flatter in Bower06 (cyan) and Font08 (green) with \( \alpha \approx 0.3 \), and steeper in DeLucia06 (pink) and Bertone07 (blue) with \( \alpha \approx 0.6-0.7 \). That is, for all redshifts, galaxies merge more rapidly in high-density regions than in underdense regions by a factor of \(~4\) in Bower06 and Font08 and by a factor of \(~20\) in DeLucia06 and Bertone07. The positive correlation between the galaxy merger rate and the local density is in broad agreement with the measurement from Fakhouri & Ma (2009), in that for galaxy-mass halos, mergers occur \(~2.5\) times more frequently in the densest regions. The strong environment dependence is also consistent with the results in the recent observational works of Lin et al. (2010), de Ravel et al. (2011), and Kampczyk et al. (2011) over the redshift range \( 0.2 < z < 1.2 \). In contrast, \( F_{mg} \) in \( \Lambda CDM_{100} \) (black) shows nearly flat profiles, implying that it is roughly independent of environment. This finding of a lack of environmental dependence is close to what Hester & Tastisiomi (2010) concluded using a merger tree of subhalos from the Millennium Simulation. The difference between the SAMs and \( \Lambda CDM_{100} \) will be further discussed in Section 4.

On the other hand, when \( F_{mg} \) is expressed in terms of \( M_h \), the profile shows a turnover and has a peak in the \( M_h \) range between \( 10^{12} \) and \( 10^{13} \hbar^{-1} M_\odot \), which corresponds to group environments. The major disparity among the models is at the most massive \( M_h \) bin. Mergers occur approximately an order of magnitude more frequently in group or cluster environments than in a field environment, and the peak indicates that galaxies in group environments merge most efficiently. Because galaxies in a local density \((1 + \delta_n)\) bin are contributed partially from field, group, and cluster environments (see Figure 1), the actual enhancement in the merger rate seen in high local density regions in the left panel of Figure 6 is mainly contributed from galaxies in a group environment. This finding is in good agreement with that of Tran et al. (2008) that the group environment is critical for mergers to form massive galaxies. The fact that group galaxies have a high merger rate is expected, since in such environments...
galaxy close pairs have a low velocity dispersion and hence are easier to merge. In addition, as we will discuss in Section 3.4, close pairs in group environments are also less contaminated from the projection effect.

3.4. Environment Dependence of the Merger Timescale $T_{mg}$ and the Merger Probability of Close Pairs $C_{mg}$

Because $C_{mg}$ and $T_{mg}$ are two important quantities for observations to convert $N_{c}$ into a galaxy merger rate and can be determined only theoretically, we explore them in detail in this section. We evaluate $T_{mg}$ from Equation (6), previously defined. In Figure 7, $T_{mg}$ is expressed in terms of two environmental estimators, $(1 + \delta_{n})$ (left) and $M_{b}$ (right). On both panels, the merger time $T_{mg}$ shows a weak dependence on environments. In the densest region, $T_{mg}$ is $\sim 10\%$ shorter than that in an underdense region, and the deviation of $T_{mg}$ among different models is small. Moreover, the merger timescale $T_{mg}$ is much longer in the SAMs than in $\Lambda$CDM100b. The treatment of orphan galaxies to add dynamical friction time in the SAMs is responsible for the longer timescale. We also observe that $T_{mg}$ depends slightly on redshift $z$ and declines as $(1 + z)^{-1}$ for SAMs. However, we argue that the redshift dependence may not be a real effect. The shorter $T_{mg}$ obtained at a low redshift is simply because many of the projected close pairs identified at low $z$ have no time to merge before the present. That is, the shorter $T_{mg}$ represents only a small merger population.

Regarding the evaluation of $C_{mg}$, we follow the merger tree forward in time in the simulations to examine whether projected close pairs will merge before the present. If close pairs do not merge before the present time, then they will not be counted as mergers. The merger probability of close pairs $C_{mg}$ is the fraction of the merger number to the close-pair number and is to account for the effect of interloper contamination.

The merger probability of close pairs $C_{mg}$ is plotted as a function of local density $(1 + \delta_{n})$ (left) and $M_{b}$ (right) in Figure 8. Contrary to a weak dependence on environments in $T_{mg}$, $C_{mg}$ reveals a strong dependence on environments. In the left panel, $C_{mg}$ monotonically declines with the local density $(1 + \delta_{n})$, while it has a peak at the mid-$M_{b}$ bin $(12 < \log_{10}(M_{b}/M_{\odot}) < 13)$, corresponding to the group environment. The profiles of $C_{mg}$ in different SAMs also show significant discrepancies by a factor of three in both the left and right panels. At low redshift, the $C_{mg}$ profiles become flatter; this is understandable since a number of projected close pairs do not have enough time to merge before the present, and $C_{mg}$ does not vary with environment richness sensitivity, thereby yielding a flatter profile and having less difference between the underdense and overdense regions. In contrast, $C_{mg}$ at a low $z$ in $\Lambda$CDM100b still shows a steep profile and differs with those of the SAMs by a factor of $\sim 2$ in low-density regions. This is mainly due to the short merging timescale $T_{mg}$ in $\Lambda$CDM100b (see Figure 3), which results in a narrow distribution of merging time, and hence there is little difference between high and low redshifts.

To understand the origin leading to the environment dependence found in $C_{mg}$, the ratio of $N_{3D}/N_{pair}$ is investigated to give an idea of how many projected close pairs are really close in a three-dimensional (3D) space, where $N_{3D}$ is the number of galaxy pairs that are close in a 3D space in the two-dimensional (2D) close-pair sample. The ratio is computed as a function of local density $(1 + \delta_{n})$ and $M_{b}$, and the results are shown in Figure 9. The ratio of $N_{3D}/N_{pair}$ displays curves similar to the
Figure 8. Merger fraction $C_{mg}$ as a function of local density $(1 + \delta_n)$ (left) and $M_{h}$ (right). $C_{mg}$ is not only affected by the density, but also by the models. Left: $C_{mg}$ declines with the density. The variation between the lowest density and the highest density region is able to reach a factor of $\sim 5$ in Bower06 and Font08, but a factor of $\sim 1.5$ in DeLucia06 and Bertone07. At the same density bin, different models deviate as large as a factor of $\sim 3.5$. Right: the highest value of $C_{mg}$ is in the bin with $12.0 < \log_{10}(M_{h}/M_{\odot}) < 13.0$ (group environment). The deviation among different models is as large as a factor of $\sim 10$.

Figure 9. Ratio of $N_{3D}/N_{pair}$ as a function of local density $(1 + \delta_n)$ (left) and $M_{h}$ (right). From this plot we are able to know in these 2D-selected close pairs how many of them are three dimensionally close. It is found that the ratio has environmental dependence similar to $C_{mg}$, and it is thus inferred that the projection effect is responsible for the environmental dependence of $C_{mg}$. However, the slope of the ratio is flatter than that of $C_{mg}$, and it is suspected that some other physical mechanisms in dense environments prevent close pairs from merging.
pairs are due to the projection effect, and prevent 3D close pairs from merging. The projection effect appears to be the main factor for close pairs but fail to merge. The projection effect is very likely the main cause responsible for the drop of $C_{mg}$ in the overdense region. However, the slope in the profile of the ratio of $N_{3D}/N_{pair}$ is not as steep as in that of $C_{mg}$. It is possible that in the overdense region, projected close pairs are affected by some other physical processes other than the projection effect, such as high velocity dispersion, to make merger harder to occur.

To investigate this issue, we also plot 3D separation versus 3D peculiar velocity difference for those 2D-selected close pairs that merge (top) and that do not merge before the present (bottom) at $z \sim 1$ using Font08 as an example. In the top panel, the color bar indicates the merging time of the close pairs. Additionally, in the top-right corner the red-color numbers 31% and 69% indicate the merger and non-merger probability of close pairs, respectively. The blue-color numbers inside and outside the box show the ratios that pairs satisfy and do not satisfy from the projected close-pair criterion. It is found that ~64% of the non-merger pairs are due to the projection effect, and ~36% of them are really 3D close pairs but fail to merge. The projection effect appears to be the main factor for close-pair contamination. It seems that it is likely that high relative velocities prevent 3D close pairs from merging.

Figures 10. Illustration on how galaxies populate in the two-dimensional parameters space of 3D physical separation and 3D velocity difference for those 2D-selected close pairs that merge (top) and that do not merge before the present (bottom) at $z \sim 1$ using Font08 as an example. In the top panel, the color bar indicates the merging time of the close pairs. Additionally, the top-right corner the red-color numbers 31% and 69% indicate the merger and non-merger probability of close pairs, respectively. The blue-color numbers inside and outside the box show the ratios that pairs satisfy and do not satisfy from the projected close-pair criterion. It is found that ~64% of the non-merger pairs are due to the projection effect, and ~36% of them are really 3D close pairs but fail to merge. The projection effect appears to be the main factor for close-pair contamination. It seems that it is likely that high relative velocities prevent 3D close pairs from merging.

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4. DISCUSSION

By using galaxy catalogs based on four SAMs, we find that the normalized galaxy merger rate $F_{mg}$ reveals a strong environmental dependence, and this dependence is similar at all redshifts but strongly model dependent. We observe that when the galaxy merger rate is expressed in terms of $(1 + \delta_n)$ as $F_{mg} \propto (1 + \delta_n)^{\alpha}$, $\alpha \sim 0.3$ in Bower06 and Font08, and $\alpha \sim 0.6$–0.7 in DeLucia06 and Bertone07. The merger rate $F_{mg}$ between low-density and high-density regions can differ by a factor of ~4 in Bower06 and Font08, and by a factor of ~20 in DeLucia06 and Bertone07. In contrast, $F_{mg}$ in $\Lambda$CDM$_{1000}$, representing a case of subhalo–subhalo mergers, shows less or no environmental dependence. Despite a large discrepancy in the environmental dependence of $F_{mg}$ among the SAMs, the increasing trend is broadly consistent with the result found by Fakhouri & Ma (2009) that for galaxy-mass halos, mergers occur ~2.5 times more frequently in the densest regions, whereas the result in $\Lambda$CDM$_{1000}$ is similar to what Hester & Tastisiomi (2010) obtained, which is that the merger rate does not correlate with environment. However, it may not be fair to make direct comparisons between our results and that of Fakhouri & Ma (2009), simply because our sample contains different halo populations, whereas theirs did not. The fact that the positive correlation between $F_{mg}$ and the local density is observed in the SAMs and not in $\Lambda$CDM$_{1000}$ arises mainly from competition...
between the increasing \( N_c \) and decreasing \( C_{mg} \), with the local density of \( T_{mg} \) remaining roughly constant. The pair fraction \( N_c \) in the SAMs has a steeper increasing slope than that in \( \Lambda\text{CDM}_{100} \), while the merger probability of close pairs \( C_{mg} \) in the models has a flatter decreasing slope than that in \( \Lambda\text{CDM}_{100} \). (We note that the enhanced \( N_c \) at high local density in the SAMs is attributed to the presence of orphan galaxies.) In the end, the combined effect exhibited in \( T_{mg} \) turns out to be a flat profile in \( \Lambda\text{CDM}_{100} \) and a strongly increasing profile in the SAMs. As Kitzbichler & White (2008) pointed out, the inclusion of orphan galaxies is crucial when calibrating the conversion from pair counts to merger rates.

Deviation in the \( C_{mg} \) and \( T_{mg} \) determination among different SAMs is another interesting topic to be discussed. We notice that \( C_{mg} \) and \( T_{mg} \) adopted by observations vary with the referenced simulations, and the four SAMs we analyze give smaller \( C_{mg} \) and longer \( T_{mg} \) than those taken by observations (e.g., Patton et al. 2002; Lin et al. 2004, 2008, etc.). This leads to a significant deviation in the merger rate between the observation inference and the model predictions. In our analysis, \( C_{mg} \) ranges from 0.27 to 0.55 depending on the models and \( T_{mg} \) is about 2 Gyr with nearly no model dependence at \( z \sim 1 \). However, \( T_{mg} \) is assumed to be 0.5 Gyr in the observation work in Patton et al. (2002). In addition to the larger projection separation, with \( 50 \ h^{-1} \) kpc taken in our study to derive \( T_{mg} \) as opposed to 20 or \( 30 \ h^{-1} \) kpc taken by observations, the merger timescale is actually longer in the SAMs compared with simulation results from what Lotz et al. (2008b, 2010) obtained, \( \sim 1 \) Gyr. Our merging time distribution is wide and nearly flat (see Figure 3), and its median is \( \sim 3 \) Gyr at \( z \sim 1 \). This value may be considered to be a representative merger timescale. If the merger timescale is estimated following the definition in Kitzbichler & White (2008) that \( \langle T_{\text{merge}} \rangle = T_{mg}/C_{mg} \), then it can result in an even longer timescale \( \sim 2–4 \) Gyr. Additionally, Lotz et al. (2008b) gave a morphological analysis from a large suite of \( N \)-body/hydrodynamical gas-rich disk galaxy merger simulations processed through realistic radiative transfer models. For the same projected separation and velocity selection as in this paper, the timescale they obtained ranges from \( \sim 0.3 \) to 1.4 Gyr and the median is \( \sim 1 \) Gyr. Lotz et al. (2010) further explored the effect of gas fraction, and mergers with a different gas ratio result in a timescale of \( \sim 0.9 \) Gyr for 1:1 baryonic mergers and \( \sim 1.2 \) Gyr for 3:1 baryonic mass ratio mergers. Therefore, depending on what simulation is adopted and what the definition for the timescale is, the uncertainty of the merger rate can be as large as \( \sim 4 \).

In addition to the uncertainty of the merger time \( T_{mg} \) as discussed above, the merger probability of close pairs \( C_{mg} \) also shows large variation depending on how they are calculated. In particular, the environmental dependence of \( C_{mg} \) was addressed to a much lesser extent in the past. In Lin et al. (2010), the decrease of \( C_{mg} \) in high and low local density regions is by a factor of \( \sim 4 \), approximately independent of \( z \). However, this result corresponds to the case of subhalo–subhalo mergers. From our analysis, \( C_{mg} \) is apparently model and redshift dependent. The decline is by a factor of \( \sim 4 \) in Bower06 and Font08 and \( \sim 1.5 \) in DeLucia06 and Bertone07 at redshift \( z \sim 1 \), while the decline is by a factor of \( \sim 2 \) in Bower06 and Font08, and nearly flat in DeLucia06 and Bertone07 at \( z \sim 0.4 \). The uncertainty thus introduced by \( C_{mg} \) could be as large as \( \sim 2–3 \).

5. SUMMARY

We make use of publicly available galaxy catalogs from four SAMs, including Bower06, DeLucia06, Bertone07, and Font08, implemented in the Millennium Simulation to explore
the relation between the galaxy merger rate and its underlying environment, as well as to evaluate the model dependence of the merger rate. The approach taken by us closely follows the close-pair observations by giving selections with an evolution-corrected B-band magnitude range, \(-21 \leq M_B \leq -19\), with the projection separation in physical length \(\Delta r\) between 10 and 50 \(h^{-1}\) kpc, and with the line-of-sight velocity difference less than 500 km s\(^{-1}\). In this study, environment is quantified using the local density \((1 + \delta_0)\) and the host halo mass \(M_h\). Given these two estimators, we have been able to investigate the impact of environment on the galaxy merger rate. The results are summarized as follows.

1. The whole \((1 + \delta_0)\) distribution is decomposed into four bins based on the host halo mass \(M_h\) that galaxies reside in to understand how these two environment estimators are correlated and how the correlation evolves with redshift. It is found that galaxies in more massive host halos tend to have higher values of \((1 + \delta_0)\). However, the total number of galaxies in massive clusters is smaller than that in groups or small clusters. In other words, high density \((1 + \delta_0)\) is dominated by galaxies from groups or small clusters.

2. Although the pair fraction \(N_c\) among the SAMs displays large discrepancies among them and slightly deviates from the observational data, their redshift evolution is consistently flat and in agreement with the same trend as the observational results and as the theoretical results of Berrier et al. (2006).

3. The normalized merger rate \(\delta_n\) and the volumetric merger rate \(R_{mg}\) are both below the observational results. This is mainly because the ratio of the merger probability of close pairs \(C_{mg}\) to the merger timescales \(T_{mg}\) (the normalization constant) found in the SAMs is much smaller than those adopted in observations.

4. When the pair fraction \(N_c\) is expressed in terms of environment, \(N_c\) is found to be higher in a higher density or more massive \(M_h\) environment and the environmental dependence of \(N_c\) evolves little with time. In addition, difference among different SAMs is found mainly in high-density bins.

5. We observe a strong environmental dependence of the galaxy merger rate in the SAMs, where higher density regions have larger merger rates. When the galaxy merger rate is expressed as \(F_{mg} \propto (1 + \delta_0) \alpha\), the logarithmic slope is flatter in Bower06 and Font08 with \(\alpha \sim 0.3\), and steeper in DeLucia06 and Bertone07 with \(\alpha \sim 0.6-0.7\). That is, the merger rate between the low and high densities can differ by over an order of magnitude in certain SAMs. By contrast, the profile of the merger rate as a function of the halo mass is not power law dependent, but exhibits a more complicated dependence. The group environment turns out to be the regime where galaxies merge most frequently, consistent with what Tran et al. (2008) observed; the high merger rate in high local density regions is, in fact, due to significant contributions from galaxies in group environments.

6. The merger time \(T_{mg}\) shows approximately no environmental and no model dependence. The difference between the densest and underdense regions is \(\sim 10\%\). Different environments have little influence on the merger timescale if these projected close pairs are true bound pairs. The merger time is \(\sim 2\) Gyr at \(z \sim 1\).

7. Unlike \(T_{mg}\), the merger probability of close pairs \(C_{mg}\) depends on environments and on SAMs. Despite the discrepancies among different SAMs, their profiles all have a similar trends that \(C_{mg}\) drops as \((1 + \delta_0)\) increases, and on the other hand, all SAMs have a peak in the bin with \(\log_{10}(M_h / \delta_0)\) between 12 and 13.

8. Through evaluating the ratio of real 3D close pairs to 2D close pairs, we find that the projection effect is responsible for the environmental dependence of \(C_{mg}\). At \(z \sim 1\), only \(\sim 31\%\) of projected close pairs will eventually merge by \(z = 0\). For those close pairs that do not merge, the projection effect appears to be the origin of major contamination.

9. Because there is no dependence on environments for the fraction of pairs satisfying the mass ratio criterion to total pairs and the similarity among different \(F_{mg}\) profiles, we conclude that the impact of the mass ratio on the merger rate in different environments should be a minor effect.

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REFERENCES

Allen, P. D., Driver, S. P., Graham, A. W., et al. 2006, MNRAS, 371, 2
Barnes, J. E., & Hernquist, L. E. 1991, ApJ, 370, L65
Bell, E. F., Phleps, S., Somerville, R. S., et al. 2006, ApJ, 652, 270
Berrier, J. C., Bullock, J. S., Barton, E. J., et al. 2006, ApJ, 652, 56
Bertone, S., De Lucia, G., & Thomas, P. A. 2007, MNRAS, 379, 1143
Bonoli, S., Shankar, F., White, S. D. M., et al. 2010, MNRAS, 404, 399
Bower, R. G., Benson, A. J., Malbon, R., et al. 2006, MNRAS, 370, 645
Bundy, K., Fukugita, M., Ellis, R. S., et al. 2009, ApJ, 697, 1369
Carlberg, R. G. 1990, ApJ, 350, 505
Chou, R. C. Y., Bridge, C. R., & Abraham, R. G. 2011, AJ, 141, 87
Coll, A. L., Newman, J. A., Cooper, M. C., et al. 2006, ApJ, 644, 671
Conselice, C. J., Bershady, M. A., Dickinson, M., & Papovich, C. 2003, AJ, 126, 1183
Cooper, M. C., Newman, J. A., Maddick, D. S., et al. 2005, ApJ, 634, 833
Cox, T. J., Jonsson, P., Primack, J. R., & Somerville, R. S. 2006, MNRAS, 373, 1013
Croton, D. J., Springel, V., White, S. D. M., et al. 2006, MNRAS, 365, 11
da Costa, L. N., Willmer, C. N. A., Pellegrini, P. S., et al. 1998, AJ, 116, 1
Darg, D. W., Kaviraj, S., Lintott, C. J., et al. 2010, MNRAS, 401, 1552
Davis, M., Efstathiou, G., Frenk, C. S., & White, S. D. M. 1985, ApJ, 292, 371
Davis, M., Faber, S. M., Newman, J., et al. 2003, Proc. SPIE, 4834, 161
Davis, M., Guhathakurta, P., Konidaris, N. P., et al. 2007, ApJ, 660, L1
de Lucia, G., & Blaizot, J. 2007, MNRAS, 375, 2 (DeLucia06)
De Propris, R., Conselice, C. J., Liske, J., et al. 2007, ApJ, 666, 212
de Ravel, L., Kampczyk, P., Le Fèvre, O., et al. 2011, arXiv:1104.5740v1
de Ravel, L., Le Fèvre, O., Tresse, L., et al. 2009, A&A, 498, 379
Driver, S. P., Liske, J., Cross, N. J. G., De Propris, R., & Allen, P. D. 2005, MNRAS, 360, 81
Ellison, S. L., Patton, D. R., Simard, L., et al. 2010, MNRAS, 407, 1514
Faber, S. M., Willmer, C. N. A., Wolf, C., et al. 2007, ApJ, 665, 265
Fakhouri, O., & Ma, C.-P. 2008, MNRAS, 386, 577
Fakhouri, O., & Ma, C.-P. 2009, MNRAS, 394, 1825
Fakhouri, O., & Ma, C.-P. 2010, MNRAS, 406, 2267
Font, A. S., Bower, R. G., McCarthy, I. G., et al. 2008, MNRAS, 389, 1619
Font, A. S., Bower, R. G., McCarthy, I. G., et al. 2008, MNRAS, 389, 1619
Fonseca, S., Genzel, R., Bouché, N., Naab, T., & Sternberg, A. 2009, ApJ, 701, 2002
Guo, Q., & White, S. D. M. 2008, MNRAS, 384, 2
Hester, J. A., & Tastisiomi, A. 2010, ApJ, 715, 342
Hopkins, P. F., Bundy, K., Croton, D., et al. 2010a, ApJ, 715, 202
Hopkins, P. F., Croton, D., Bundy, K., et al. 2010b, ApJ, 724, 915
Hopkins, P. F., Hernquist, L., Cox, T. J., et al. 2006, ApJS, 163, 1
Hsieh, B. C., Yee, H. K. C., Lin, H., Gladders, M. D., & Gilbank, D. G. 2008, ApJ, 683, 33
