THE MERGER–DRIVEN EVOLUTION OF MASSIVE GALAXIES

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Draft version June 30, 2010

ABSTRACT

We explore the rate and impact of galaxy mergers on the massive galaxy population using the amplitude of the two-point correlation function on small scales for $M_* > 5 \times 10^{10} M_\odot$ galaxies from the COSMOS and COMBO–17 surveys. Using a pair fraction derived from the *Sloan Digital Sky Survey* as a low-redshift benchmark, the large survey area at intermediate redshifts allows us to determine the evolution of the close pair fraction with unprecedented accuracy for a mass-selected sample: we find that the fraction of galaxies more massive than $5 \times 10^{10} M_\odot$ in pairs separated by less than 30 kpc in 3D space evolves as $F(z) = (0.0130 \pm 0.0019) \times (1+z)^{1.21 \pm 0.25}$ between $z = 0$ and $z = 1.2$. Assuming a merger time scale of 0.5 Gyrs, the inferred merger rate is such that galaxies with mass in excess of $10^{11} M_\odot$ have undergone, on average, 0.5 (0.7) mergers involving progenitor galaxies both more massive than $5 \times 10^{10} M_\odot$ since $z = 0.6$ (1.2). We also study the number density evolution of massive red sequence galaxies using published luminosity functions and constraints on the M/L_B evolution from the fundamental plane. Moreover, we demonstrate that the measured merger rate of massive galaxies is sufficient to explain this observed number density evolution in massive red sequence galaxies since $z = 1$.

Subject headings: galaxies: general — galaxies: evolution — galaxies: interactions — galaxies: ellipticals and
lenticulars, cD — galaxies: formation — galaxies: statistics

1. INTRODUCTION

The distribution of galaxies in a colour-magnitude diagram shows a bimodality: galaxies with red optical colors occupy a relatively tight sequence in color (the red sequence) while blue galaxies show a wider dispersion and populate the so-called 'blue cloud' (Blanton et al. 2003). This bimodality has existed for most of the history of the universe (e.g., Bell et al. 2004; Faber et al. 2007; Taylor et al. 2009). However, the stellar mass density of red sequence galaxies has increased by a factor ~ 2 since $z = 1$, while it has remained approximately constant for blue galaxies (Bell et al. 2004; Faber et al. 2007; Brown et al. 2007). Yet, the majority of stars are formed in blue galaxies (Bell et al. 2007; Walcher et al. 2008), which implies that galaxies migrate from the blue cloud to the red sequence (see, e.g., the discussion by Faber et al. 2007).

While significant evolution of the integrated mass function of red galaxies is generally agreed upon, the evolution in the number density of high-mass galaxies has been shown to be consistent with zero (e.g., Cimatti et al. 2006; Cool et al. 2008). However, given the large uncertainties, the constraints are not tight. There is ample room for considerable evolution, and such evolution is expected in a ΛCDM hierarchichal cosmology, which predicts significant growth of galaxies through merging, especially at the high-mass end (De Lucia & Blaizot 2007).

The most massive, non-starforming galaxies are essentially all spheroidal (i.e., have ellipticities < 0.4; van der Wel et al. 2009), indicating that they formed through merging (Toomre & Toomre 1972; Schweizer & Seitzer 1992; Kormendy et al. 2009). Shape distributions do not specify *when* merging happened. Some valuable constraints have been placed by the study of the clustering properties of red galaxies in this mass range by White et al. (2007), who found that 1/3 of massive red satellites disappear between z=0.9 and z=0.5 by merging with the central galaxies

in their halos.

The goal of this paper is to estimate the impact of galaxy mergers on the evolution of massive galaxies from $z \sim 1$ to the present day, and more specifically, on the massive end of the red sequence. To that end we measure the merger fraction since $z = 1.2$ in a large sample of mass-selected galaxies. We will test whether these measurements are consistent with predictions from hierarchichal formation models, and, providing an independent estimate of the number density of the most massive red galaxies, with the observed evolution of the bright tail of the luminosity function of red galaxies.

It is observationally challenging to identify galaxy mergers, especially at large cosmological distances. Mergers are found either in an early phase of the interaction, when the two galaxies have not yet coalesced and are found in a close pair (Patton et al. 2000; Le Fèvre et al. 2000; Lin et al. 2004, 2008; Bell et al. 2006a; Kartaltepe et al. 2007; Robaina et al. 2009), or in a later phase, when they display signatures of gravitational interaction and are just prior to or after coalescence (Abraham et al. 1996; Conselice et al. 2003; Lotz et al. 2004; Bell et al. 2005; McIntosh et al. 2008; Jogee et al. 2009; Heiderman et al. 2009; Robaina et al. 2009). A wide range of results have been found for the merger fraction evolution, parameterized as $(1 + z)^m$, with m ranging from 0 to 4 (e.g., Patton et al. 2000; Le Fèvre et al. 2000; Lin et al. 2004; Kartaltepe et al. 2007).

Here, we use robust 2–point correlation function techniques on a sample of galaxies with $0.2 < z < 1.2$ with stellar masses in excess of $5 \times 10^{10} M_\odot$ selected from the COSMOS and COMBO–17 surveys to quantify the merger rate of massive galaxies and its evolution. We augment the statistical significance of our analysis by using an estimate of the pair fraction found in Sloan Digital Sky Survey (SDSS) at $z \sim 0.1$. The total volume probed by this study at intermediate redshifts is at least

4 times larger than any previous mass–selected study on the evolution of the merger fraction, and reduces dramatically the systematic uncertainties related to cosmic variance by the use of four independent fields. Then we compare the inferred galaxy merger rate with the observed number density evolution of massive ($M_* > 10^{11} M_\odot$), red galaxies from $z \sim 1$ to the present day, which we obtain by converting Brown et al. (2007) LFs to stellar–mass functions. We assume $H_0 = 70$ km/s, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

2. SAMPLE AND METHOD

The bulk of our sample is drawn from the ~ 2 sq. degree COSMOS survey (Scoville et al. 2007). We use photometric redshifts calculated from 30-band photometry by Ilbert et al. (2009); comparison with spectroscopic redshifts shows excellent accuracy. We use those redshifts to derive rest-frame quantities and stellar masses by using the observed broad-band photometry in conjunction with a non-evolving template library derived using Pégase stellar population model (see Fioc & Rocca-Volmerange 1999) and a Chabrier (2003) stellar initial mass function (IMF). The use of a Kroupa et al. (1993) or a Kroupa (2001) IMF would yield similar stellar masses to within $\sim 10\%$. The reddest templates are produced through single exponentially–declining star formation episodes, intermediate templates also have a low-level constant star formation rate (SFR) and the bluer templates have superimposed a recent burst of star formation. A full description of the stellar masses will be provided in a future paper; comparison with Pannella et al. (2009) masses shows agreement at the 0.1 dex level.

To combat the sample variance of a single 2 sq. degree field, we augment the COSMOS sample with a sample drawn from three widely-separated 0.25 sq. degree fields from COMBO-17. COMBO–17 photo-z's, colors and stellar masses have been extensively described in Wolf et al. (2003),Wolf et al. (2004), Borch et al. (2006) and Gray et al. (2009). Given the different depths of the two surveys we only include galaxies from the COMBO-17 catalog at $z < 0.8$, where it is complete for our mass limit. The final sample comprises ~ 18000 galaxies with $M_* \geq 5 \times 10^{10} M_\odot$ over an area of ~ 2.75 sq. deg. in the redshift range $0.2 < z < 1.2$.

We use the fraction of galaxies with a companion closer than 30 kpc (close pairs) as a proxy for the merger fraction, as those systems are very likely to merge in a few hundred Myr[1]. As redshift errors translate into line-of-sight (l.o.s.) distance uncertainties of the order of $\sim 50 - 100$ Mpc we use projected 2-point correlation functions (2pcf) to find the number of projected close pairs and then deproject into the 3D space.

The projected correlation function $w(r_P)$ is the integral along the line of sight of the real-space correlation function:

$$w(r_p) = \int_{-\infty}^{\infty} \xi([r_p^2 + \pi^2]^{1/2}) d\pi, \qquad (1)$$

where r_p is the distance between the two galaxies projected on the plane of sky and π the line-of-sight separation. A convenient and simple estimator of the 2pcf at small scales is $w(r_p) = \Delta(DD/RR - 1)$ (e.g. Bell et al. 2006a; Robaina et al. 2009), where Δ is the path length being integrated over, $DD(r_P)$ is the histogram of separations between real galaxies and $RR(r_P)$ is the histogram of separations between galaxies in a randomly-distributed catalog. As shown in the literature (e.g. Davis & Peebles

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[1] As the lower mass limit of our sample is $5 \times 10^{10} M_\odot$, we are automatically selecting both members of the pair to be above that mass.

1983; Li et al. 2006), the real-space 2pcf can be reasonably well fit by a power-law. Assuming $\xi(r) = (r/r_0)^{-\gamma}$, then $w(r_p) = Cr_0^\gamma r_p^{1-\gamma}$, with $C\sqrt{\pi}\{\Gamma[(\gamma-1)/2]/\Gamma(\gamma/2)\}$. We fit the latter expression to our data to find the parameters γ and r_0 and use them in the real-space 2pcf to find the fraction of galaxies in close pairs.

As we wish to preserve S/N we did not integrate along the entire l.o.s. when calculating $w(r_P)$. Instead we allowed galaxies to form a pair only if the redshift difference was smaller than $\sigma_{pair} = \sqrt{2} \times \sigma_z$, with σ_z being the redshift error of the primary galaxy. As the photo-z errors follow a Gaussian distribution with width σ_z (Wolf et al. 2003, 2004) a fraction of the pairs would be missing by simply imposing the l.o.s. criteria. Thus, following Bell et al. (2006a) the fraction of galaxy pairs is

$$f = \int_{-\sigma_{pair}}^{\sigma_{pair}} \frac{1}{\sqrt{2\pi}\sigma_z} e^{-z^2/2\sigma_z^2} dz. \qquad (2)$$

Then, $w(r_P)$ is multiplied by $1/f$ in order to account for missing pairs; in our case a correction factor of 1.19.

Given the 3D correlation function $\xi(r)$, the differential probability of finding a galaxy occupying a volume δV at a distance r of another galaxy is $\delta P = n[1 + \xi(r)]\delta V$, where n is the number density of secondary galaxies. Then, by a simple integration of this expression, we obtain the probability of a galaxy being within a distance r_f of any other galaxy (Patton et al. 2000; Bell et al. 2006a; Masjedi et al. 2006):

$$P(r \leq r_f) = \int_0^{r_f} n[1 + \xi(r)]dV \qquad (3)$$

Because $\xi(r) = (r/r_0)^{-\gamma}$ and $\xi(r) \gg 1$ at the small scales, we obtain:

$$P(r \leq r_f) = f_{pair} = \frac{4\pi n}{3 - \gamma} r_0^\gamma r_f^{3-\gamma}, \qquad (4)$$

where f_{pair} is the fraction of *galaxies* in close pairs. As galaxy interactions are completely decoupled from the Hubble flow, we calculate probabilities as a function of the proper (physical) separation between the two galaxies. Errors in the correlation function are calculated by means of bootstrap resampling.

3. RESULTS AND DISCUSSION

This work aims to an understanding of the impact of galaxy mergers on the evolution of massive galaxies and the evolution of the red sequence at its massive end. To that end we apply the above method to our sample of galaxies with $M_* > 5 \times 10^{10} M_\odot$, regardless of their optical colors, to find the fraction of galaxies in close physical pairs, which we will use as a proxy for the fraction of galaxies undergoing a galaxy interaction. Hereafter, all reference to close pairs will refer to galaxy pairs with inferred separations smaller than 30 kpc in 3D space. Fig. 1 and Table 1 show the result of our 2pcf analysis.

The projected correlation functions in Fig. 1 are shown over the range $10 < r_p/kpc < 1000$, in physical (not comoving) units, as is appropriate for a process such as galaxy merging that has decoupled from the Hubble flow. One can see that the fitted power laws are good descriptions of the run of $w(r_p)$ with radius, down to the resolution limit of ~ 15 kpc. Below this radius, we extrapolate the power law fit. We have checked the accuracy of this extrapolation by comparison with extremely close pairs resolved by HST in the study of two of the four fields used in this paper by Robaina et al. (2009). An extrapolation of

z	γ	r_0	$n(Mpc^{-3})$	f_{pair} (< 30 kpc)
$0.2 < z \leq 0.4^a$	2.03 ± 0.05	3.50 ± 0.50	0.0031	0.0171 ± 0.0050
$0.4 < z \leq 0.6^a$	2.06 ± 0.04	3.60 ± 0.50	0.0034	0.0238 ± 0.0043
$0.6 < z \leq 0.8^a$	1.94 ± 0.04	3.80 ± 0.30	0.0064	0.0241 ± 0.0038
$0.8 < z \leq 1.0^b$	1.93 ± 0.03	2.85 ± 0.25	0.0131	0.0277 ± 0.0031
$1.0 < z \leq 1.2^b$	1.96 ± 0.03	2.55 ± 0.20	0.0162	0.0315 ± 0.0030

[a] Combined COSMOS+COMBO–17 sample
[b] COSMOS–only sample

our power-law fits to small radius would predict that $\sim 40\%$ of all our galaxies in $r < 30$ kpc pairs should have $r < 15$ kpc separations; we find that $\sim 30\%$ of galaxies in close pairs have $r < 15$ kpc separations using HST data. Accounting for the fact that Robaina et al. (2009) required additional interaction signatures such as tidal tails for a pair to be assigned to that category[2], and that some extremely close pairs will be classified as already coalesced merger remnants, we argue that this level of agreement is remarkable, and we conclude our extrapolation to radii $r < 15$ kpc is appropriate[3].

In Table 1 we show the parameters for the 3D correlation function that we obtain by deprojecting the 2D 2pcf. The evolution of the merger fraction is mainly driven by the evolution in the number density of galaxies above $5 \times 10^{10} M_\odot$ in physical coordinates, together with some evolution in the clustering length r_0.

In Fig. 2 we show the fraction of massive galaxies found in pairs with separations $r < 30$ kpc as a function of z. To augment the data at $z \sim 0.1$, we calculate the SDSS close pair fraction using γ and r_0 given by Li et al. (2006). We adjust their r_0 by $\sim 5\%$ (an empirical adjustment based on the COSMOS+COMBO-17 sample) to account for different lower mass limits and binning. We also use the number density of galaxies fulfilling our mass criteria, adopting the g-band selected stellar-mass function in Bell et al. (2003) after correcting for stellar IMF and H_0.

We perform an error-weighted least-squares fit of the form $F(z) = f(0) \times (1+z)^m$ to the filled points in Fig. 2, i.e., the SDSS pair fraction, the combined COSMOS+COMBO–17 pair fraction at $0.2 < z < 0.8$ and the COSMOS pair fraction at $0.8 < z < 1.2$. We find $f(0) = 0.0130 \pm 0.0019$ and $m = 1.21 \pm 0.25$. These associated uncertainties are at the same level as the systematic uncertainties in close pair fraction evolution caused by uncertainty in the overall stellar M/L scale, and its evolution since $z = 1$.

In our correlation function we do not impose a specific mass ratio criteria, but given the shape of the mass function above

[2] While most of the projected close pairs at $r < 15$ kpc are likely to be undergoing an interaction, the morphological signatures do not need to be necessarily evident. Gas fractions and orbital parameters strongly influence the strength of the tidal features. Then, we would expect to find a fraction of extremely close pairs (respect to the total number of close pairs with $r_p < 30$ kpc) slightly below the expected 40%.

[3] Note that we could have seemingly sidestepped this issue by using pairs with $15 < r < 30$ kpc for the close pair measurement, and adjusting the timescale to reflect the amount of time pairs spend separated by $15 < r/kpc < 30$. Nonetheless, in this case, one would still want to confirm that systems that reached 15 kpc continue to approach smaller radii, amounting to an exercise equivalent to confirming the power law extrapolation.
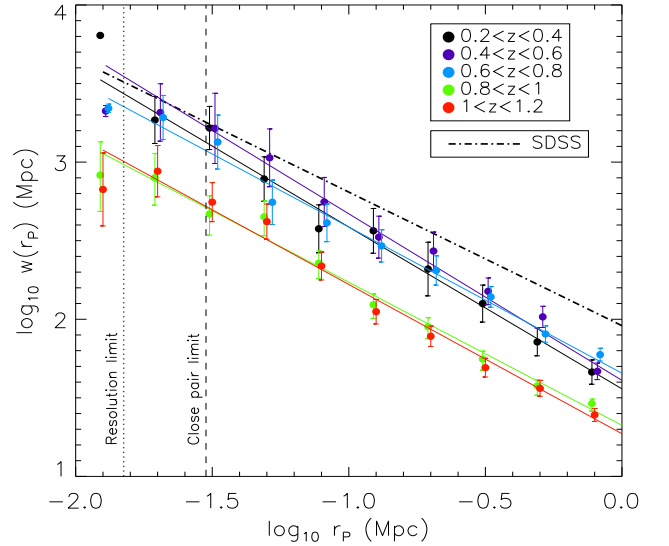

FIG. 1.— Projected 2–point correlation functions for galaxies with masses $\geq 5 \times 10^{10} M_\odot$ from our combined COSMOS + COMBO–17 sample in different redshift bins. The best–fit power law is overplotted following the color code of the different redshift bins. The power-law parameters are given in Table 1. The dot-dashed line represents the best–fit power law to the SDSS sample derived from results by Li et al. (2006). The vertical dashed line represents the separation limit for close pairs of 30 kpc (physical). The vertical dotted line represents the (average of the redshift bins) limit where one can no longer reliably resolve individual galaxies in a pair from the ground–based photometry.

$M_* > 5 \times 10^{10} M_\odot$, we expect most of the mergers to be majors; i.e., with mass rations between 1:1 and 1:4. We measure the fraction of pairs in projection which fulfill such a mass ratio criterion, finding a value between 70 and 90 percent in the different redshift bins.

Galaxies from the COSMOS survey represent 70% of our sample in the bins ranging from $z = 0.2$ to $z = 0.8$, however, the addition of COMBO–17 galaxies helps to decrease the sample variance. From the work by Moster et al. (2010), we estimate that the sample variance is reduced by a factor of $\sim 30\%$ by including the three ~ 0.25 sq. deg independent fields from COMBO–17. This effect is clearly seen in Fig. 2. Considering only galaxies from COSMOS, there is an abrupt transition between $z = 0.7$ and $z = 0.9$, which is smoothed by the inclusion of COMBO–17 galaxies.

In Fig. 2 we also show the prediction for the close-pair fraction from the semi-analytic models (SAM) of Somerville et al.
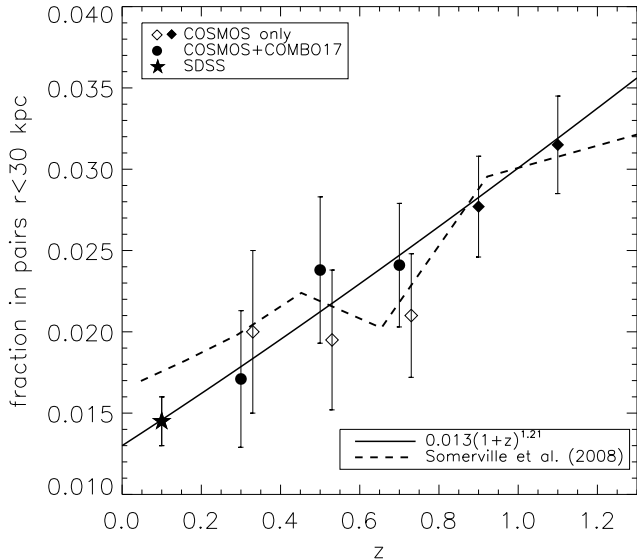
FIG. 2.— Fraction of $M_* > 5 \times 10^{10} M_\odot$ galaxies in close (3D) pairs ($r < 30$ kpc) as a function of redshift. *Diamonds:* Pair fraction found using only the COSMOS catalog. *Black circles:* Pair fraction found when adding galaxies from the COMBO–17 survey at $z < 0.8$ (we do not include galaxies from the COMBO–17 catalog in the two higher z bins). *Star:* Pair fraction from SDSS. The line shows the best fit to a real space pair fraction evolution with shape $F(z) = f_0 \times (1+z)^m$, with $f_0 = 0.0130 \pm 0.0019$ and $m = 1.21 \pm 0.25$ (fit to all black-filled points: star, circles and diamonds). *Dashed line:* Fraction of galaxies above $M_* > 5 \times 10^{10} M_\odot$ involved in mergers, predicted by Somerville et al. (2008) models when assuming a timescale of 0.5 Gyrs to transform from merger rate to fraction.

FIG. 3.— Evolution of the number of galaxies in close pairs. The estimate for major pair fraction of galaxies $M > 3 \times 10^{10} M_\odot$ from Bell et al. (2006a) is shown as empty squares. The point by Xu et al. (2004) is shown as the grey diamond. McIntosh et al. (2008) is shown as the grey star. The results of Bundy et al. (2009) have been corrected down by 33% in order to match our pair definition (see text for details).

(2008), updated as described in Hopkins et al. (2009). The models shown here adopt the best-fit cosmological parameters given in Komatsu et al. (2009). We extract the merger rate of galaxies where both progenitors have stellar masses above $5 \times 10^{10} M_\odot$, normalize by the total number density of galaxies above this mass and multiply by two to obtain the fraction of galaxies involved in mergers (the quantity that we estimate observationally), per Gyr. Then we multiply by the timescale over which a merger would be observed as a "close pair", which here we assume to be $\tau = 0.5$ Gyr following Patton & Atfield (2008) and Bell et al. (2006a) in order to convert this merger rate into the equivalent of the observed fraction. With this assumed timescale the model predictions are in excellent agreement with our observational results. Assuming an uncertainty of $\sim 30\%$ in the timescale (matching the numbers from Lotz et al. 2009 for close galaxy pairs timescales) would correspondingly shift vertically the model line by a similar number. Predictions from other SAMs tend to agree reasonably well with those of the Somerville et al. (2008) models, as shown in Fig. 11 of Jogee et al. (2009; see also Guo & White 2008 and Hopkins et al. 2010).

3.1. *Comparison with previous works*

Very few studies of close pair fraction evolution use mass-limited samples. Bell et al. (2006a) used COMBO–17 data (0.75 sq. deg., the same catalog we use here to complement our COSMOS catalog) to find a fraction of galaxies in close major pairs ($r < 30$ kpc) of 2.8% for galaxies more massive than $3 \times 10^{10} M_\odot$ at $0.4 < z < 0.8$, in excellent agreement with our result despite the slightly different mass limit. They also performed an autocorrelation of all galaxies with
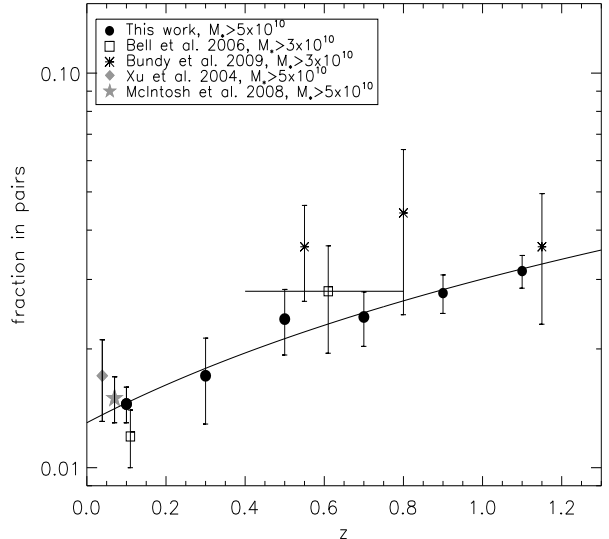
$M_* > 2.5 \times 10^{10} M_\odot$ finding a pair fraction of $\sim 5\%$. Adopting in our analysis instead a mass limit of $M_* > 2.5 \times 10^{10} M_\odot$ we recover a pair fraction of $\sim 5\%$. The main driver of this higher pair fraction is the fact that $\sim 50\%$ of close pairs in a sample limited to have $M_* > 2.5 \times 10^{10} M_\odot$ have mass ratios between 1:4 and 1:10; i.e., the major merger fraction is similar, but the close pair fraction is boosted by a considerable contribution from minors.

Recently, Bundy et al. (2009) performed a similar measurement by studying a sample of galaxy pairs from the GOODS fields (total area ~ 0.1 sq. deg.). In Fig. 3 we show their results for the mass range $> 3 \times 10^{10} M_\odot$ after converting their fraction of pairs to the fraction of *galaxies in pairs*. Bundy et al. (2009) study the fraction of major mergers in galaxies with $M_* > 3 \times 10^{10} M_\odot$, including galaxies 1.5 mags fainter than that mass limit, while by our definition of a close pair, both galaxies need to be above our mass limit. It is natural that they find a higher pair fraction, but we quantify this difference by performing a test in which we try to reproduce the Bundy et al. (2009) methodology. Given the nature of our method it is difficult to perform a cross-correlation in order to match their pair definition; instead we study the 2D distribution of galaxies in a similar fashion as Bundy et al. (2009). That is, we look for galaxies with separations $r < 30$/kpc and matched in redshift space and subtract random counts. We perform such a test in the redshift range $0.2 < z < 0.6$, where we are complete for stellar masses of $\sim 1-2 \times 10^{10} M_\odot$, with both our pair definition (both galaxies above $5 \times 10^{10} M_\odot$) and also keeping such a mass limit for the primary but allowing the secondary to be a factor 4 less massive. In the first case we find, as expected, a result compatible with the one found with the 2pcf, and in the second we find that the pair fraction is larger by a factor of ~ 1.5. Extrapolating this ratio to the higher redshift bins, we accordingly re-scale the Bundy et al. (2009) numbers by multiplying their results by 0.67 in order to match our pair defini-

tion. The difference is reduced to a factor of less than 2 in the lower redshift bins, while our results basically agree at $z \sim 1$. We also show the estimate from Xu et al. (2004), who used a combined sample from the 2MASS and 2dFGRS surveys, after converting their results to our IMF and H_0, and the result from McIntosh et al. (2008), who measured the merger fraction in galaxy groups based in projected pairs with additional signs of gravitational interaction. Before performing the comparison, we further correct the pair fractions found by Xu et al. (2004) and Bundy et al. (2009) down by 30% to account for pairs in their analyses that are genuinely associated with each other (so are not random projections), have projected separations of < 30 kpc but are separated by more than 30kpc in real space (i.e., galaxies in groups that are projected along the line of sight; Bell et al. 2006a)[4].

We can not compare our measurements with morphological studies of merger fractions because of uncertainties with the nature of the progenitors (differentiation between major and minor mergers can be extremely challenging, especially in the case in which one of the progenitors is very gas-rich), and selection effects related to orbital parameters, galaxy structure and gas fractions, with the latter introducing a bias in the recovery of interacting systems at higher z (Lotz et al. 2009). A more fundamental difference with respect to morphological studies, both those performed with visual classifications (Jogee et al. 2009) and with automated classifiers (Conselice et al. 2009; Lotz et al. 2008), is the fact that both merger remnants and closely interacting pairs can show signatures of gravitational interactions (see Robaina et al. 2009, for a discussion on the relative numbers of merger remnants and close pair interactions with morphological disturbances). These two groups are related to different time scales, and the strength and abundance of tidal features is also different (often degenerate with other parameters such as gas fraction). Studies on close pair statistics aim to detect the galaxy interaction in an early stage, where both progenitors can be studied separately, while morphological studies include systems both before and after the coalescence. For this reason, a direct, quantitative comparison is impossible. It is also hazardous to compare with close pair measurements based on luminosity-selected samples. Lin et al. (2008) used a sample of galaxies with B-band magnitudes (corrected for passive luminosity evolution) $-21 < M_B < -19$. For red galaxies, this is roughly compatible with our mass–selected sample, but it includes many low-mass blue galaxies, which makes a comparison impossible because their clustering properties are very different. As an extreme example, in which one close pair is formed by a very red $M_B = -21$ galaxy and a very blue one with $M_B = -19$, the stellar-mass ratio in this hypothetical interaction could be as high as 40. This pair definition is clearly not compatible with one in which both galaxies are selected by stellar mass. Furthermore, as merging can enhance the star formation activity (Barton et al. 2000; Robaina et al. 2009), selecting galaxies in rest-frame blue bands is biased in favor of mergers, as such a selection would recover merging systems with lower mass given the decreased M/L ratio induced by the interaction. All of these effects will be more pronounced in gas–rich galaxies, and gas fractions were likely higher in the past, leading to a redshift dependent bias.

Kartaltepe et al. (2007) derived the evolution of the pair fraction from a luminosity-selected sample from a similar dataset

as analyzed in this paper. Their very different result (they find $m = 3.1 \pm 0.1$) is caused at least in part by the difference between mass– and luminosity–selected samples, as described above, as well as by the fact that they do not correct for passive luminosity evolution. In addition, they identify pairs in both the ground-based and HST/ACS-based catalogues. Because their sample is selected by ground-based luminosity, very close pairs that are only resolved by ACS can be as bright as a single galaxy in a more widely separated pair that is resolved in the ground-based imaging. This artificially raises that close pair fraction, especially at high redshift.

Summarizing, we choose not to compare with merger fractions obtained by morphological indicators, nor with those obtained by close pair counts in luminosity-selected samples; these provide measurements of different merger-related quantities and can not, in general, be compared to our measurement.

3.2. *The impact of galaxy merging on the creation of $M_* > 10^{11} M_\odot$ galaxies.*

Our measured fraction of $M_* > 5 \times 10^{10} M_\odot$ galaxies in close pairs as a function of redshift constrains the impact that merging-induced mass assembly has on the creation rate of $M_* > 10^{11} M_\odot$ systems.

As only $\sim 6\%$ of our galaxies with a projected companion at $r < 30$ kpc has a *second* companion at such separation, we assume that the number of close pairs is simply one half of the number of galaxies in close pairs, neglecting the very minor influence of such a small number of galaxies in triplets. The fraction of newly created $M_* > 10^{11} M_\odot$ galaxies due to merging is $f_{rem} = N_{cp}/N_{11}$, where N_{cp} is the number of close pairs of galaxies above $5 \times 10^{10} M_\odot$ each (regardless of their optical colors) and N_{11} is the total number of galaxies with stellar masses in excess of $10^{11} M_\odot$.

Following Patton & Atfield (2008) or Bell et al. (2006a), the merger timescale for galaxy pairs at this separation is approximately $\tau = 0.5$ Gyrs, so we compute the creation rate of newly assembled galaxies, R_{rem}, as $R_{rem} = f_{rem}/\tau$. We integrate the merger rate over cosmic time finding that, on average, present day galaxies with stellar masses larger than $10^{11} M_\odot$ have undergone 0.5 (0.7) mergers since $z = 0.6$ (1.2) from interactions between galaxies more massive than $5 \times 10^{10} M_\odot$.

3.3. *The merger–driven evolution of the red sequence.*

In the previous sections we have studied the impact of merging of the evolution of the mass function of galaxies, without restriction to the optical colors of the progenitors or descendants. Now we want to address the question whether our observed merger rate evolution can explain the observed number density evolution in the massive end ($M_* > 10^{11} M_\odot$) of the red sequence.

First, we convert the evolution of the B-band luminosity function (LF) of red galaxies as measured by Brown et al. (2007) to the evolution in the number density of galaxies more massive than $10^{11} M_\odot$. For this conversion we use the typical stellar mass-to-light ratio of nearby red galaxies ($M/L_B = 3.4 \pm 0.6$, e.g., Bell et al. 2003; Kauffmann et al. 2003) and apply a correction to account for its evolution with redshift, derived from the evolution of the fundamental plane (FP) zero point ($\Delta \log(M/L_B) = 0.555 \pm 0.042$ between $z = 1$ and $z = 0$; van Dokkum & van der Marel 2007). We repeat the process 10000 times allowing the luminosity function parameters, as well as the M/L_B constraints, to vary randomly within their un-

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[4]This effect is present also in pair fractions determined from spectroscopic redshifts as long as a deprojection to the 3D space is not performed.

certainties. We estimate the final uncertainty by estimating the typical dispersion of those 10000 realizations. The results from this exercise are shown in Fig. 4. We find an evolution in the number density of the massive end of the red sequence of a factor ~ 4 between $z = 1$ and $z = 0$.

Our inference of a factor ~ 4 evolution in the number density of red sequence galaxies with $M_* > 10^{11} M_\odot$ is somewhat larger than a number of recent estimates. The main reason for this is our adoption of the recent results by van Dokkum & van der Marel (2007) for the evolution of M/L determined through FP evolution, who find relatively rapid evolution of M/L leading to more rapid inferred fading of the stellar population than assumed by many previous works. For example, Cimatti et al. (2006) found a result compatible with a constant number density of $M_* > 10^{11} M_\odot$ galaxies in the interval $0 < z < 0.8$. In order to obtain that result they applied a passive luminosity correction of $\Delta \log(M/L_B) = 0.46 \pm 0.04$ to a sample drawn from COMBO–17 and DEEP2 (Davis et al. 2003; Faber et al. 2007). This luminosity correction was obtained from the works by van Dokkum & Stanford (2003) and Treu et al. (2005) and is lower than the one found a few years later by van Dokkum & van der Marel (2007) with a larger sample. This apparently small difference in $\Delta \log(M/L_B)$ has strong implications when studying the number density evolution of massive red galaxies at the level of $\sim 1.5 - 2$ between $z = 1$ and $z = 0$. Also, the number of galaxies in their COMBO–17 or DEEP2 samples is relatively small when compared to the ~ 7 sq. deg. of the NOAO Deep Wide–Field Survey (NDWFS, Jannuzi & Dey 1999) used by Brown et al. (2007). Cool et al. (2008) used a sample of luminous red galaxies (LRG) from SDSS and spectroscopic follow–up from MMT to address a similar question. They found no evolution in the number density of LRGs since $z = 0.9$. We believe that the main driver of the difference between Cool et al.'s result and ours is, again, the correction for M/L ratio evolution. They used stellar population models from Bruzual & Charlot (2003) and Maraston (2005), which gives slower evolution than FP zeropoint evolution constraints.

In a recent work, Matsuoka & Kawara (2010) studied the number density evolution of massive galaxies since $z \sim 1$ from a sample drawn from UKIRT Infrared Digital Sky Survey and SDSS. Instead of applying an average M/L correction, they calculated stellar masses for individual galaxies at all redshifts, finding a factor ~ 4 evolution at $M_* > 10^{11} M_\odot$ (when adding-up their two mass bins). Unlike our present work, they did not differenciate between red and blue galaxies, but given the predominance of red galaxies at such high stellar masses (they report a blue fraction $< 30\%$ at all redshifts in the same mass range) we believe that our factor ~ 4 evolution agrees remarkably well with their result.

We now address the question of whether galaxy mergers between massive galaxies can drive the observed number density evolution of massive red galaxies. For that purpose, we use the result for the merger rate found in Section 3.2 and work under the assumption that mergers between massive galaxies will produce remnants with red optical colors. Dry (gas–free) mergers are likely to play an important role in the build-up of the massive end of the red sequence (van Dokkum 2005; Bell et al. 2006b), and the descendant systems of such interactions will clearly be red systems as well. Moreover, mergers involving massive blue, disk–like galaxies are also expected to produce red ellipticals as remnants. Major interactions, independently of the color of the progenitors, are expected to perturb the or-
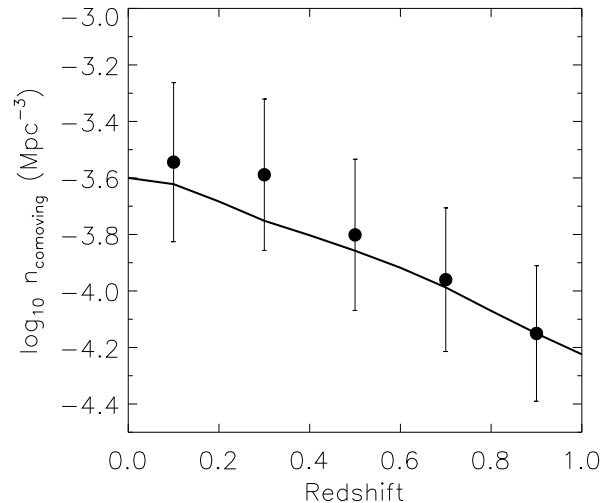

FIG. 4.— Number density evolution of red galaxies with $M_* > 10^{11} M_\odot$. Filled points with error bars represent the number density observed by Brown et al. (2007) when translated to stellar mass (see text for details). The solid line shows the expected growth implied by our measurement of the merger rate.

bits of the stars in the galaxies and form elliptical systems, but the observed fraction of spheroidal galaxies with blue optical colors is a negligible fraction of the total at masses above $10^{11} M_\odot$ (see Schawinski et al. 2009; Kannappan et al. 2009; Huertas-Company et al. 2010). It is likely that even those few systems will passively evolve to the red sequence in $\lesssim 1$ Gyr, so, our assumption that merger remnants with masses above such stellar mass will become red sequence galaxies is justified.

We use the number density of massive systems at $z \sim 0.9$ that we have obtained as the starting point and calculate the growth in the number of massive red galaxies implied by our measurement of the merger rate. We show the result of this exercise as the solid line in Fig. 4. We stress that the observed evolution (filled circles) and the one implied by our measurement (solid line) are *completely independent* except for the fact that we use the observed density at $z \sim 0.9$ to anchor the evolution predicted by our close pair fractions. We find that mergers of massive galaxies *can explain* the evolution in the observed number density of massive red galaxies since $z = 1$. In different words, the majority of galaxies observed today at the massive end of the red sequence have been assembled in the last 8 Gyrs through mergers of massive galaxies.

We have used $\tau = 0.5$ Gyrs, but using the $\tau \sim 1$ Gyr timescale from Kitzbichler & White (2007) produces a somewhat slower evolution that is still compatible within the error bars.

There are two caveats we would like to mention. Firstly, given the nature of our method, some of the progenitor galaxies have masses above $10^{11} M_\odot$, so strictly speaking they are not *newly formed* massive galaxies. Second, because we adopt a lower mass limit of $5 \times 10^{10} M_\odot$, we underestimate the number of major mergers that could lead to the formation of a massive galaxy. For example, a pair with individual masses $M_* = 6 \times 10^{10} M_\odot$ and $M_* = 4 \times 10^{10} M_\odot$ would not make it into our pair sample but would produce a major merger remnant of $10^{11} M_\odot$. Assuming that the merging population has a composition similar to our overall sample, we estimate that this latter

lower mass limit issue has an impact a factor ~ 2 larger on the creation of $> 10^{11}M_\odot$ galaxies than the overestimate caused by double counting already massive red galaxies (i.e., for every 10 massive galaxies we are counting as produced by mergers, there would be 1-2 which were already above $10^{11}M_\odot$ and ~ 3 that we are not accounting for because one of the progenitors has a mass below our mass limit of $5 \times 10^{10}M_\odot$). This means that our results are uncertain at the level of $\lesssim 20\%$ when counting newly formed massive red galaxies. We do *not* apply this correction to our results but would like to stress that, if anything, we slightly underestimate the real creation rate of massive galaxies induced by merging.

Hopkins et al. (2008) found by using HOD models a merger-driven evolution of a factor 3–4 in the integrated stellar mass density in red elliptical galaxies between $z = 1$ and $z = 0$. Given that we focus on the massive end of the distribution, a quantitative comparison is impossible, but we argue that our results are in qualitative good agreement with the trend seen in that work and in Hopkins et al. (2006), where they found some evolution in $M_* > 10^{11}M_\odot$ red galaxies in the same redshift range by evolving the mass function of red galaxies in a manner compatible with the predicted merger rates.

White et al. (2007) studied the clustering of luminous red galaxies in the NDWFS in conjunction with HOD models, finding that $\sim 1/3$ of red luminous satellites present at $z = 0.9$ have dissapeared by $z = 0.5$. The most likely explanation to this phenomenon is that merging has taken place, decreasing the number of such galaxies, in good qualitative agreement with our result.

Also, in a recent work, van der Wel et al. (2009) studied the shape (axis ratio) distribution of a large sample of quiescent galaxies drawn from the SDSS. Quiescent galaxies with prominent disks are exceedingly rare at stellar masses above $10^{11}M_\odot$, providing a strong indication that most, if not all, massive quiescent galaxies form through major mergers. Our results are consistent with this entirely indepent result, and, moreover, suggest that most of this merger activity occurred over the past ~ 8 Gyrs, since $z = 1$.

4. CONCLUSIONS

We have studied the impact of galaxy mergers on the evolution of massive galaxies by using 2–point correlation functions to measure the fraction of galaxies in close pairs from a sample of ~ 18000 galaxies more massive than $5 \times 10^{10}M_\odot$ drawn from the COSMOS and COMBO–17 surveys and a pair fraction estimate from SDSS. We have also used constraints from the observed evolution of the fundamental plane zeropoint to calculate the number density evolution of $M_* > 10^{11}M_\odot$ red galaxies from Brown et al. (2007) LFs. Our main findings are:

1-. The fraction of galaxies more massive than $5 \times 10^{10}M_\odot$ in close pairs evolves as $F(z) = (0.0130 \pm 0.0019) \times (1+z)^{1.21\pm0.25}$ in the redshift range $0 < z < 1.2$. Assuming a merging timescale of $\tau = 0.5$ Gyr this implies that galaxies more massive than $10^{11}M_\odot$ have undergone, on average, 0.5 (0.7) major mergers since $z = 0.6$ (1.2) involving progenitors more massive than $5 \times 10^{10}M_\odot$.

2-. The number density of $M_* > 10^{11}M_\odot$ galaxies on the red sequence increases by a factor of ~ 4 between $z = 1$ and $z = 0$. This result depends strongly on the assumed evolution of the M/L ratio, which we have assumed here to be $\Delta \log(M/L_B) = 0.555 \pm 0.042$ between $z = 1$ and $z = 0$ following

recent estimates by van Dokkum & van der Marel (2007).

3-. The evolution implied by our measured merger rate is sufficient to explain this observed number density evolution of massive red galaxies since $z = 1$; major mergers between massive ($M_* > 5 \times 10^{10}M_\odot$) galaxies are the main driver of the red sequence growth at its massive end.

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