

GALAXY MERGERS AND DARK MATTER HALO MERGERS IN LCDM: MASS, REDSHIFT, AND MASS-RATIO DEPENDENCE

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ABSTRACT

We employ a high-resolution LCDM N-body simulation to present merger rate predictions for dark matter halos and investigate how common merger-related observables for galaxies—such as close pair counts, starburst counts, and the morphologically disturbed fraction—likely scale with luminosity, stellar mass, merger mass ratio, and redshift from $z = 0$ to $z = 4$. We provide a simple ‘universal’ fitting formula that describes our derived merger rates for dark matter halos a function of dark halo mass, merger mass ratio, and redshift, and go on to predict galaxy merger rates using number density-matching to associate halos with galaxies. For example, we find that the instantaneous merger rate of $m/M > 0.3$ mass ratio events into typical $L \gtrsim fL_*$ galaxies follows the simple relation $dN/dt \simeq 0.03(1+f) \text{ Gyr}^{-1} (1+z)^{2.1}$. Despite the rapid increase in merger rate with redshift, only a small fraction of $> 0.4L_*$ high-redshift galaxies ($\sim 3\%$ at $z = 2$) should have experienced a major merger ($m/M > 0.3$) in the very recent past ($t < 100$ Myr). This suggests that short-lived, merger-induced bursts of star formation should not contribute significantly to the global star formation rate at early times, in agreement with observational indications. In contrast, a fairly high fraction ($\sim 20\%$) of those $z = 2$ galaxies should have experienced a morphologically transformative merger within a virial dynamical time. We compare our results to observational merger rate estimates from both morphological indicators and pair-fraction based determinations between $z = 0 - 2$ and show that they are consistent with our predictions. However, we emphasize that great care must be made in these comparisons because the predicted observables depend very sensitively on galaxy luminosity, redshift, overall mass ratio, and uncertain relaxation timescales for merger remnants. We show that the *majority* of bright galaxies at $z = 3$ should have undergone a major merger (> 0.3) in the last 700 Myr and conclude that mergers almost certainly play an important role in delivering baryons and influencing the kinematic properties of Lyman Break Galaxies (LBGs).

Subject headings: cosmology: theory — dark matter — galaxies: formation — galaxies: halos — methods: N-body simulations

1. INTRODUCTION

In the current theory of hierarchical structure formation (LCDM), dark matter halos and the galaxies within them are assembled from the continuous accretion of smaller objects (Peebles 1982; Blumenthal et al. 1984; Davis et al. 1985; Wechsler et al. 2002; Fakhouri & Ma 2008; Stewart et al. 2008; Cole et al. 2008; Neistein & Dekel 2008; Wetzel et al. 2008). It is well-established that galaxy and halo mergers should be more common at high redshift (e.g. Governato et al. 1999; Carlberg et al. 2000; Gottlöber et al. 2001; Patton et al. 2002; Berrier et al. 2006; Lin et al. 2008; Wetzel et al. 2008), but the precise evolution is expected to depend on details of the mergers considered. Moreover, it is unclear how these mergers manifest themselves in the observed properties of high- z galaxies and what role they play in setting the properties of galaxies in the local universe. Interestingly, there are indications that the familiar bimodality of galaxies as disks versus spheroids at $z = 0$ might be replaced by a categorization of disk-like versus merger-like at higher redshift (Förster Schreiber et al. 2006; Genzel et al. 2006; Law et al. 2007a; Kriek et al. 2008; Melbourne et al. 2008; Shapiro et al. 2008; Wright et al. 2008), although this shift in the dichotomy of galaxy morphologies is by no means robust and requires fur-

ther study. In this paper, we use N-body simulations to provide robust predictions and simple fitting functions for dark matter halo merger rates and merger fractions as a function of redshift, mass, and mass ratio. We use our predictions to address two observable consequences of galaxy-halo mergers—merger-driven starbursts and morphological disturbances—and investigate their evolution with redshift.

The tidal interactions inherent in galaxy mergers produce concentrations of gas in the remnant centers. For major mergers ($m/M \gtrsim 0.3$), models predict that this effect results in a significant burst of increased star formation rate (SFR) compared to the central galaxy’s past star formation history (e.g. Mihos & Hernquist 1996; Cox et al. 2008). It also enables supermassive black hole growth and the fueling of AGN (e.g., Heckman et al. 1986; Springel et al. 2005a; Somerville et al. 2008). Cox et al. (2008) used Smooth Particle Hydrodynamical (SPH) simulations to show that the timescale over which merger-induced starbursts are active depends sensitively on the treatment of poorly-understood feedback and ISM physics; they demonstrate that future observational constraints on this timescale may provide a means to constrain feedback models (Barton et al. 2007, and references therein). Historically, SPH simulations have treated star forming gas as isothermal, and this treatment results in starburst timescales in major mergers that are quite short-lived, with $t_* \sim 100$ Myr (e.g. Mihos & Hernquist 1996; Cox et al. 2008). Recently, it has become popular in SPH simulations to impose a stiff equation of state for star-forming gas in order to mimic the

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effects of a multi-phase ISM and to suppress star formation and disk fragmentation (Yepes et al. 1997; Springel & Hernquist 2003; Governato et al. 2007). Cox et al. (2008) showed that a stiff equation of state of this kind significantly lengthens the timescale for starburst activity in major mergers to $t_* \sim 500$ Myr. Below we investigate the evolution of merger fractions with 100 Myr and 500 Myr as a first-order means of addressing the differences between merger-induced starburst fractions in different feedback schemes.

A second observationally-relevant consequence of mergers is morphological disturbance. Very large mergers, especially those with moderately low gas fractions, likely play a role in transforming late type disk galaxies into ellipticals (e.g., Toomre & Toomre 1972; Barnes & Hernquist 1996; Robertson et al. 2006a,b; Burkert et al. 2007). If gas fractions are high in major mergers (as expected at high redshift) then they may play a role in building early disks (Robertson et al. 2006a; Hopkins et al. 2008a,b; Robertson & Bullock 2008). More common are moderate-size ($m/M > 0.1$) dark matter halo mergers (Stewart et al. 2008), which can produce morphological signatures like disk flaring, disk thickening, and ring and bar-like structures in disk galaxies (Barnes & Hernquist 1996; Kazantzidis et al. 2007; Younger et al. 2007; Villalobos & Helmi 2008; Purcell et al. 2008) as well as tidal features seen in massive elliptical galaxies (Feldmann et al. 2008).

Below we explore two possibilities for the evolution of the morphological relaxation time with redshift. First, we explore a case where the remnant relaxation time scales with redshift with dark matter halo dynamical times ($\tau \propto (1+z)^{-\alpha}$, $\alpha \simeq 1.1 - 1.5$; see below), and second we investigate the possibility that relaxation times remain constant with redshift at $\tau \simeq 500$ Myr. The latter timescale is motivated by the results of Lotz et al. (2008) who studied outputs from SPH merger simulations of $z = 0$ galaxies in great detail (see Cox et al. 2006; Jonsson et al. 2006; Rocha et al. 2008; Cox et al. 2008, for additional descriptions of these simulations and their analysis). These choices bracket reasonable expectations and allow us to provide first-order estimates for the evolution in the morphologically disturbed fraction with redshift. More simulation work is needed to determine how the relaxation times of galaxy mergers should evolve with redshift, including an allowance for the evolution in approach speeds, galaxy densities, and orbital parameters (if any).

Though not discussed in detail here, a third consequence of mergers is the direct, cumulative deposition of cold baryons (gas and stars) into galaxies. For this question, one is interested in the full merger history of individual objects, rather than the instantaneous merger rate or recent merger fraction. Specifically, one may ask about the total mass that has been deposited by major mergers over a galaxy’s history. We focus on this issue in a companion paper (Stewart et al., 2008, in preparation).

In what follows we use a high-resolution dissipationless cosmological LCDM N-body simulation to investigate the merger rates and integrated merger fractions of galaxy dark matter halos of mass $M = 10^{11} - 10^{13} h^{-1} M_\odot$ from redshift $z = 0$ to 4. We adopt the simple technique of monotonic abundance-matching in order to associate dark matter halos with galaxies of a given luminosity

or stellar mass (e.g., Kravtsov et al. 2004; Conroy et al. 2006; Berrier et al. 2006; Conroy & Wechsler 2008), and make predictions for the evolution of the galaxy merger rate with redshift.

The outline of this paper is as follows. In §2 we discuss the numerical simulation used and the method of merger tree construction, while we present merger statistics for dark matter halos in §3. In §4 we discuss the method of assigning galaxies to dark matter halos both as a function of stellar mass, and alternatively as a function of galaxy luminosity (compared to $L_*(z)$). In §5 we present our principle results, which characterize the merger rate of galaxies as a function of redshift, with comparison to observed properties of bright galaxies. We summarize our main conclusions in §6.

2. SIMULATION

We use a simulation containing 512^3 particles, each with mass $m_p = 3.16 \times 10^8 h^{-1} M_\odot$, evolved within a comoving cubic volume of $80 h^{-1}$ Mpc on a side using the Adaptive Refinement Tree (ART) N-body code (Kravtsov et al. 1997, 2004). The simulation uses a flat, Λ CDM cosmology with parameters $\Omega_M = 1 - \Omega_\Lambda = 0.3$, $h = 0.7$, and $\sigma_8 = 0.9$. The simulation root computational grid consists of 512^3 cells, which are adaptively refined to a maximum of eight levels, resulting in a peak spatial resolution of $1.2 h^{-1}$ kpc (comoving). Here we give a brief overview of the simulation and methods used to construct the merger trees. They have been discussed elsewhere in greater detail (Allgood et al. 2006; Wechsler et al. 2006; Stewart et al. 2008) and we refer the reader to those papers for a more complete discussion.

Field dark matter halos and subhalos are identified using a variant of the bound density maxima algorithm (Klypin et al. 1999). A *subhalo* is defined as a dark matter halo whose center is positioned within the virial radius of a more massive halo. Conversely, a *field halo* is a dark matter halo that does not lie within the virial radius of a larger halo. The virial radius R and mass M are defined such that the average mass density within R is equal to $\Delta_{\text{vir}} (\simeq 337$ at $z = 0$) times the mean density of the universe at that redshift (see, e.g. Stewart et al. 2008). Our halo catalogs are complete to a minimum halo mass of $M = 10^{10} h^{-1} M_\odot$, and our halo sample includes, for example, $\sim 15,000(10,000)$ and $2,000(500)$ field halos at $z = 0(3)$ in the mass bins 10^{11-12} and $10^{12-13} h^{-1} M_\odot$, respectively.

We use the same merger trees described in Stewart et al. (2008), constructed using the techniques described in Wechsler et al. (2002) and Wechsler et al. (2006). Our algorithm uses 48 stored timesteps that are approximately equally spaced in expansion factor between $a = (1+z)^{-1} = 1.0$ and $a = 0.0443$. We use standard terminologies for progenitor and descendant. Any halo at any timestep may have any number of progenitors, but a halo may have a single descendant — defined to be the halo in the next timestep that contains the majority of this halo’s mass. The term *main progenitor* is used to reference the most massive progenitor of a given halo, tracked back in time.

Throughout this work we present results in terms of the *merger ratio* of an infalling object, m/M , where we always define m as the mass of the smaller object just *prior* to the merger and M is the mass *main progenitor*

of the larger object at the same epoch. Specifically, M in the ratio does not incorporate the mass m and therefore m/M has a maximum value of 1.0.

In what follows we investigate two types of mergers. The first and most robust of our predicted rates is the *infall rate*: the rate at which infalling halos become subhalos, as they first fall within the virial radius of the main progenitor. These are the results we present in Section 3, which describes our ‘universal’ merger rate function for dark matter halos. The second rate is aimed more closely at confronting observations and is associated with central mergers between galaxies themselves. Specifically we define the *destruction rate* by counting instances when each infalling subhalo loses 90% of the mass it had prior to entering the virial radius of the larger halo.³ We are unable to measure central crossings directly because the time resolution in our snapshot outputs (typically $\Delta t \simeq 250$ Myr) is comparable to a galaxy-galaxy crossing time at the centers of halos. However, this mass-loss approximation provides a reasonable proxy for central disk-interaction time (Boylan-Kolchin et al. 2007). Note that this second rate is more uncertain than the first because, in principle, the orbital evolution of infalling galaxies will depend upon the baryonic composition of both the primary and secondary objects. Fortunately, as presented in detail below (see Table 1) for the relatively high mass-ratio merger events we consider, the merger rates (and their evolution with redshift) do not depend strongly on whether we define a merger to occur at halo infall or at this central mass-loss epoch.

3. DARK MATTER HALO MERGER RATES

We begin by investigating infall and destruction merger rates as a function of mass, merger ratio, and redshift. Merger rates are shown for several of these choices in the four panels of Figure 1. The upper panels show merger rates per unit time for $> m/M$ mass ratio objects falling into host halos of mass $M = 10^{11}$ (blue), 10^{12} (black), and $10^{13} h^{-1} M_\odot$ (red) at three different redshifts: $z = 0$ (crosses), $z = 2$ (squares), and $z = 3$ (diamonds). Host halo mass bins span $\Delta \log_{10} M = 0.5$, centered on the mass value listed. The upper left panel presents rates measured at subhalo infall — i.e., the merger rates of distinct halos — and the upper right panel presents rates of subhalo destruction (when the associated subhalo loses 90% of the mass it had prior to entering the virial radius of the larger halo), which we expect to more closely trace the galaxy merger rates. The lower left panel presents infall rates, now plotted at a fixed mass ratio ($> m/M = 0.1, \dots, 0.7$ from top to bottom) and host mass ($M = 10^{12.5} h^{-1} M_\odot$, upper triangles; $M = 10^{11.5} h^{-1} M_\odot$, lower squares) as a function of redshift. The same information is presented in the lower right panel, but now presented as the rate per unit redshift instead of per unit time. We see that merger rates increase with increasing mass and decreasing mass ratio, and that the merger rate per unit time increases with increasing redshift out to $z \sim 4$.

We quantify the measured dependences using simple fitting functions. The merger rate per time for objects with mass ratio larger than m/M into halos of mass M

at redshift z is fit using

$$\frac{dN}{dt}(> m/M) = A_t(z, M) F(m/M). \quad (1)$$

For the infall rate, we find that the normalization evolves with halo mass and redshift as $A_t(z, M) = 0.02 \text{ Gyr}^{-1} (1+z)^{2.2} M_{12}^b$ with M_{12} the mass in units of $10^{12} h^{-1} M_\odot$ and $b = 0.15$. The merger mass ratio dependence is fit by

$$F(m/M) \equiv \left(\frac{M}{m}\right)^c \left(1 - \frac{m}{M}\right)^d, \quad (2)$$

with $c = 0.5$, and $d = 1.3$. A similar fit describes the destroyed rate, as summarized in Table 1. The fits are illustrated by solid lines that track the simulation points in each of the dN/dt panels in Figure 1.

The solid and dotted lines in the lower-right panel of Figure 1 show that the merger rate per unit redshift, dN/dz , is well described by the same mass-dependent function, but with a normalization that is only weakly dependent on redshift:

$$\frac{dN}{dz}(> m/M) = A_z(z, M) F(m/M), \quad (3)$$

where $A_z(z, M) = 0.27 (d\delta_c/dz)^2 M_{12}^{0.15}$. As discussed by Fakhouri & Ma (2008) (hereafter FM08), a redshift evolution of this form is motivated by the expectations of Extended Press-Schechter theory. Note that since $d\delta_c/dz$ asymptotes to a constant ~ 1.3 for $z \gtrsim 1$ and evolves only mildly to ~ 0.9 at $z \simeq 0$, the overall redshift dependence is weak.

To a large extent, our results confirm and agree with those of FM08, who studied merger rates for halos in the Millennium simulation (Springel et al. 2005b) and presented a fitting function for the merger rate per unit redshift per unit mass-ratio for halos as a function of mass and redshift (the differential of our rate, dN/dz , with respect to the merger rate m/M), and concluded that it was nearly universal in form. For comparison, the pink dashed lines in the left and right panels of Figure 1 show the implied expectations based on the FM08 fit for $M = 10^{12} h^{-1} M_\odot$ halos.⁴ The agreement is quite remarkable, especially in light of the fact that the simulations, merger tree algorithm, and halo finders all differed substantially from our own. Note that the agreement is particularly good over the mass ratios $m/M \simeq 0.05 - 0.5$ that are likely the most important for galaxy formation (in terms of their potential for morphological transformation and overall mass deposition, see Stewart et al. 2008). We note however that our infall (destruction) rate data are lower (higher) than FM08 by a factor of ~ 2 for very large mass-ratio mergers $m/M \gtrsim 0.7$ and both rates are smaller by a factor of ~ 2 for very small mass-ratio mergers $m/M \lesssim 0.01$. In addition, we find a slightly stronger mass dependence, $dN/dt \propto M^{0.15}$ as opposed to $dN/dt \propto M^{0.1}$ as found by FM08, and our infall rates are lower than FM08 by a factor of ~ 2 for $z \lesssim 0.3$.

4. ASSOCIATING HALOS WITH GALAXIES

³ Subhalo masses are defined to be the mass within a truncation radius R_t , which is set to be the minimum of the virial radius and the radius where the subhalo density profile begins to encounter the background halo density.

⁴ We use their fit for the ‘stitching’ merger rate, which corresponds most closely to our own definition for halo mergers.

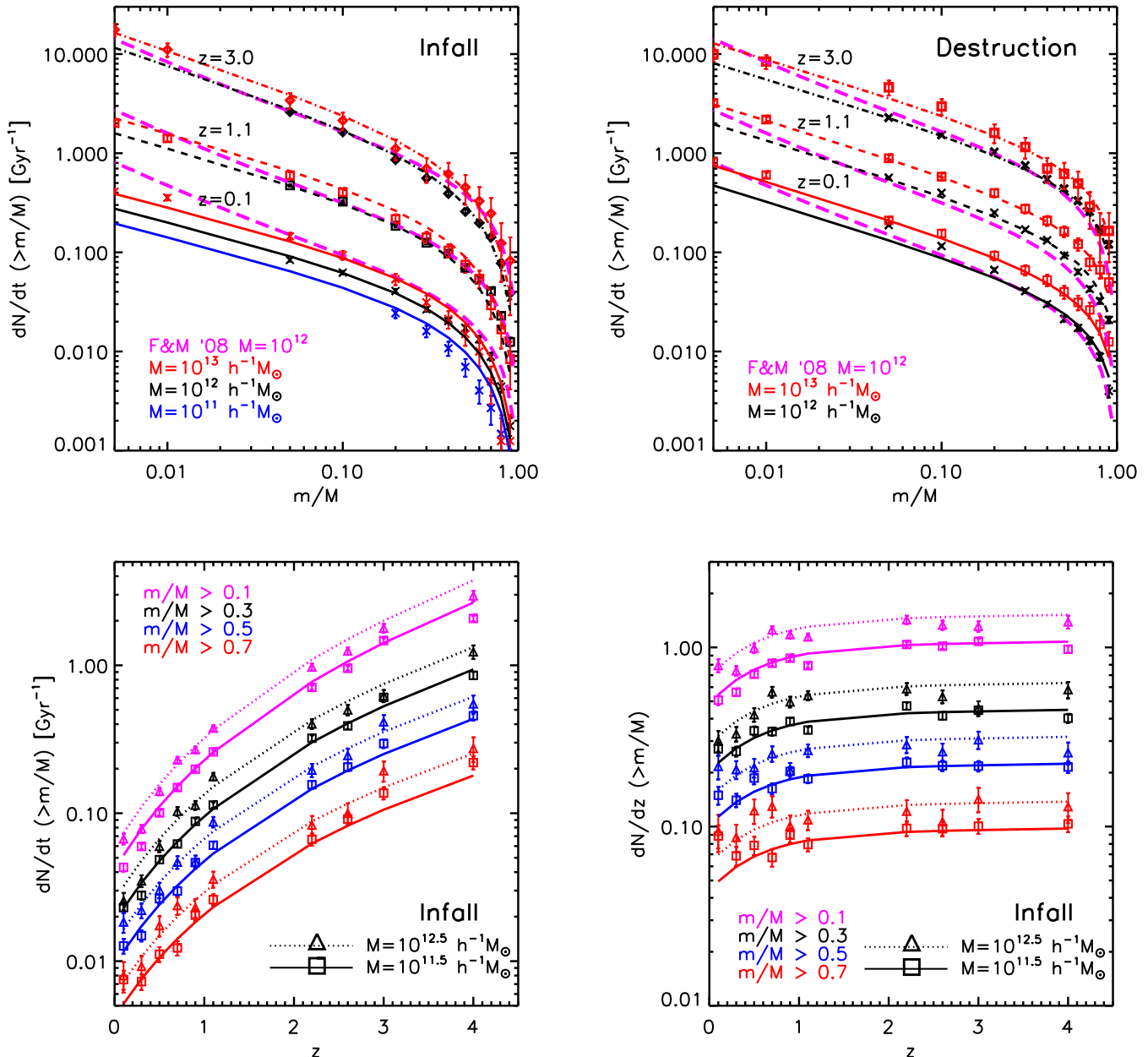


FIG. 1.— Dark matter halo infall and destruction rates (see §2) as a function of mass, merger-mass ratio, and redshift. Host halo mass bins span $\Delta \log_{10} M = 0.5$, centered on the mass value listed. *Top Left*: Infall rate per Gyr as a function of merger mass ratio, m/M , where m and M are both defined prior to the infall of the smaller system. The dashed (pink) line is a comparison to the results of Fakhouri & Ma (2008) for $M = 10^{12} h^{-1} M_{\odot}$ halos. *Top Right*: Identical to top left, but for the destruction rate of halos instead of the infall rate. *Bottom Left*: Infall rate per Gyr as a function of redshift. *Bottom Right*: Infall rate per unit redshift, as a function of redshift. Note the relatively weak redshift dependence, compared to dN/dt . In the top panels, blue, black and red lines correspond to different host halo masses ($10^{11}, 10^{12}, 10^{13} h^{-1} M_{\odot}$, respectively), while different symbols show different redshifts (crosses for $z \sim 0$, squares for $z \sim 1$, and diamonds for $z \sim 3$.) In the bottom panels, magenta, black, blue and red lines correspond to different merger ratios ($m/M > 0.1, 0.3, 0.5, 0.7$) while the solid vs. dotted lines represent two different host masses ($10^{11.5}, 10^{12.5} h^{-1} M_{\odot}$). Error bars are Poissonian based on both the number of halos and the total number of mergers used to calculate each data point. Horizontal error bars on the bottom figures, based on the redshift bin used to measure the merger rate, have been omitted for clarity, but are identical to those in Figure 2.

While dark matter halo merger rates at a given mass are theoretically robust quantities to compute in our simulation, they are difficult to compare directly with observations. One particularly simple, yet surprisingly successful approach is to assume a monotonic mapping between dark matter halo mass M (or similarly the halo maximum circular velocity) and galaxy luminosity L (Kravtsov et al. 2004; Tasitsiomi et al. 2004; Vale & Os-

striker 2004; Conroy et al. 2006; Berrier et al. 2006; Purcell et al. 2007; Marin et al. 2008; Conroy & Wechsler 2008). With this assumption, provided that we know the cumulative number density of galaxies brighter than a given luminosity, $n_g(> L)$, we may determine the associated halo population by finding the mass $M(L)$ above which the number density of halos (including subhalos) matches that of the galaxy population $n_h(> M) = n_g(> L)$. Ta-

TABLE 1
MERGER RATE FITTING FUNCTION PARAMETERS FOR EQUATIONS 1,2, AND 3.

Dark Matter Halos: $M = 10^{11.0-13.5} h^{-1} M_{\odot}$		$A(z, M)^{\dagger}$	c	d
dN/dt: (INFALL) simple fit		$0.020 (1+z)^{2.2} M_{12}^{0.15}$	0.50	1.30
dN/dt: (INFALL) complex fit		$0.020 (1+z)^{2.3} M_{12}^{0.15}$	$0.45 + .05z$	1.30
dN/dz: (INFALL)		$0.27 (d\delta_c/dz)^2 M_{12}^{0.15}$	0.50	1.30
dN/dt: (DESTROYED)		$0.022 (1+z)^{2.2} M_{12}^{0.2}$	0.54	0.72
dN/dz: (DESTROYED)		$0.32 (d\delta_c/dz) M_{12}^{0.2}$	0.54	0.72
Galaxy Luminosity Cuts: $L > fL_*$, $f = 0.1 - 1.0$		$A(z, f)^{\dagger}$	c	d
dN/dt:		$0.02 (1+f) (1+z)^{2.1}$	0.54	0.72
Merger Fraction in past T Gyr: (Frac < 0.6 and $T < 4$)		$0.02 T (1+f) (1+z)^{2.0}$	0.54	0.72
Galaxy Stellar Mass Ranges: $F(x) = F(m_*/M_*)$		$A(z)^{\dagger}$	c_*^{\ddagger}	d_*^{\ddagger}
dN/dt ($10^{10.0} M_{\odot} < M_* < 10^{10.5} M_{\odot}$):		$0.015 e^{1.0z}$	0.30	1.1
dN/dt ($10^{10.5} M_{\odot} < M_* < 10^{11.0} M_{\odot}$):		$0.035 e^{0.7z}$	0.25	1.1
dN/dt ($10^{11.0} M_{\odot} < M_*$):		$0.07 e^{0.2z}$	0.20	1.0

[†]When not dimensionless, units are Gyr^{-1} .

[‡]Mass-ratio variable for galaxy stellar mass merger rates are identified with a *stellar mass* ratio, $r = m_*/M_*$.

TABLE 2
DARK MATTER–LUMINOSITY RELATIONSHIP BY NUMBER DENSITY MATCHING.

z	Source & Rest-Frame Band	$> 0.1L_*$		$> 0.4L_*$		$> L_*$		$\tau(z)$ [Gyr]
		n_g^{\dagger}	M_{DM}^{\ddagger}	n_g^{\dagger}	M_{DM}^{\ddagger}	n_g^{\dagger}	M_{DM}^{\ddagger}	
0.1	SDSS ($r^{0.1}$ -band) ¹	9.9	$10^{11.2}$	3.6	$10^{11.7}$	1.10	$10^{12.3}$	1.79
0.3	COMBO-17/DEEP2 (B-band) ²	6.9	$10^{11.4}$	2.0	$10^{12.0}$	0.51	$10^{12.6}$	1.50
0.5	COMBO-17/DEEP2 (B-band) ²	8.2	$10^{11.3}$	2.4	$10^{11.9}$	0.61	$10^{12.5}$	1.28
0.7	COMBO-17/DEEP2 (B-band) ²	6.8	$10^{11.4}$	2.0	$10^{12.0}$	0.50	$10^{12.6}$	1.09
0.9	COMBO-17/DEEP2 (B-band) ²	8.6	$10^{11.3}$	2.5	$10^{11.9}$	0.64	$10^{12.5}$	0.95
1.1	COMBO-17/DEEP2 (B-band) ²	6.5	$10^{11.4}$	1.9	$10^{12.0}$	0.48	$10^{12.5}$	0.81
2.2	Keck Deep Fields (UV) ³	6.9	$10^{11.3}$	2.2	$10^{11.7}$	0.61	$10^{12.2}$	0.49
~ 2.6	Extrapolation (UV)	~ 6.1	$10^{11.3}$	~ 1.8	$10^{11.8}$	~ 0.41	$10^{12.3}$	0.40
3	Keck Deep Fields (UV) ³	5.3	$10^{11.2}$	1.3	$10^{11.7}$	0.31	$10^{12.2}$	0.32
3	Lyman Break Galaxies (V-band) ⁴	NA	NA	1.7	$10^{11.7}$	0.28	$10^{12.2}$	0.32
4	HUDF + HST ACS Fields (UV) ⁵	6.2	$10^{11.0}$	1.1	$10^{11.6}$	0.21	$10^{12.0}$	0.25

[†] 10^{-3} Mpc^{-3}

[‡] $h^{-1} M_{\odot}$

¹Blanton et al. (2003)

²Faber et al. (2007) with DEEP2 optimal weights.

³Sawicki & Thompson (2006)

⁴Shapley et al. (2001) – note that rest-frame V number densities match well with $> 0.4L_*$ and $> L_*$ values in rest-UV at $z = 3$.

⁵Bouwens et al. (2007)

ble 2 shows the number densities of various galaxy populations from redshifts $z = 0.1 - 4$ obtained using a variety of surveys for galaxies brighter than $L = fL_*$, where $f = 0.1, 0.4$, and 1.0 . We list the associated number-density matched dark matter halo mass in each case and we use this association to identify halos with galaxies below. An important point of caution is that the luminosity functions used to make these assignments at different redshifts vary in rest-frame band, as indicated in Column 2. Nevertheless, the halo masses associated with a given relative brightness should be indicative. Specifically, one concern might be that UV luminosity at low redshift is not strongly correlated with dark matter halo mass, so assuming such a correlation for high redshift galaxies is not valid. Unlike their low redshift counterparts, however, there is a strong correlation in high redshift ($z > 2$) galaxies between star formation and total baryonic mass, as well as a trend for more UV luminous galaxies to be more strongly clustered, suggesting that connecting UV luminosity to halo mass at these redshifts is a valid tech-

nique (see discussion in Conroy et al. 2008, and references therein). Encouragingly, as shown in the two $z = 3$ rows, the number density of fL_* galaxies from Sawicki & Thompson (2006; rest-frame UV) and Shapley et al. (2001; rest-frame V) are quite similar.

A related approach is to use observationally-derived stellar mass functions and to assume a monotonic relationship between halo mass and stellar mass M_* . Though a monotonic relationship between total stellar mass and dark matter mass avoids the issue of color band that arises in luminosity mapping, we cannot use it explore merger rates as a function of stellar mass above $z \sim 2$ because the stellar mass function is poorly constrained beyond moderate redshifts. For our analysis, we will adopt the relation advocated by Conroy & Wechsler (2008, hereafter CW08; interpolated from their data, as shown in Figure 2). For example, CW08 find that the halo mass M associated with stellar masses of $M_* = (1, 3, 10) \times 10^{10} M_{\odot}$ at $z = 0, 1, 2$ are $M(z = 0) \simeq (2.5, 7.0, 47) \times 10^{11} h^{-1} M_{\odot}$; $M(z = 1) = (4.0, 9.6, 41) \times$

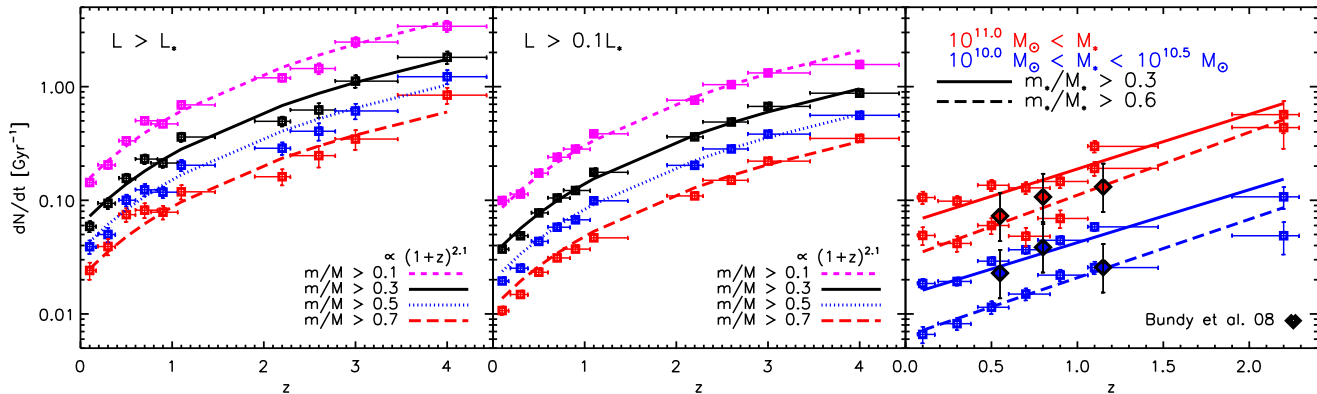


FIG. 2.— Expected merger rates per Gyr for galaxies of an indicated type as a function of redshift. The vertical error bars show Poisson errors on both the number of main halos and the total number of mergers averaged over per redshift bin while the horizontal error bars show the redshift bins used to compute the merger rate at each redshift. The error bars do not include uncertainties in the mapping of mass to luminosity or stellar mass. *Left:* Merger rate into galaxies with $L > L_*$ involving objects with *total* mass ratios $m/M > 0.1, \dots, 0.7$ as indicated. *Middle:* Merger rate into galaxies with $L > 0.1L_*$. *Right:* Merger rates for galaxies of a given *stellar* mass involving objects with *stellar mass ratios* $m_*/M_* > 0.3$ and 0.6 as a function of redshift. (Note that the redshift range in this panel only goes to $z = 2$.) We include two different stellar mass cuts in this panel, represented by the red and blue lines. The dotted lines in this panel show an extrapolation out to $z \sim 4$, based on our fit to the $z < 2$ simulation data. The filled diamonds show observational results for the same stellar mass cuts from Bundy et al. (2008).

10^{11} ; and $M(z=2) = (2.1, 3.9, 10) \times 10^{12} h^{-1} M_\odot$.

Note that while the dark matter halo merger rates presented in §3 give robust theoretical predictions, the merger rates we will present in terms of luminosity (or stellar mass) are sensitive to these mappings between halo mass and L (or M_*). In addition, it is difficult to perform a detailed investigation into the errors associated with these mappings, as there are inherent uncertainties in the luminosity and stellar mass functions, especially at $z > 1$. It is also possible that the monotonic mapping between halo mass and L (or M_*) may break down at $z > 1$ (see discussion in CW08). These uncertainties must be kept in mind when comparing our predicted merger rates (in terms of L or M_*) to observations, especially at high redshift.

5. GALAXY MERGER PREDICTIONS

5.1. Merger Rates

Our predicted merger rates and their evolution with redshift for $L > L_*$ and $L > 0.1L_*$ galaxies are illustrated in the left and middle panels of Figure 2. Rates are presented for a few selected *dark matter halo* mass ratio cuts $m/M > 0.1, 0.3, 0.5$, and 0.7 . Here, galaxy merger rates are defined using the *destruction rate*, when the infalling subhalo is identified as destroyed in the simulation (see §2). The solid lines correspond to a fit in the form of Equation (1), with the normalization evolving as $A_t(z, f) \propto (1+f)(1+z)^{2.1}$ for $L > fL_*$ galaxies. The explicit best-fit parameters for the merger rate as a function of luminosity cut are given in Table 1.

For comparison, the right panel in Figure 2 shows the predicted evolution in the merger rates per galaxy for two bins of stellar mass, according to the CW08 mapping described above: $10^{10.0} M_\odot < M_* < 10^{10.5} M_\odot$ (lower, blue) and $M_* > 10^{11} M_\odot$ (upper, red). Shown are merger rates for two choices of *stellar mass* ratio mergers, $(m_*/M_*) > 0.3, 0.6$ (solid and dashed lines respectively). The solid and dashed lines correspond to fits to our simulation results in the form of Equation (1), with $A_t(z) \propto e^{1.2z}$. The explicit best-fit parameters for these

two stellar mass bins (as well as an intermediate bin, $10^{10.5} M_\odot < M_* < 10^{11.0} M_\odot$) can be found in Table 1. Table 1 also provides best fit parameters for the function $F(r)$ (Equation 2) where now we associate the ratio r with the stellar mass ratio $r = m_*/M_*$. Note that we only show our simulation points for $z \lesssim 2$ in this panel, due to uncertainties in the stellar mass function at high redshift.

While the galaxy merger rate cannot be observed directly, it can be inferred using a number of different techniques. Mergers that are about to occur may be forecast by counting galaxy close pairs, and close pair fractions are often used as a proxy for the merger rate. The filled diamonds in the right panel of Figure 2 are recent merger-rate estimates from the pair count study of Bundy et al. (2008), for the same two stellar mass bins shown in the simulations (blue for the lower mass bin, red for the upper mass bin). Bundy et al. (2008) have used the simulation results of Kitzbichler & White (2008) to derive merger rates from the observed pair fraction. Overall, the trends with mass and redshift are quite similar and this is encouraging. However, the Bundy et al. (2008) results correspond to mergers with stellar mass-ratios larger than $m_*/M_* \gtrsim 0.25$. Our normalization is too high compared to this, and only matches if we use larger merger-ratios $m_*/M_* \gtrsim 0.5$. It is possible that this mismatch is associated with the difficulty in assigning merger timescales to projected pairs (see, e.g. Berrier et al. 2006) or that it may be traced back to uncertainties in assigning stellar masses to dark matter halo masses.

There are a number of other observational estimates of the merger rate based on pair counts of galaxies (e.g., Patton et al. 2002; Lin et al. 2004; Bell et al. 2006; Kartaltepe et al. 2007; Kampczyk et al. 2007; de Ravel et al. 2008; Lin et al. 2008; McIntosh et al. 2008; Patton & Atfield 2008; Ryan et al. 2008). We choose to compare our results to Bundy et al. (2008) as a recent representative of such work, primarily because it is more straightforward for us to compare to samples that are defined at a fixed stellar mass and stellar mass ratio. It is also

difficult to compare to many different observational results on the same figure self-consistently, because different groups adopt slightly different cuts on stellar mass (or luminosity) and on mass ratios for pairs. We note that if we were to extrapolate our best-fit curves to higher redshift than our data ($z \sim 4$), we find good agreement between our simulation data and the merger rate estimates using CAS (concentration, asymmetry, clumpiness) morphological classifications from Conselice et al. (2003) for galaxies with $M_* > 10^{10} h^{-1} M_\odot$. However, the mapping between stellar mass and halo mass adopted from Conroy & Wechsler (2008) is only valid to $z = 2$ (and most robust for $z < 1$), so extrapolating these fits to $z \sim 4$ is only a first-order check, and should not be considered a reliable prediction.

5.2. Merger Fractions

Another approach in measuring galaxy merger rates is to count galaxies that show observational signatures of past merging events such as enhanced star formation, AGN activity, and morphological disturbances. Unfortunately, the timescale over which any individual signature will be observable is often extremely uncertain, and will depend on the total mass and baryonic makeup of the galaxies involved as well as many uncertain aspects of the physics of galaxy formation (e.g. Berrier et al. 2006; Cox et al. 2008; Lotz et al. 2008b; Kitzbichler & White 2008). In order to avoid these uncertainties, we present results for merger fractions using several choices for look-back timescale here.

The three panels of Figure 3 show the predicted evolution of the merger fraction in galaxies brighter than $0.4L_*$ for three different choices of merger lookback time and for various choices for the total mass merger fraction $m/M > 0.1, \dots, 0.7$. The horizontal error bars on this figure show the *actual* redshift bins used to compute the merger fractions. The left and right panels show the merger fraction within 100 Myr and 500 Myr, respectively⁵, and the middle panel shows the fraction of galaxies that have had a merger within the past halo dynamical time⁶ $\tau(z)$, where $\tau(z) \simeq 2.0 \text{ Gyr} (1+z)^{-1.15}$ for $z \leq 1$ and $\tau(z) \simeq 2.6 \text{ Gyr} (1+z)^{-1.5}$ for $z > 1$.

5.2.1. Merger-driven starbursts

Several recent studies of star formation rates in galaxies at $z = 0 - 1$ suggest that the cosmic SFR density is not dominated by strongly disturbed systems with brief periods of intense star formation, as might be expected if merger-driven starbursts are common. Instead, the SFR density appears to be dominated by normal, non-merging galaxies (Wolf et al. 2005; Bell et al. 2005; Jogee et al. 2008; Noeske et al. 2007). As discussed in the introduction, the briefest timescales we expect for merger-triggered starbursts is ~ 100 Myr (Mihos & Hernquist 1996; Cox et al. 2008), and for these models we expect the star formation to increase to ~ 20 times the isolated value for $m/M \gtrsim 0.3$ events (Cox et al. 2008). As we see

⁵ In most cases, the available timesteps ($\Delta t \simeq 250$ Myr) are too widely spaced to directly measure fractions within 100 Myr. For this reason, the left panel is actually the merger fraction within the last Δt timestep, scaled down by a factor of $(\Delta t/100\text{Myr}) \simeq 2.5$.

⁶ We use $\tau = R/V \propto (\Delta_v(z) \rho_u(z))^{-1/2}$, such that the halo dynamical time is independent of halo mass.

from the left-panel of Figure 3, the fraction of galaxies that have a merger large enough ($m/M > 0.3$) to trigger such a burst is quite small, $\lesssim 1\%$ for $z \lesssim 1$. It is therefore not surprising that stochastic starbursts of this kind do not dominate the SFR density at moderate to low redshifts. Even at higher redshift ($z = 3 - 4$), the fraction of galaxies with major mergers on these timescales is less than $\sim 6\%$ of the total bright galaxy population. This is consistent with the results presented in Somerville et al. (2008), for their semi-analytic model.

Alternatively, if merger-driven starbursts remain active for ~ 500 Myr, as other models suggest, then their enhancements are expected to be less pronounced (with an SFR ~ 5 times isolated; Cox et al. 2008). In this case, the right panel of Figure 3 is the relevant prediction, and we see that (at most) $\sim 3 - 9\%$ of bright galaxies could exhibit signs of such elevated activity between $z = 0$ and $z = 1$. It seems that in either case, we would not expect merger-triggered activity to play a major role in driving the integrated star formation rate at these epochs. Only at the highest redshifts $z \gtrsim 3$ would this seem possible. A comparison of the clustering of galaxies to that of dark matter halos also suggests that star-forming galaxies at $z \sim 2$ are most likely massive galaxies quiescently forming stars as opposed to less massive galaxies in the midst of merger-induced starbursts (Conroy et al. 2008).

We note that our numbers are an upper limit on the fraction of bright galaxies that could be experiencing merger-induced starbursts, because high gas fractions are also necessary. For example, a study of 216 galaxies at $z \sim 2 - 3$ by Law et al. (2007b) found that galaxy morphology (in rest-frame UV) was not necessarily correlated with star formation rate, and in a recent examination of two Chandra Deep Field South sources using adaptive optics, Melbourne et al. (2005) found an example of a merger of two evolved stellar populations, in which the major merger signature was not accompanied by a burst of star formation, presumably because both galaxies were gas-poor. Lin et al. (2008) finds that $\sim 8\%$ (25%) of mergers at $z \sim 1.1$ (0.1) are gas-poor, suggesting that this issue, while less dominant at high redshift, is a significant effect and must be taken into consideration.

5.2.2. Morphological signatures

Even if the contribution to the overall SFR due to very recent mergers remains low, this does not necessarily imply that there would be a lack of morphological signature. The timescale for morphological relaxation may be significantly longer than starburst activity. Though the precise timescales for relaxation are uncertain, the middle and right panels of Figure 3 explore merger fractions for two reasonable choices: a fixed 500 Myr timescale and a redshift-dependent halo dynamical time τ .

Lotz et al. (2008a) used AEGIS survey data to study the morphological evolution and implied galaxy merger fraction from redshift $z = 0.2$ to 1.2. The merger fraction results for $> 0.4L_*$ galaxies from Lotz et al. (2008) are shown by the green pluses in the middle and right panels of Figure 3. In a similar investigation, Jogee et al. (2008) study $z = 0.2 - 0.8$ galaxies using a combination of HST, ACS, Combo-17, and Spitzer 24 μm data to estimate the fraction of “strongly disturbed” galaxies. Their

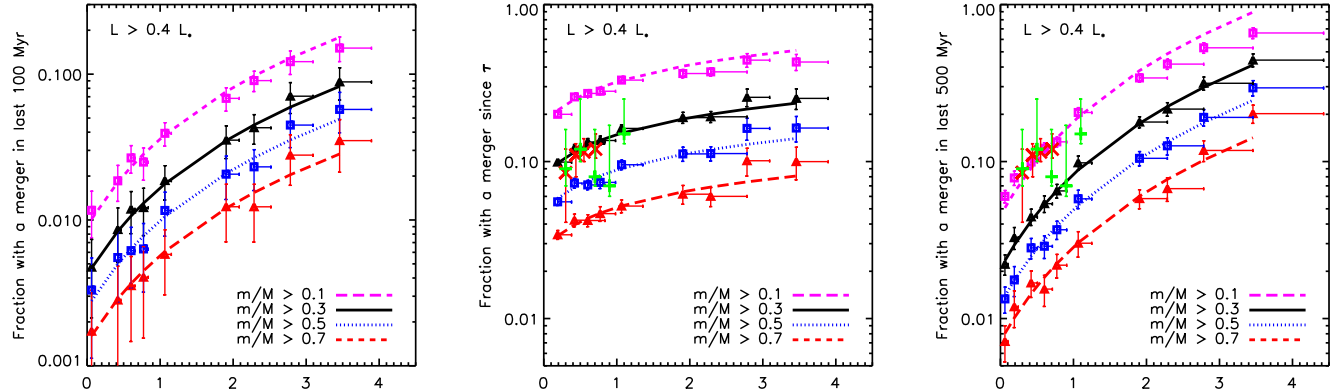


FIG. 3.— The fraction of halos that experience at least one merger larger than m/M in the past 100 Myr (left), halo dynamical time τ (middle), or 500 Myr (right), as a function of z . Error bars show the Poisson \sqrt{N} error based on the both the number of main halos and the total number of mergers averaged over, while the horizontal error bars show the redshift bins used to compute the merger rate at each redshift. The error bars do not include uncertainties in the mapping of mass to luminosity. The crosses and plus signs represent estimates of the observed merger fraction at various redshifts, based on Jogee et al. (2008, red) and Lotz et al. (2008a, green), respectively.

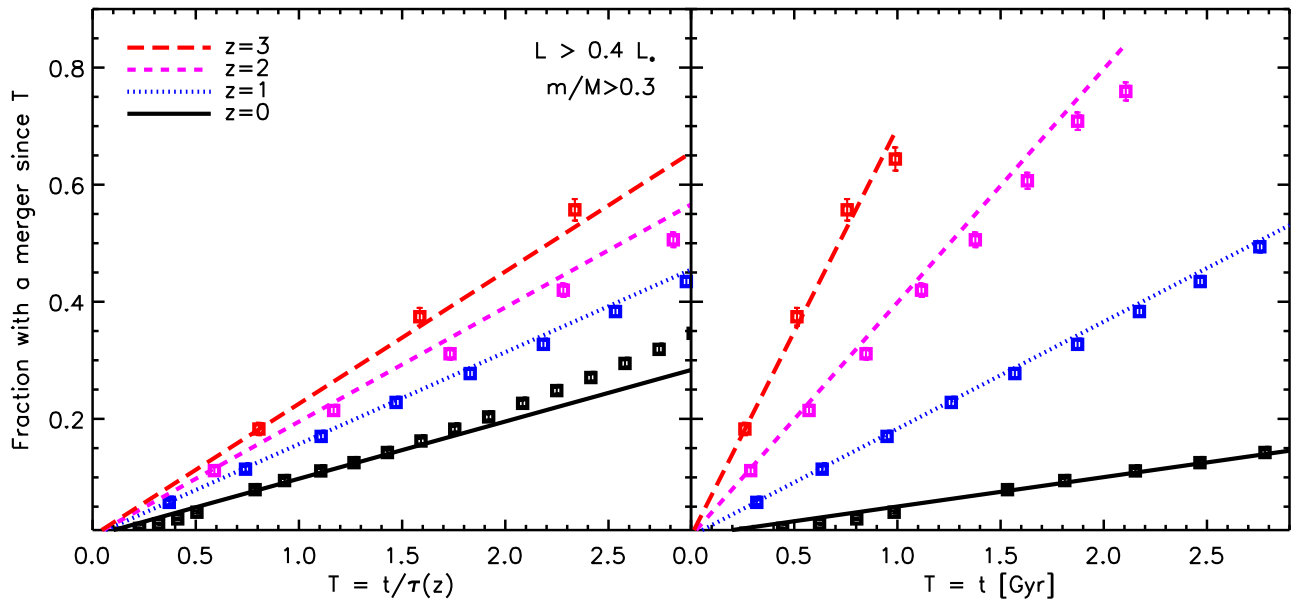


FIG. 4.— The fraction $> 0.4L_*$ galaxies at $z \sim 0, 1, 2, 3$ (black solid to red dashed lines) that have experienced a major merger ($m/M > 0.3$) over a given time period. Symbols show the simulation data, while the lines are given by the fit in Table 1. *Left*: Merger fraction since t , normalized by the halo dynamical time at each redshift, $\tau(z = 0, 1, 2, 3) \simeq 1.95, 0.92, 0.49, 0.32$ Gyr. *Right*: Merger fraction in the past t Gyr. Error bars show the Poisson \sqrt{N} error based on the total number of mergers, and are comparable to the symbol sizes. The error bars do not take uncertainties in the mapping of mass to luminosity into account.

results⁷ are shown by the red crosses in Figure 3, and are in reasonably good agreement with the points from Lotz et al. (2008). We note that the data from these very recent works seem to be in good agreement with the $m/M > 0.3$ merger fraction if the relaxation time is close to τ . This case in particular has a fairly weak evolution because τ is decreasing with time. Interestingly, however, due to the rather large measurement uncertainties, the data are also in reasonable agreement with the

⁷ The data from Jogee et al. (2008) correspond to a fixed stellar mass cut at $M_* \sim 2.5 \times 10^{10} M_\odot$, but the associated dark matter halo mappings from CW08 are close to those for galaxies with $> 0.4L_*$ (see Table 1 and our discussion in §4).

fixed relaxation timescale case of 500 Myr (which has a steeper evolution with z), as long as more minor mergers ($m/M > 0.1$) can trigger the observed activity. The fact that the data matches both the predictions in the middle panel and right panel of Figure 3 draws attention to the inherent degeneracies in this comparison. The same merger fractions are obtained with high-mass ratio merger events and lookback times or with lower mass ratio mergers with slightly shorter lookback times.

We may also compare our predictions with the results of Melbourne et al. (2008), who imaged 15 $z \sim 0.8$ luminous infrared galaxies (LIRGs) with the Keck Laser Guide Star (LGS) AO facility, and found that 3/15 of

the galaxies showed evidence for a *minor* merger, while only 1/15 was consistent with a major merger. These results match our expectations for major ($m/M > 0.3$) and minor ($m/M > 0.1$) merger fractions at $z \sim 0.8$ fairly well, considering the small number statistics. Similarly, Shapiro et al. (2008) study 11 rest-frame UV/optical-selected $z \sim 2$ galaxies with spectroscopic data from SINFONI on the VLT, and estimate that $\sim 25\%$ of these systems are likely undergoing a major (mass ratio $\leq 3:1$) merger. Again, our expectations as shown in the middle and right panels of Figure 3 are consistent with these numbers.

The above discussion makes it clear that meaningful comparisons between observed morphologically disturbed fractions and predicted merger fractions rely fundamentally on understanding how the mass ratio involved affects the morphological indicator and on the associated relaxation timescales of the associated remnants. In addition, merger rates are expected to depend sensitively on the galaxy luminosity and redshift (see Table 1). Comparisons between observational results and theory therefore require great care, especially as it concerns the evolution of the merger rate. If, for example, higher redshift measurements are biased to contain brighter galaxies than lower redshift measurements, then the redshift evolution will likely be steeper than the underlying halo merger rate at fixed mass. Or, if higher redshift measurements are sensitive to only the most massive mergers, while lower redshift measurements detect more subtle effects, then the evolution in the merger rate will be biased accordingly.

5.2.3. High Redshift Expectations

As seen clearly in Figures 2 and 3, the merger rate per galaxy and the corresponding merger fraction at a fixed time are expected to rise steadily towards high redshift. Even after normalizing by the halo dynamical time, which decreases with redshift, this evolution with redshift persists, as seen in Figure 3 (middle). This point is emphasized in Figure 4, which shows the fraction of $L > 0.4L_*$ galaxies that have had a merger larger than $m/M = 0.3$ within the last t Gyr (right) and within the last $t/\tau(z)$ Gyr (left). The left-hand panel scales out the evolution in the halo dynamical time. We see that $\sim 50\%$ of $z=3$ galaxies are expected to have had a major merger in the last 700 Myr, and that these galaxies are ~ 4 times as likely to have had a significant merger in the last dynamical time than bright galaxies at $z=0$. It would be surprising then if mergers did not play an important role in setting the the properties of most $z = 3$ galaxies like Lyman Break Galaxies (LBGs). These major mergers should (at least) deliver a significant amount of gas to fuel star formation, affect LBG dynamics, and perhaps trigger starburst activity. If LBGs represent a biased sample of $z = 3$ galaxies⁸ then it is possible that the merger fraction is even higher.

At higher redshifts, $z > 3$, we expect major mergers to become increasingly common. The brightest galaxies $L > 0.4L_*$ should be undergoing mergers frequently, with an overwhelming majority of $z = 4$ galaxies having experienced some significant merger activity in the last

~ 500 Myr.

6. CONCLUSION

We have used a high-resolution Λ CDM N -body simulation to investigate the instantaneous merger rate of dark matter halos as a function of redshift (from $z = 0 - 4$), merger mass ratio, and host halo mass from $M = 10^{11}$ to $10^{13}h^{-1}M_\odot$. Merging companions as small as $m = 10^{10}h^{-1}M_\odot$ were tracked. We use number density matching to associate galaxies with dark matter halos and present predictions for the merger rate and merger fraction as a function of galaxy luminosity and stellar mass. The principle goal has been to present raw merger statistics that can be compared directly to observations of galaxies to high redshift. Fitting functions that describe our results as a function of luminosity, mass, mass-ratio, and redshift are provided in Table 1.

Our main results may be summarized as follows:

1. A simple fitting function describes the accretion rate of small dark matter halos of mass m into larger dark matter halos of mass M as a function of redshift: $dN/dt = A(z, M) F(m/M)$, where typically $A(z, M) \propto (1+z)^{2.2} M^{0.15}$ and $F(m/M) = (M/m)^c (1 - m/M)^d$. Fit parameters for merger rates in terms of dark halo mass, luminosity, or stellar mass are given in Table 1.
2. The merger rate of galaxies of luminosities $L > fL_*$ should evolve in a similar manner, with a redshift and luminosity dependence that follows $A(z, f) \propto (1+f)(1+z)^{2.1}$.
3. Only a small fraction (0.5% at $z = 0$, 10% at $z = 4$) of bright ($> 0.4L_*$) galaxies should have experienced a major (> 0.3) merger in their very recent history (100 Myr, Figure 3 left panel). Even if mergers trigger the kind of short-lived, highly-efficient star formation bursts that are expected in some models, they cannot contribute significantly to the overall distribution of star formation rates at any given epoch.
4. The predicted fraction of galaxies with a merger in the past 500 Myr, or alternatively within a past halo dynamical time, are in reasonable agreement with the fraction of galaxies that show observational signs of morphological disturbance between redshifts $z = 0 - 2$ (Figure 3, middle and left panels). We emphasize, however, that comparisons between theory and observations suffer from significant uncertainties associated with mass-ratio dependences and relaxation timescales.
5. Galaxy merger rates should depend on at least three parameters: mass (or luminosity), merger mass ratio, and redshift (see Table 1). Therefore any attempt to compare two observational indicators of the merger rate or to relate specific observations to theoretical predictions must take great care in the respective comparisons.
6. Mergers must become increasingly important in shaping galaxy properties at $z > 3$. At $z = 3$, the fraction of galaxies with a merger in the past dynamical time is ~ 4 times higher than at $z = 0$. We

⁸ It is estimated that $\sim 75\%$ of all bright galaxies at $z \sim 3$ are LBGs (Marchesini et al. 2007; Quadri et al. 2007).

expect $\sim 30\%$ (60%) of $> 0.4L_*$ galaxies to have experienced a $m/M > 0.3$ major ($m/M > 0.1$ minor) merger in the past 500 Myr at $z = 3$. Though it is unlikely that short-lived starbursts associated with these mergers drive the increase in the global star formation rate of galaxies with redshift, the broader implications of these mergers (fresh supply of gas brought in to the central galaxy through accreted satellites, etc.) are undoubtedly linked to star formation and the general growth of galaxies on longer timescales.

As this work was being completed, Wetzel et al. (2008) reported on an investigation of the merger rate of halos and subhalos. They found that the infall rate for halos evolves with redshift as $dN/dt = A(1+z)^\alpha$ (with $\alpha = 2.0 - 2.3$) from $z = 0.6 - 5$, in agreement with our infall rates (see Table 1). Wetzel et al. (2008) also reported that the subhalo merger rate in their simulations tend to be lower than that field halo rates and that the redshift evolution slope, α , changes for subhalos as a function of halo mass and redshift (e.g. $\alpha \simeq 1.1$ for $z = 5 - 2.5$ and $\alpha \simeq 2.35$ for $z = 1.6 - 0.6$). Our measured halo destruction rates and halo infall rates, on the other hand, are similar to each other, even though our destruction rate attempts to track a similar physical phenomenon as their subhalo merger rate—the rate of impact of satellite galaxies onto central galaxies. We speculate that the discrepancy between their results and ours is due to differences in definition. We define an infalling halo “destroyed” once it loses 90% of its infall mass, at which point (especially for major mergers) it is likely that

the subhalo has significantly impacted the central galaxy. Wetzel et al. (2008) defines subhalo mergers by tracking the evolution of the subhalo’s 20 most-bound particles, and this results in a much more stringent definition of mergers. At the very least, the differences between our two results highlight the differences that are manifest in defining mergers, even between dark matter structures, and motivate the need for focused simulations in order to determine the timescales and observational consequences associated with the much more clearly defined rate with which dark matter subhalos first fall within the virial radii of their hosts.

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