GALAXY GROWTH BY MERGING IN THE NEARBY UNIVERSE

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ABSTRACT

We measure the mass growth rate by merging for a wide range of galaxy types. We present the small-scale (0.014 h−1 70 Mpc < r < 11 h−1 70 Mpc) projected cross-correlation functions w(rp) of galaxy subsamples from the spectroscopic sample of the NYU Value-Added Galaxy Catalog (5 × 107 galaxies of redshifts 0.03 < z < 0.15) with galaxy subsamples from the Sloan Digital Sky Survey imaging (4 × 107 galaxies). We use smooth fits to de-project the two-dimensional functions w(rp) to obtain smooth three-dimensional real-space cross-correlation functions ξ(r) for each of several spectroscopic subsamples with each of several imaging subsamples. Because close pairs are expected to merge, the three-space functions and dynamical evolution time estimates provide galaxy accretion rates. We find that the accretion onto massive blue galaxies and onto red galaxies is dominated by red companions, and that onto small-mass blue galaxies, red and blue galaxies make comparable contributions. We integrate over all types of companions and find that at fixed stellar mass, the total fractional accretion rates onto red galaxies (∼3 h70 percent per Gyr) are greater than that onto blue galaxies (∼1 h70 percent per Gyr). These rates are almost certainly overestimates because we have assumed that all close pairs merge as quickly as the merger time that we used. One conclusion of this work is that if the total growth of red galaxies from z = 1 to z = 0 is mainly due to merging, the merger rates must have been higher in the past.

Key words: cosmology: observations – galaxies: evolution – galaxies: fundamental parameters – galaxies: general – galaxies: interactions – methods: statistical

1. INTRODUCTION

Galaxy mergers may play an important role in the evolution of the galaxies. In the color–magnitude space, galaxies are separated into two distinct regions: (1) the “red sequence”: the “early-type,” red galaxies; (2) the “blue cloud” or “blue sequence”: the “late-type,” blue galaxies with strong ongoing star formation (Strateva et al. 2001; Blanton et al. 2003). Some recent studies in the high-redshift (z ∼ 1) universe find that the early-type galaxy population is growing over time (Bell et al. 2004; Willmer et al. 2006; Blanton et al. 2006; Brown et al. 2007; Faber et al. 2007; Zhu et al. 2011), which is also found at very high (z ∼ 2) redshift (Daddi et al. 2005; Trujillo et al. 2007; Longhetti et al. 2007; Toft et al. 2007; Conselice et al. 2007; Cimatti et al. 2008; van Dokkum et al. 2008; Saracco et al. 2009). In numerical simulations, some studies show us that major mergers of intermediate-stellar-mass late-type galaxies maybe play an important role in the growth of the intermediate-stellar-mass early-type galaxies (Barnes & Hernquist 1996; Naab & Burkert 2003). However, the massive early-type galaxies may grow in a different way (Naab & Burkert 2003). Some recent studies show us that “dry mergers”—the mergers between early-type galaxies—might play an important role in the growth of massive early-type galaxies (Bell et al. 2006a; van Dokkum 2005; Masjedi et al. 2008). There are a lot of studies that estimate the merger rate among galaxies. These studies can be separated into two general categories. The studies in the first category count the “pre-merger” close pairs and convert the “pre-merger” pairs to a merger rate (e.g., Zepf & Koo 1989; Carlberg et al. 1994, 2000a, 2000b; Patton et al. 1997, 2000; van Dokkum et al. 1999; Lin et al. 2004, 2008; Bell et al. 2006b; Kartaltepe et al. 2007; Masjedi et al. 2006, 2008; Patton & Atfield 2008; Kitzbichler & White 2008; Bundy et al. 2009; De Propris et al. 2007, 2010; de Ravel et al. 2009; Robaina et al. 2010). The studies in the second category count the “post-merger” galaxies that have recently experienced at least one merger event. These “post-merger” galaxies are chosen by some observable special properties caused by merging. An example might be by star formation indicators of “post-merger” galaxies (Quintero et al. 2004) or by morphological signatures caused by merger events (Abraham et al. 1996; Conselice et al. 2003; van Dokkum et al. 2005; Lotz et al. 2006; de Propris et al. 2007; Lotz et al. 2008; Conselice et al. 2009).

Our work builds on the earlier works of Masjedi et al. (2006, 2008), which have found previously that luminous red galaxies (LRGs) are growing on average by less than 2 h70 percent per Gyr from merger activity at redshifts 0.16 < z < 0.30 (Masjedi et al. 2008). In this paper, we consider both red and blue galaxies. We use the previous technique for measuring the close pairs (Masjedi et al. 2008) on NYU Value-Added Galaxy Catalog (VAGC) spectroscopic sample and Sloan Digital Sky Survey (SDSS) imaging sample, and extend this type of analysis beyond LRGs to a wide range of galaxies in both stellar mass and color.

The primary uncertainty in turning a de-projected three-dimensional (3D) cross-correlation function at small scales into a merger rate is in estimating the mean time for two galaxies to merge as a function of stellar mass and separation. There are different estimates of merger timescale: free-fall time, orbital time, and dynamical friction time (e.g., Binney & Tremaine 1987; Boylan-Kolchin & Ma 2007; Conroy et al. 2007; Kitzbichler & White 2008; Bundy et al. 2009; Lotz et al. 2010). In this paper, we will use an approximation to the two kinds of merger times under the assumption of Kitzbichler & White (2008) and Binney & Tremaine (1987) as our standard estimate. Both of these times are likely to be an underestimate of the mean merger time because some close pairs will not merge at all. Any underestimate of the merger time leads to an overestimate of the growth rate.
Throughout this paper, all magnitudes are AB, all apparent magnitudes are model Mag, all masses are stellar masses (in units of $h^{-2} M_\odot$), all velocities are in units of km s$^{-1}$, all radii of galaxies are $r_{90}$, which contain 90% of the Petrosian flux (Blanton et al. 2003; Blanton & Moustakas 2009), and all volumes and distances are comoving, calculated for a cosmological world model with $(\Omega_m, \Omega_\Lambda) = (0.3, 0.7)$ and Hubble constant $H_0 \equiv 70 h_{70}$ km s$^{-1}$ Mpc$^{-1}$.

2. DATA

We use the NYU VAGC Ver. 7.2 data (Blanton et al. 2005), which is built from SDSS data, as our source of spectroscopic data. We use all the SDSS imaging data as our source for cross-correlation samples. The SDSS is a survey of about 10$^4$ deg$^2$ (Fukugita et al. 1996; Gunn et al. 1998, 2006; York et al. 1999; York & SDSS Collaboration 2001; Stoughton et al. 2002; Abazajian et al. 2003, 2004).

2.1. Spectroscopic Subsample

Our spectroscopic sample is drawn from NYU VAGC Ver. 7.2 data. We removed galaxies with apparent magnitudes $r < 14$ mag because SDSS photometric catalog missed many luminous galaxies nearby (Zhu et al. 2010). Our spectroscopic sample contains about $8.6 \times 10^5$ main galaxies, of which about $5 \times 10^5$ SDSS Main Samples galaxies (Strauss et al. 2002) are in the redshift range $0.03 < z < 0.15$ (see Figure 1) with apparent magnitudes $r < 17.77$. We cut the redshift at $z < 0.15$ because we want to avoid all quasars, and we cut the redshift at $z > 0.03$ because we want to avoid all stars. We use the code sdss_kcorrect (Blanton & Roweis 2007) to calculate the $K$-corrected absolute magnitude at $z = 0.1$ and stellar mass for each. We cut this sample into 10 subsamples by stellar mass and make sure that in each subsamples the number of galaxies is the same. After that, we cut them into red and blue using the cut (Hogg et al. 2004):

$$0.1 g - 0.1 r = 0.0625 \times \log(M) + 0.15,$$

where $M$ is the stellar mass. These cut the spectroscopic sample into 20 spectroscopic subsamples; we call these subsamples $D_s$ (see Figure 2). For the red spectroscopic subsamples, we name the smallest stellar-mass subsample “red0,” then name the second smallest stellar-mass subsample “red1,” and so on, so the largest stellar-mass subsample is named “red9;” the same type of naming convention is used for the blue spectroscopic subsamples. Figures 3 and 4 show the number density of galaxies of the 18 spectroscopic subsamples as a function of redshift. The red0 and blue0 subsamples are low in number density, and highly affected by survey selection effects, so we do not use them further. We can see that blue8, blue9, and red9 appear to rise in number density with redshift; this is because we removed galaxies with apparent magnitudes $r < 14$ mag.

The SDSS suffers from the “fiber collision”: the angular separation between any two spectroscopic targets must be larger than 55 arcsec. There are about $\sim 9\%$ of target galaxies that do not have redshifts because of this fiber collision. Using the counting-close-pairs technique of Masjedi et al. (2008), the fiber collision will not affect our pair counts directly under the approximation that the unmeasured galaxies and the measured galaxies are similar in cross-correlation with fainter galaxies.
Figure 3. Number densities of each of the nine red spectroscopic subsamples as a function of redshift. The vertical lines in each graph show the redshift limits used. The number density in red9 appears to rise with redshift because we have removed galaxies with $r < 14$ mag (see the text).

Following the technique of Masjedi et al. (2008), we estimate the weight $p_j$ that accounts the spectroscopic incompleteness from fiber collisions effects, and the weight $f_j$ that accounts the spectroscopic incompleteness from all other selection effects in SDSS. For each galaxy $j$ in the spectroscopic subsample, we calculated $p_j$ by using a two-dimensional “FOF” (friends-of-friends) grouping algorithm on our main galaxies targets with a 55 arcsec linking length:

$$p_j = \frac{N_j^s}{N_j^{total}},$$

where $N_j^{total}$ is the total number of main galaxies targets in group $j$, $N_j^s$ is the number of main galaxies with redshift measurement in group $j$, and the group that contains galaxy $j$ is called group $j$. All $p_j \geq 1$ because $N_j^{total} \geq N_j^s$.

For each spectroscopic subsample $D_s$, we create a random spectroscopic subsample $R_s$ that matches the redshift distribution of $D_s$, and $R_s$ is isotropic within the SDSS survey region.

The SDSS survey region is separated into small unique region “sector.” For each random point $j$ in $R_s$:

$$f_j = \frac{1}{F_j},$$

where $F_j$ is the fraction of main galaxy targets for which a classification was obtained in the object’s sector (in our NYU VAGC spectroscopic sample, the average $F_j$ is $\bar{F} \approx 0.91$).

Our correction of fiber collisions is as follows: We weight the target $j$ in spectroscopic subsample $D_s$ as $p_j$ and weight the target $j$ in random spectroscopic subsample $R_s$ as $f_j$. From the previous work (Masjedi et al. 2006), we know that this correction will improve in the spectroscopic incompleteness due to fiber collisions at very small separations ($w(r_p) < 100 h^{-1}_{70}$ kpc). In Section 4.1, we will compare our result with the result of Zehavi et al. (2011), and will show that our result with this correction of fiber collisions fits better than the result without this correction of fiber collisions.

For each spectroscopic sample “s” ($D_s$ or $R_s$), in which there are $N_s$ spectroscopic galaxies, we divide it into the 50 bins by...
Figure 4. Same as Figure 3, but for the nine blue spectroscopic subsamples. The number density in blue 8 and blue 9 appears to rise with redshift because we have removed galaxies with \( r < 14 \) mag (see the text).

lines of constant dec, so that there are \( N_c/50 \) spectroscopic galaxies in each bin. Then we resample them into 50 leave-one-out resampling samples, so that there are \( 49/50 \times N_c \) spectroscopic galaxies in each sample. We call them the “50 resampling samples,” with which we can calculate our jackknife resampling covariance matrix.

2.2. Imaging Subsamples

For our imaging data, we use a sample drawn from the full SDSS imaging catalog in which there are about \( 4 \times 10^7 \) galaxies. We include from the SDSS imaging sample only galaxies with apparent magnitude \( 14 \) mag < \( r < 21.5 \) mag, and apparent color \( -0.5 \) mag < \( g - r \) < 2 mag, see Figures 5 and 6. We removed galaxies with apparent magnitudes \( r < 14 \) mag for the same reason with our spectroscopic sample. We also removed galaxies with apparent magnitudes \( r > 21.5 \) mag because these galaxies are not well observed and their observed number density is much lower than their real number density. Please note that this cut will affect our minor merger near mass ratio 1:100. Similar to the spectroscopic sample, we create a random imaging sample \( \mathcal{R}_i \) as large as possible. The angular positions of galaxies in \( \mathcal{R}_i \) are taken from the two-dimensional random sample. So \( \mathcal{R}_i \) is isotropic within the SDSS survey region.

2.3. Grid Method K-corrections for Galaxies from the Imaging Sample

We also need to compute the stellar mass of galaxies in the imaging subsamples in order to determine the mass ratio, so we want to \( K \)-correct galaxies in the imaging subsamples. However, we cannot \( K \)-correct individual galaxies in the imaging subsamples once and for all because we do not have spectroscopic redshifts for them. Each time we consider a pair of galaxies, one from the spectroscopic subsample and one from the imaging subsample, we assign the spectroscopic redshift to the galaxy from the imaging sample. This allows us to calculate for each galaxy from the imaging sample in each spectroscopic–imaging pair a temporary \( K \)-corrected stellar mass and \( [0.1 \ g - 0.1 \ r] \) color for the purposes of that pair. We discard these values and compute new ones when the galaxy from the imaging sample is used in another pair with another galaxy from the spectroscopic sample.

To save time, we take galaxies from the NYU VAGC spectroscopic sample as representative of all galaxy types, and
apply the code \texttt{sdss\_kcorrect} on the galaxies from a grid named “B” of observed $r$-band magnitude (0.5 mag bin$^{-1}$), $[g-r]$ color (0.1 mag bin$^{-1}$), and redshifts between 0.03 and 0.15 (0.0002 bin$^{-1}$). We saved the mean $K$-corrected stellar mass $M_B$ and $[0.1^g - 0.1^r]$ color in a grid of observed $r$-band magnitude, $[g-r]$ color, and redshift, also save the mean redshift $z_B$, mean $r_B$, and mean $[g_B - r_B]$ color. Thereafter we estimated the $K$-corrected stellar mass and $[0.1^g - 0.1^r]$ color for a galaxy $G$ in grid B, and the $[g_G - r_G]$ color of galaxy G is between $[g_B - r_B]$ color of grid B and $[g_C - r_C]$ color of grid C, which is next to grid B (that means $z_B$ and $z_C$ are the same, and $r_B$ and $r_C$ are the same):

$$\log M_G = \log \left( \frac{M_B \times \left( \frac{d_G^L}{d_B^L} \right)^{r_G - r_B}}{\left( \frac{d_G^L}{d_B^L} \right)^{0.5}} \right) - \frac{r_G - r_B}{2.5} \times \frac{(\log M_C - \log M_B) \times ([g_G - r_G] - [g_B - r_B])}{[g_C - r_C] - [g_B - r_B]} \quad (4)$$

$$[0.1^g - 0.1^r_G] = [0.1^g - 0.1^r_B] + [g_G - r_G] - [g_B - r_B] \quad (5)$$

where $d_L$ is the luminosity distance calculated from redshift, and galaxy G is in grid B, so the difference between $z_B$ and $z_G$ is small, similarly, the difference is small between $d_G^L$ and $d_B^L$, $r_B$ and $r_G$, $[g_B - r_B]$ and $[g_G - r_G]$. Because of these small differences, Equations (4) and (5) can be used. This speeds up the $K$-correction procedure immensely and only introduces a 12\% 1$\sigma$ error for each galaxy and there is little bias (see Figure 7), so only introduces percent-level errors in the results. We call this “Grid Method” hereafter.

For grids with observed $r$-band magnitude $r > 17.77$ mag, we cannot get the mean stellar mass and $[0.1^g - 0.1^r]$ color directly because there are no galaxies from the spectroscopic sample at observed $r$-band magnitude $r > 17.77$ mag. In order to estimate the color and stellar mass of the galaxies in grid A with mean observed $r$-band magnitude $r_A > 17.77$ mag, we find the grid point B that has the nearest mean observed $r$-band magnitude $r_B$ ($r_B > 17.77$ mag) and has the same observed $[g - r]$ color and the same redshift, also there are at least 10 galaxies from the spectroscopic sample in grid B. Then we estimate $M_G$ and $[0.1^g - 0.1^r]$ color of galaxy G in grid A using Equations (4) and (5). If we cannot find a grid B satisfying the conditions, we will leave all the galaxies in grid A empty.

Figure 8 shows the difference between the color estimate using the Grid Method above and the color calculated using the
code sdss_kcorrect. The 1σ error for each galaxy is about 0.04 mag and there is little bias (see Figure 8).

2.4. Velocities for Merger Rate Estimates

In this section, we will estimate the average orbital velocity, which will be used to estimate the merger time in Section 3.4. Please note that this approximation will induce a large error in the estimate of merger time because we assume that all close pairs merge under the following orbital velocity, which is not true for close pairs in high-velocity dispersion.

The average orbital velocity for a galaxy from the imaging sample around a more massive red galaxy from the spectroscopic subsample $s$ with average velocity dispersion $\sigma_r$ is very roughly 1.5 times the velocity dispersion, here we have included the factor of 1.5 to be conservative (Masjedi et al. 2008). We estimate the $\sigma_r$ with Faber–Jackson relation:

$$\log \sigma_r = a_1 + b_1 \log M_\text{s}^\text{red},$$

where $M_\text{s}^\text{red}$ is the mean stellar mass of the red galaxies from spectroscopic subsample $s$. We performed a linear fit to the data to obtain $a_1 = -1.588$ and $b_1 = 0.354$ (Figure 9). Please note that the method above will induce a small enough error ($<1\%$) into our final result.

We estimate the average orbital velocity $V_c$ for a galaxy from the imaging sample around a more massive blue galaxy from the spectroscopic subsample $s$ with the Tully–Fisher relation:

$$\log V_c = a_2 + b_2 \log \langle L_I \rangle,$$

where $\langle L_I \rangle$ is the mean $I$-band luminosity of the blue galaxies from spectroscopic subsample $s$, calculated from $L_I = M/r_1$, where $M$ is the stellar mass of the galaxy and $r_1$ is the $I$-band mass-to-light ratio of the galaxy calculated from the code sdss_kcorrect. We used for this relationship $a_2 = -0.835$ and $b_2 = 0.291$ (Courteau et al. 2007).

Table 1 provides this information for all 20 spectroscopic subsamples.

3. METHOD

For each spectroscopic subsample $\mathbb{D}_s$, we cut the imaging sample into 16 subsamples by stellar mass: $10^{-18.5} < M_\text{s}^\text{red} / M_\odot < 10^{-17.5}$, where $M_\text{s}^\text{red}$ is the stellar mass of a galaxy from the imaging sample, calculated by the Grid Method using the redshift of the spectroscopic galaxy and $M_\odot$ is the mean stellar mass of the galaxies from spectroscopic subsample $s$, and $j$ is an integer $1 \leq j \leq 16$, that means a mass ratio of 1:1 to 1:100 is covered. After that, we cut them into red and blue using Equation (1) by $0.1 g - 0.1 r$ color calculated by Grid Method. For each spectroscopic subsample $\mathbb{D}_s$, these cut the imaging sample into 32 imaging subsamples $\mathbb{D}_i$.

In this section, we will show our method to estimate the merger rate between galaxies in spectroscopic subsample $\mathbb{D}_s$ and galaxies in imaging subsample $\mathbb{D}_i$: (1) we estimate the projected two-dimensional cross-correlation function $w_{si}(r_p)$ as a function of tangential projected separation $r_p$, (2) we de-project the smooth fit for the cross-correlation function $w_{si}(r_p)$ to obtain the 3D real-space cross-correlation function $\xi_{si}(r)$ as a function of real-space separation $r$, (3) we estimate the merger rate using $\xi_{si}(r)$ and our two kinds of merger times (Binney & Tremaine 1987; Kitzbichler & White 2008). In addition, we will also discuss our method of photometry correction.

3.1. Projected Cross-correlation Function

To estimate the $w_{si}(r_p)$ between spectroscopic subsample $\mathbb{D}_s$ and imaging subsample $\mathbb{D}_i$, we can integrate $\xi_{si}(r)$ along the line of sight (e.g., Davis & Peebles 1983):

$$w_{si}(r_p) = 2 \int_0^\infty dy \xi_{si} \left[ \left( r_p^2 + y^2 \right)^{1/2} \right].$$

This integral is dominated by scales $y \lesssim r_p$.

Using the previous approach (Masjedi et al. 2006, 2008), we estimate not $w_{si}(r_p)$ but $\rho_i w_{si}(r_p)$, where $\rho_i$ is the average.
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The bottom sum is over galaxies where the top sum counts the weighted pairs \( D_i, D_j \) and \( R_i, R_j \) represent the spectroscopic and imaging data subsamples, and \( R_i \) and \( R_j \) represent the spectroscopic and imaging random subsamples. Similar to the previous method (Masjedi et al. 2006, 2008), Equation (9) measures the mass-weighted abundance of pairs \( (D_i, D_j, R_i, R_j) \) and subtracts the mean background level \( (R_i D_i / R_j R_j) \). This method has been well tested in Masjedi et al. (2006).

In detail, the factors are defined as follows:

\[
D_i D_j = \frac{\sum_{j \in D_i} p_j}{\sum_{j \in D_i} p_j}, \tag{10}
\]

where the top sum counts the weighted pairs \( p_j \) of galaxies from \( D_i \) and \( D_j \) separated by tangential projected distance \( r_p \) and the bottom sum is over galaxies \( j \) from \( D_j \). This factor \( D_i D_j \) is dimensionless.

\[
D_i R_j = \frac{\sum_{j \in D_i} p_j}{\sum_{j \in D_i} p_j} \frac{d\Omega_j}{dA}, \tag{11}
\]

where the top sum counts the weighted pairs \( j \) of galaxies from \( D_i \) and \( R_j \) separated by tangential projected distance \( r_p \). In the bottom, \( (d\Omega/dA)_j \) is the inverse square of the transverse comoving distance (Hogg 1999) to galaxy \( j \) from \( D_j \), and \( (dM_j/d\Omega) \) is calculated by \( (dM_j/d\Omega) = (dN_j/d\Omega) \times M_j \), where \( (dN_j/d\Omega) \) is the two-dimensional number density of \( R_j \) per solid angle, and

\[
M_i = M_j \times \frac{\Omega_j}{\Omega_i}, \tag{12}
\]

where \( M_i \) is the mean stellar mass of galaxies from the imaging subsample \( i \) and \( j \) is an integer \( 1 \leq j \leq 16 \). Then \( (d\Omega_j/dA)_i \times (dM_j/d\Omega) \) represents the average stellar mass of galaxies in \( R_i \) per unit comoving area around each galaxy from \( D_j \). This factor \( D_i D_j \) has dimensions of comoving area divided by stellar mass:

\[
R_i D_j = \frac{\sum_{j \in D_j} f_j}{\sum_{j \in D_j} f_j}, \tag{13}
\]

this is similar to Equation (10), but \( \mathbb{R}_i \) represents now the random catalog mentioned in Section 2.1. This factor \( R_i D_j \) is dimensionless:

\[
R_i R_j = \frac{\sum_{j \in \mathbb{R}_j} f_j}{\sum_{j \in \mathbb{R}_j} f_j} \frac{d\Omega_j}{dA} \frac{dM_j}{d\Omega}, \tag{14}
\]

this is similar to Equation (11), but \( \mathbb{R}_i \) represents now the random catalog mentioned in Section 2.1. This factor \( R_i R_j \) has dimensions of comoving area divided by stellar mass.
For some experiments, we need to estimate \( n_i w_s(r_p) \), where \( n_i \) is the average comoving 3D number density of the imaging subsample \( i \). We estimate this by the following estimation:

\[
n_i w_s(r_p) = \frac{D_i D_i}{[D_i R_i]_N} - \frac{R_i D_i}{[R_i R_i]_N}. \tag{15}
\]

For \( D_i D_i \) and \( R_i D_i \), it is as the same as Equations (10) and (13). For \([D_i R_i]_N\) and \([R_i R_i]_N\):

\[
[D_i R_i]_N = \sum_{j \in D_i} p_j \int \frac{d\Omega}{dA} \frac{dN}{d\Omega}, \tag{16}
\]

this is similar to Equation (11), but \( \frac{dN}{d\Omega} \) is the two-dimensional number density of the random imaging catalog per solid angle. This factor \( D_i R_i \) has dimensions of comoving area.

\[
[R_i R_i]_N = \sum_{j \in R_i} f_j \int \frac{d\Omega}{dA} \frac{dN}{d\Omega}, \tag{17}
\]

which is similar to Equation (14). This factor \( R_i R_i \) has dimensions of comoving area.

In range of our interest \( 0.0149 h^{-1}_{70} \text{Mpc} < r_p < 11.9 h^{-1}_{70} \text{Mpc} \), we bin the spectroscopic–imaging pairs counting by the comoving projected separation \( r_p \) of the pair where \( r_p = r_k = 0.0149 \times 10^{k/5} h^{-1}_{70} \text{Mpc} \) and \( k \) is an integer \( 0 \leq k \leq 14 \). We have already discussed how to bin the spectroscopic sample \( D_i \) and the imaging sample \( R_i \) in Section 2. We have combined the 16 stellar-mass bins into four to simplify the figures. Figures 10–13 show the results of our measurements of \( \rho_i w_s(r_p) \).

The uncertainties on the results shown in these figures are estimated using jackknife resampling covariance matrix with 50 resampling samples (see Section 2.1): it should be noted that all the error bars in our graphs only come from the jackknife resampling covariance matrix (there are some other errors like the error of the color and stellar mass estimated by the Grid Method, and so on). On hundreds of kiloparsec scales, the error bars for each subsample are smallest. On smaller scales, the error bars become larger because of the “shot noise”: The smaller the separations are, the fewer the pair counts will be. On larger scales (>1 h^{-1}_{70} \text{Mpc}) , the error bars become larger because there are more and more interlopers on larger scales, which means that the background subtraction is more noisy.

Figures 10–13 show that \( n_i w_s(r_p) \) is a complex function of \( r_p \). However, on very small scales—tens of kiloparsec scales—we assume that \( n_i w_s(r_p) \) scales (something) like \( r_p^{-1} \) (Masjedi et al. 2006, 2008). We fit each set of \( w_s(r_k) \) data with the smooth
Figure 11. Same as Figure 10, but for the nine red spectroscopic subsamples cross-correlated with all blue imaging subsamples.

Figure 12. Same as Figure 10, but for the nine blue spectroscopic subsamples cross-correlated with all red imaging subsamples.
model: 
\[ \tilde{w}(r_p) = w_0 \left[ 1 + \frac{r_p}{r_c} \right]^\gamma \left( \frac{r_p}{r_c} \right)^{\gamma-1} \]  
(18)

by minimizing 
\[ \chi^2 = \sum_i \frac{(\rho_i \tilde{w}(r_k) - \rho_i w_0(r_k))^2}{\rho_i^2 \sigma(r_k)^2} \]  
(19)

We choose \( r_c = 12.5 r_{90} \) for Figures 10–13 (where \( r_{90} \) is the median radii of the galaxies in the corresponding spectroscopic subsamples); then we find the \( \gamma \) and \( \rho_i w_0 \) that minimizes \( \chi^2 \).

Figures 10–13 show us these fits.

3.2. Photometry Correction

One important issue with all clustering measurements on small scales is possible photometric biases when measuring close pairs. This issue can directly lead to biased flux measurements (Masjedi et al. 2006) and biased color measurements for galaxies, and will indirectly affect stellar masses, k-corrections, etc. This can be due to poor photometry in crowded systems (Patton et al. 2011).

We build our method to correct photometric biases upon the photometry test of Masjedi et al. (2006). In Masjedi et al. (2006), they created fake images of pairs of identical galaxies with separations ranging from 2 to 35 arcsec. These galaxies represent passively evolving LRG galaxies observed at a redshift of \( z = 0.3 \) with de Vaucouleurs profiles \( (n = 4 \text{ Sérsic profiles}) \). Then they placed one such galaxy pair onto RUN 2662 (which has a typical SDSS seeing of about 1 arcsec) of SDSS imaging. After inputting the known info into the mock galaxy images, they processed these images as raw SDSS images using the standard SDSS pipeline, PHOTO, to determine the effect of proximity of galaxies on their measured properties (see plot 1 in Figure 14). At separations larger than 20 arcsec, the Petrosian flux measures 79.5% of the input Sérsic flux, which is calculated by 3σ outlayer rejected average. In other words, the Petrosian flux only measures about 80% of a galaxy’s light. We are interested in intermediate separations, 5 arcsec < s < 20 arcsec, in which the fraction of the recovered flux to input flux increases to 83%. This increase is likely due to a double counting of the low level diffuse emission from the two galaxies that is being poorly deblended between the two objects.

For pairs of main galaxies, we study two different cases: one for galaxy pairs consisting of two identical galaxies and another with galaxies of different stellar mass. For Case 1, we consider a pair of identical main galaxies with radii of \( r_{90}^{\text{main}} \) (at redshift \( 0.03 < z_{\text{main}} < 0.15 \)) than that of the LRGs \( r_{90}^{\text{LRG}} \) at redshift \( z = 0.3 \) (see plots 1 and 2 in Figure 16). We take the following two approximations: (1) If we consider a pair of identical main galaxies that are at the same redshift \( z = 0.3 \), then the only difference between this pair of main galaxies and the pair of LRGs (see plot 1 in Figure 14) is that the angular radii of the main galaxies are smaller than that of LRGs by a factor of \( r_{90}^{\text{main}} / r_{90}^{\text{LRG}} \). So we compress the result of plot 1 in Figure 14 by a factor of \( r_{90}^{\text{main}} / r_{90}^{\text{LRG}} \) (see plot 2 in Figure 14 as an example) as the effect of proximity of a pair of identical main galaxies. (2) If we consider a pair of LRGs that are at a different redshift \( z = z_{\text{main}} \), then the only difference between this pair of LRGs and the pair of LRGs at redshift \( z = 0.3 \) (see plot 1 in Figure 14) is that the angular radii of this pair of LRGs are larger than that of the LRGs at redshift \( z = 0.3 \) by a factor of \( D_{\text{main}} / D_{\text{LRG}} \), where \( D_{\text{main}} \) is the comoving distance from \( z = z_{\text{main}} \) to us and \( D_{\text{LRG}} \)
Figure 14. Recovered Petrosian flux to input Sérsic flux as a function of the separation of the two galaxies in the pair. We show both LRG and small galaxy whose radius is only 80% of that of LRG. The vertical line shows the smallest separation in our research at $z = 0.15$ and $r_p = 14.9 h_{70}^{-1} \text{kpc}$. For LRG, on average there is an excess in the recovered flux of galaxies separated by less than 20 arcsec.

is the comoving distance from $z = 0.3$ to us. So we stretch the result of plot 1 in Figure 14 by a factor of $D_{\text{main}}/D_{\text{LRG}}$ (see plot 1 in Figure 15 as an example, and $D_{\text{main}}$ at redshift $z = 0.144246$ is nearly half of $D_{\text{LRG}}$) as the effect of proximity of a pair of LRGs at redshift $z = z_{\text{main}}$. Combining the above two approximations, the final effect of proximity of a pair of identical main galaxies at a different redshift $z = z_{\text{main}} \neq 0.3$ will be stretched by a factor of $D_{\text{main}}/D_{\text{LRG}}$ (see plot 2 Figure 15 as an example). Using this method, we correct the flux measurement of our sample on small scales of a major merger between main galaxies and we assume that the correction of stellar mass is equal to that of flux. For Case 2, it is based on the above Case 1 but involving the radii $r_{90}$ of the pair of galaxies ($r_A$ and $r_B$) in our estimation. In plot 2 of Figure 16, we take the third approximation: (3) The flux density from the left galaxy onto the right galaxy is a constant $D_A$ (this approximation lead to a small error comparing to the flux density from the galaxy A onto the galaxy B in plot 3 of Figure 16). We mark the percent increase of flux from the other galaxy as $P_{\text{flux}}$, that of stellar mass as $P_{\text{mass}}$, radius of galaxy A as $r_A$, total flux as $F_A$, and stellar mass as $M_A$. Then we get the following result:

$$P_{\text{mass}} = P_{\text{flux}} = \frac{D_A \times \pi r_A^2}{F_A}.$$  \hspace{1cm} (20)

In plot 3 of Figure 16, we assume that the flux density from the galaxy A onto the galaxy B is equal to $D_A$ and the flux density from galaxy B onto galaxy A is equal to $D_B$. We mark the percent increase of flux of galaxy B from the galaxy A as $P_{\text{flux}}^B$, that of stellar mass as $P_{\text{mass}}^B$, radius of galaxy B as $r_B$, total flux as $F_B$, stellar mass as $M_B$, and the percent increase of flux of galaxy A from the galaxy B as $P_{\text{flux}}^A$, and that of stellar mass as $P_{\text{mass}}^A$. Then we get the following results:

$$D_B = D_A \times \frac{F_B}{F_A} = D_A \times \frac{M_B}{M_A}.$$  \hspace{1cm} (21)

$$P_{\text{mass}}^A = P_{\text{flux}}^A = \frac{D_B \times \pi r_B^2}{F_A} = P_{\text{mass}} \times \frac{M_B}{M_A}.$$  \hspace{1cm} (22)

$$P_{\text{mass}}^B = P_{\text{flux}}^B = \frac{D_A \times \pi r_A^2}{F_B} = P_{\text{mass}} \times \frac{M_A}{M_B} \times \frac{r_B^2}{r_A^2}.$$  \hspace{1cm} (23)

Using this result we correct the flux and stellar-mass measurements of our sample on small scales of minor merger between main galaxies.

Please note that our photometry correction is overestimated because of the above approximations (1) and (2). In approximations (1) and (2), we assume that the absolute angular scale does not matter; and the only change comes from the ratio of the absolute angular radii of the pair of galaxies to the absolute angular separation of the pair of galaxies. However, we know that absolute angular scale does matter: At the same ratio the larger the absolute angular is, the easier the deblending will be. So approximations (1) and (2) will contribute a few percent error in our final result of photometry correction.

After the above photometry correction, we reset our spectroscopic and imaging subsamples to recalculate the $\rho_i w_{\text{rd}}(r_p)$ using the method in Section 3.1 (see the first and second data points in Figures 10–13). Please note that we also apply our photometry correction on the galaxies with no nearby companions,
however these galaxies have zero weight in our pair-counting and will not affect our result, because there are no companions near these galaxies during counting pairs. In order to show our method of photometry correction is robust, we double our photometry correction and find that all the percentage difference between the result of our photometry correction and double our photometry correction is below 26% for one data point. Then, this data point with 26% change will only contribute a few percent error in our final result of the total fractional accretion rate after our fitting curve (see Equations (18) and (19)). So, if we assume that the percent error of our photometry correction in flux is 100%, the final effect onto the total fractional accretion rate is at most a few percent.

We use the above method to correct the photometric biases, and we find that our correction due to photometric biases is much smaller than that of Masjedi et al. (2006) because (1) main galaxies have smaller radii than LRGs, so it is easier to deblend a pair of main galaxies than a pair of LRGs. (2) Photometry correction of autocorrelation of Masjedi et al. (2006) is larger than that of our cross-correlation, this is because of the difference of the stellar-mass cut of spectroscopic/imaging sample between us: For autocorrelation, the stellar-mass cut of spectroscopic/imaging sample will be $M_\text{stellar} > M_\text{threshold}$ and $M_\text{stellar} > M_\text{threshold}$, so after photometry correction, the only effect is that some spectroscopic (and imaging) galaxies near $M_\text{threshold}$ will be cut off from the spectroscopic (and imaging) sample, which will decrease the pair-counting. However, this is not the only effect on cross-correlation. For cross-correlation, the stellar-mass cut of spectroscopic and imaging sample will be $M_\text{threshold} < M_\text{stellar} < M_\text{upper}$ and $M_\text{threshold} < M_\text{stellar} < M_\text{upper}$, so after photometry correction, besides the above effect there is another effect that some spectroscopic and imaging galaxies that are a little bit above $M_\text{upper}$ will be counted into the spectroscopic/imaging sample from outside. This effect will increase the pair-counting. Combining the two effects above for cross-correlation, the final photometry correction for cross-correlation will be smaller than that for autocorrelation.

3.3. Three-dimensional Statistics

The smooth fit $w(r_p)$ to each projected correlation functions $w_{si}(r_p)$ can be de-projected to get an estimate of the 3D space correlation function $\xi(r)$ by

$$\rho_1 \xi(r) = -\frac{1}{\pi} \int_{r_p}^{\infty} dr_p \frac{d[\rho_1 w_{si}(r_p)]}{dr_p} (r^2_p - r^2)^{-1/2} \quad (24)$$

(e.g., Davis & Peebles 1983), where $\rho_1$ is a constant.

The mean total stellar mass $M^*_i$ of galaxies from a specific imaging subsample $i$ within a given small 3D separation $r_{close}$ around each galaxy from spectroscopic subsample $s$ is

$$M^*_i = \rho_i \int dV_i [1+\xi_s(r)] = 4\pi \rho_i \int_{r_{close}}^{r_{close}} r^2 dr [1+\xi_s(r)] \quad (25)$$

At small scales, $\xi_s(r) \gg 1$, so

$$M^*_i \approx 4\pi \int_{r_{close}}^{r_{close}} r^2 dr [\rho_i \xi_s(r)] \quad (26)$$

From $[\rho_i \xi_s(r)]$ we can see that we do not need to measure $\rho_i$ and $w_{si}(r_p)$ separately.

At very small scale ($r_{close} \ll r_c$):

$$M^*_i \approx 4 \rho_i w_{0r} r_c r_{close} \quad (27)$$

Similarly, the average number $N^*_i$ of galaxies from a specific imaging subsample $i$ within a given small 3D separation $r_{close}$

$$N^*_i \approx \frac{1}{V_i} \int_0^{r_{close}} \int_{r_{close}}^{r_{close}} \rho_1 \xi_s(r) J(r) \rho_1 w_{si}(r_p) dr_p dr \quad (28)$$
Figure 16. We show the major merger of LRG (Masjedi et al. 2006), major merger of main galaxy and minor merger of main galaxy. Please note that this is only a sketch; the radius and separation may be much different.

3.4. Merger Rate

We can estimate the merger rate $\Gamma_i$ of galaxies from sample $i$ into galaxies from sample $s$ per spectroscopic galaxy per unit time by

$$\Gamma_i = \frac{N_i^*}{t_{\text{merge},i}}. \quad (29)$$

The mean fractional stellar-mass accretion rate of galaxies from spectroscopic subsample $s$ from merging with galaxies from imaging subsample $i$ per unit time is

$$\left[ \frac{d \ln M_s}{dt} \right]_i = \frac{1}{M_s} \left[ \frac{d M_s}{dt} \right]_i \approx \frac{M_i^*}{t_{\text{merge},i} M_s}. \quad (30)$$

In principle, all merger rate estimates depend on the radius $r_{\text{close}}$ inside of which we have counted close pairs. However in this work, we are interested in the instant merger rate estimates, which means that we are interested in the range of $r_{\text{close}} \ll r_e$, and this range can be reached using our fit lines. Another reason why we use our fit lines instead of using the data points at very small scales is that the error bars due to the shot noise for each subsample are very large. From these fit lines in Figures 10–13 we know, over the range of interest ($r_{\text{close}} \ll r_e$) $w_i(r_p)$ scales like $r_p^{-1}$, $\xi(r)$ scales like $r^{-2}$, $N_i^*$, and $M_i^*$ scale (something) like $r_{\text{close}}$. Similarly, both of the timescales ($t_{KW,i}$ and $t_{BT,i}$) scale like $r_{\text{close}}$. For this reason, at $r_{\text{close}} \ll r_e$ the above merger and accretion rates do not depend strongly on $r_{\text{close}}$.

In this work, we use these two merger time estimates: $t_{BT,i}$ from Binney & Tremaine (1987) and $t_{KW,i}$ from Kitzbichler & White (2008). Both of them depend on the orbital merger time $t_{\text{orbit}}$:

$$t_{\text{red orbit}} = \frac{2\pi r_{\text{close}}}{1.5\sigma v}, \quad (31)$$

where $1.5\sigma_v$ is the average orbital velocity for a galaxy from the imaging sample orbiting a more massive red galaxy from spectroscopic subsample $s$. The radius and separation may be much different.
Figure 17. Mean fractional accretion rate for the nine red spectroscopic subsamples $h_70 \text{ Gyr}^{-1} \text{ dex}^{-1}$. The thick lines are for mergers with red galaxies from the imaging sample and the thin lines are for mergers with blue galaxies from the imaging sample. The solid lines are the merger rate under assumption of $t_{\text{merge},i} = t_{\text{KW},i}$ and the dashed lines are for the merger rate under assumption of $t_{\text{merge},i} = t_{\text{BT},i}$.

the spectroscopic sample with velocity dispersion $\sigma_v$, see Equation (6). Similarly, the orbital merger time for a galaxy from the imaging sample merged into a more massive blue galaxy from the spectroscopic subsample is

$$t_{\text{blue orbit}} = \frac{2\pi r_{\text{close}}}{V_c}, \quad (32)$$

where $V_c$ is the average orbital velocity for a galaxy from the imaging sample around a more massive blue galaxy from the spectroscopic sample (see Equation (6)).

For the assumption of $t_{\text{KW},i}$ from Kitzbichler & White (2008), the approximation becomes

$$t_{\text{KW},i} = t_{\text{orbit}} \left[ \frac{M_s}{M_i} \right]^{0.3}, \quad (33)$$

where we assume $M_s > M_i$. The solid lines in Figures 17 and 18 as a function of the mass ratio $M_i/M_s$ show the merger rate under assumption of Kitzbichler & White (2008). The total fractional accretion rate is the area under each curve.

For the assumption of $t_{\text{BT},i}$ from Binney & Tremaine (1987), $t_{\text{BT},i}$ is longer than the orbital merger time $t_{\text{orbit}}$ by a factor roughly equal to the ratio of the stellar masses (Binney & Tremaine 1987; Masjedi et al. 2008):

$$t_{\text{BT},i} = t_{\text{orbit}} \frac{M_s}{M_i}, \quad (34)$$

where we assumed $M_s > M_i$. The dashed lines in Figures 17 and 18 as a function of the mass ratio $M_i/M_s$ show the merger rate under the assumption of all possible mergers taking place within one dynamical friction time (Binney & Tremaine 1987; Masjedi et al. 2008), and the total fractional accretion rate is the area under the curves.

We integrate the mass accretion rate from mergers over all imaging subsamples and find the total fractional accretion rate $(h_70 \text{ Gyr}^{-1})$ of all the main galaxies. This is shown with solid lines (for $t_{\text{KW},i}$) and dashed lines (for $t_{\text{BT},i}$) in Figure 19. Note that the errors from merger time are shown in this figure.

Table 2 shows the total fractional accretion rates of all the 20 spectroscopic subsamples for both the assumption of $t_{\text{merge},i} = t_{\text{KW},i}$ and the assumption of $t_{\text{merge},i} = t_{\text{BT},i}$.

4. COMPARISON TO PREVIOUS WORK

4.1. Comparison to Previous Clustering Results

We estimate not $w_p(r_p)$ but $n_i w_p(r_p)$. In order to estimate $w_p(r_p)$ and compare with previous results, we need to estimate $n_i$:

$$w_p(r_p) = \frac{n_i w_p(r_p)}{n_i}. \quad (35)$$

It is difficult within the SDSS data to precisely measure the real-space number densities for the imaging subsamples with stellar masses $M_i < 6 \times 10^9 h_70^{-2} M_\odot$, because there is only good spectroscopic information about bright members of the imaging sample. However, for galaxies with stellar masses $M_i > 6 \times 10^9 h_70^{-2} M_\odot$, the real-space number density $n_i$ for the imaging subsample $i$ is measurable:

$$n_i = n_i^* \frac{F}{F}. \quad (36)$$
Figure 18. Same as Figure 17, but for the nine blue spectroscopic subsamples.

Figure 19. Total fractional accretion rates for each of the 18 spectroscopic subsamples $h_{70}$ Gyr$^{-1}$ integrating over all the galaxies from the imaging sample. The thick lines are for the red spectroscopic subsamples and the thin lines are for the blue spectroscopic subsamples. The solid lines are for the merger rate under assumption of $t_{\text{merge},i} = t_{KW,i}$, and the dashed lines are for the merger rate under assumption of $t_{\text{merge},i} = t_{BT,i}$.

where $n_i^s$ is the average real-space number density for the corresponding spectroscopic subsample $s$ within its volume limit and $\bar{F}$ is the mean fraction of main targets for which a classification was obtained in the object’s sector; for the NYU VAGC spectroscopic sample $\bar{F} \approx 0.91$. We assume that $n_i$ is non-evolving over the redshift range of interest. We find the lower and upper redshift limits of the volume limit for the corresponding spectroscopic subsample $s$ in order to calculate $n_i^s$.

Galaxy clustering has been measured at intermediate and small scales (Zehavi et al. 2005, 2011; Masjedi et al. 2006; Chen 2009; Li & White 2010; White et al. 2011). Our results are consistent with the results of Zehavi et al. (2011; see Figure 20). In order to generate our mass-threshold samples, which are nearly the same as their luminosity-threshold samples, we calculated $M^*$, the mean mass of the galaxies nearby their luminosity-threshold $M_r$ as our mass threshold, and we cut $M_s > M^*$ and $M_i > M^*$ to generate the corresponding mass-threshold samples. This turns our cross-correlation into an autocorrelation. In order to calculate $n_i^s$ for the two subsamples with $M_r < -18.0$ and $M_r < -18.5$ in Figure 20, we use the peak real-space number densities instead of the average real-space number densities, because there are no obvious volume limit in these two subsamples.

Similarly, we can measure $\rho_i$ and $w_{si}(r_p)$ separately instead of $\rho_i w_{si}(r_p)$.

In order to show that our result successfully corrected the fiber collisions, we compare our result with the extension of the best-fit power law from Zehavi et al. (2011); see Figures 21 and 22. The extension dashed line is from the power fit of the first six data points of Zehavi et al. (2011) in the range $0.25 h_{70}^{-1}$ Mpc $\lesssim r_p \lesssim 2.5 h_{70}^{-1}$ Mpc. We cut at $r_p \approx 2.5 h_{70}^{-1}$ Mpc because there is a sharp break at $r_p \approx 2.5 h_{70}^{-1}$ Mpc, which will be discussed at the end of Section 5. On the other side, this extension is very robust. In Figure 22, the difference is very small among the three extension dashed lines using the first five, first six, and first seven data points of Zehavi et al. (2011). Our result (the triangle data points) with correction of fiber
Figure 20. Projected correlation function $w_p(r_p)$ for the spectroscopic subsamples corresponding to mass-threshold samples as labeled, calculated as described in the text on small scales, combined with projected correlation function on intermediate scales from Zehavi et al. (2011). Please note that in order to compare these results easily, we offset the points of Zehavi et al. (2011) by 12% of our interval to the right.

Table 2

Fractional Mass Growth Measurements

| Subsample | $d(ln M)/d t$ | Blue Fraction | $d(ln M)/d t$ | Blue Fraction |
|-----------|---------------|---------------|---------------|---------------|
| red0      | $7.9 \pm 4.2$ | 27.3          | $13.0 \pm 6.8$ | 31.5          |
| red1      | $9.1 \pm 4.8$ | 28.3          | $14.6 \pm 7.6$ | 31.4          |
| red2      | $10.2 \pm 5.3$ | 25.3         | $16.3 \pm 8.5$ | 29.3          |
| red3      | $11.8 \pm 6.1$ | 21.9          | $18.9 \pm 9.7$ | 26.3          |
| red4      | $12.5 \pm 6.4$ | 23.6          | $20.3 \pm 10.4$ | 27.7          |
| red5      | $13.0 \pm 6.7$ | 20.9          | $21.2 \pm 10.9$ | 25.6          |
| red6      | $14.3 \pm 7.3$ | 20.7          | $23.6 \pm 12.1$ | 25.3          |
| red7      | $15.2 \pm 7.8$ | 19.1          | $26.1 \pm 13.3$ | 23.5          |
| red8      | $18.2 \pm 9.3$ | 11.8          | $37.4 \pm 19.0$ | 15.7          |
| blue0     | $3.2 \pm 1.7$ | 48.3          | $6.0 \pm 3.1$ | 46.5          |
| blue1     | $3.6 \pm 1.9$ | 47.3          | $6.6 \pm 3.4$ | 47.0          |
| blue2     | $3.8 \pm 1.9$ | 44.1          | $6.8 \pm 3.5$ | 45.1          |
| blue3     | $3.9 \pm 2.0$ | 40.7          | $6.9 \pm 3.5$ | 43.2          |
| blue4     | $4.3 \pm 2.2$ | 42.4          | $7.2 \pm 3.8$ | 45.8          |
| blue5     | $4.6 \pm 2.4$ | 36.0          | $7.7 \pm 4.0$ | 41.6          |
| blue6     | $4.8 \pm 2.6$ | 36.8          | $8.3 \pm 4.4$ | 42.2          |
| blue7     | $5.5 \pm 2.9$ | 27.9          | $9.5 \pm 5.0$ | 34.4          |
| blue8     | $5.3 \pm 2.9$ | 23.0          | $10.5 \pm 5.7$ | 28.4          |
| blue9     | $5.3 \pm 2.9$ | 23.0          | $10.5 \pm 5.7$ | 28.4          |

Notes. Fractional mass growth of Main Galaxy by merging $h_70$ Gyr$^{-1}$, split by spectroscopic subsample.

Measurements under the assumption $t_{merge,i} = t_{BT,i}$.

Percent contribution of the blue galaxies from the imaging sample under the assumption $t_{merge,i} = t_{BT,i}$.

Measurements under the assumption $t_{merge,i} = t_{KW,i}$.

Percent contribution of the blue galaxies from the imaging sample under the assumption $t_{merge,i} = t_{KW,i}$.

Errors are estimated including the error from merger time.
collisions fits better than the result assuming $p_1 = 1$ and $f_j = 1$ (the diamond data points). We also show the data point before photometry correction (Figure 22).

### 4.2. Comparison to Previous Merger Rate Results

Please note that the merger time error will be shown in the error bars in the figures from now on.

Our results are consistent with recent measurements of the merger rates based on counts of close pairs (Masjedi et al. 2008; Patton & Atfield 2008; Kitzbichler & White 2008; Bundy et al. 2009; De Propris et al. 2010; Robaina et al. 2010). The dry merger rate of an upper limit of $1.8 h_{70}^{-1}$ per Gyr for massive red galaxies (red9) under assumption of $t_{\text{merge}} = t_{hT,i}$ here in good agreement with a number of other estimates: At $z < 0.36$, Masjedi et al. (2008) obtained an upper limit of $1.2 h_{70}$ percent per Gyr (converted from $1.7 h$ percent per Gyr) for the dry merger rate of SDSS LRGs with $M_i < -22.7$; at $0.45 < z < 0.65$, De Propris et al. (2010) determined a $5\sigma$ upper limit to the dry merger rate of $0.7 h_{70}$ percent per Gyr (converted from $1.0 h$ percent per Gyr) for galaxies with $-23 < M(r)_{h_{70}}^0 + 5 \log h < -21.5$ in the 2dF-SDSS LRG and QSO redshift survey.

Robaina et al. (2010) found that the fraction of galaxies ($M > 5 \times 10^{10} h_{70}^{-2} M_\odot$) in pairs separated between 15 and $30 h_{70}^{-1}$ kpc in 3D space is $f_{3D_{\text{pair}}}^{15-30 h_{70}^{-1}} = 0.01$ at $z = 0.1$, which is calculated by $(1.0 - 0.3) \times F(z)$, because they find that 30%–40% of galaxies in close pairs have $r < 15 h_{70}^{-1}$ kpc separations. They also expect most of the mergers to be major mergers; i.e., with mass ratio between 1:1 and 1:4. Our result of $f_{15-30 h_{70}^{-1}}^{3D_{\text{pair}}}$ is 0.02 at $0.03 < z < 0.15$ with mass ratio between 1:1 and 1:4, which is consistent with the result of Robaina et al. (2010).

With $t_{\text{merge}} = t_{KW,i}$ determined, we compute the volumetric merger rate (the number of mergers per unit time per unit comoving volume) as a function of the stellar mass of the primary or host galaxy. We call this the merger rate mass function (merger rate MF) and denote it using the variable, $\Psi$. Figure 23 shows the comparison of our major merger rate $MF$ at $0.03 < z < 0.15$ with the major merger rate MF of Bundy et al. (2009) at $0.4 < z < 0.7$ at mass ratio $m/M > 0.25$. We can see that both of Figures 23 and 24 show that our results are consistent with these previous results.

Our results are also consistent with recent merger rates predicted in theories of galaxy formation in a cosmological context (Maller et al. 2006; Stewart et al. 2009). We estimate our merger rate $R_{mg}$ at a certain mass ratio $m/M$ by integrating $\Gamma_i$ in Equation (29). We compare our $R_{mg}$ with the results of Maller et al. (2006) at mass ratio $m/M > 0.5$ (Figure 25) and the results of Stewart et al. (2009) at mass ratio $m/M > 0.3$ and $m/M > 0.6$ (Figure 26). We can see that both of Figures 25 and 26 show that our results are consistent with these previous results.

A. Wetzel & J. Tinker (2013, in preparation) found that from redshift $z = 2$ to now, around 27% of galaxies similar to our Milky Way experienced a merger with mass ratio $m/M > 0.1$, and around 11% experienced a merger with mass ratio $m/M > 0.33$. In our research, the galaxies in the blue7 or
Figure 22. Projected correlation function $w_p(r_p)$ same as Figure 21, but only display the last three plots. The black crosses in the second and third plots are our result before photometry correction, which are offseted by 12% of our interval to the left. Please note that the three extension dashed lines are fitting from the first five, first six, and first seven data points of Zehavi et al. (2011).

Figure 23. Comparison of our major merger rate $M\dot{F}$ at $0.03 < z < 0.15$ under assumption of $t_{\text{merge}} = t_{KW,i}$ with the major merger rate $M\dot{F}$ of Bundy et al. (2009) at $0.4 < z < 0.7$. Both of our mass ratios are $m/M > 0.25$. The open diamonds on the thick lines are our results, and the open triangles on the thin lines are the results of Bundy et al. (2009). The dashed lines show the results of excluding the approximate fraction of dry E/S0–E/S0 mergers, and the solid lines indicate the observed merger rate for all galaxies determined.

blue8 subsample are similar to our Milky Way. If we take our results under assumption of $t_{\text{merge}} = t_{KW,i}$ at face value and make the strong assumption that the growth happens at a non-evolving rate, from redshift $z = 2$ to now (a period of $\approx 10 h^{-1}_{70}$ Gyr), we expect the galaxies in the blue7 or blue8 subsample to merge by $\sim 21\%$ with mass ratio $m/M > 0.1$, and $\sim 10\%$ with mass ratio $m/M > 0.33$, which is close to the result of A. Wetzel & J. Tinker (2013, in preparation).

5. DISCUSSION

We find that under the assumption of $t_{\text{merge}} = t_{KW,i}$, the total fractional accretion rates onto red main galaxies are from $[1.3 \pm 0.7]$ to $[3.7 \pm 1.9] h_{70}^{-1}$ percent per Gyr depending on stellar mass, and those onto blue main galaxies are from $[0.6 \pm 0.3]$ to $[1.1 \pm 0.6] h_{70}^{-1}$ percent per Gyr. We find that at fixed stellar mass, the total fractional accretion rates onto red galaxies are greater than that onto blue galaxies. The total fractional accretion rate is a stronger function of primary mass for red galaxies than that for blue galaxies. We also find that more than 60\% of the total fractional accretion rates are from major mergers with mass ratio between 1:1 and 1:3, and less than 15\% of the total fractional growth rates are from minor mergers with mass ratio between 1:10 and 1:100.

The first limitation of the imaging sample arises from the lack of spectroscopic information on the galaxies from the imaging sample. However, for galaxies from imaging sample with stellar masses $M_i > 6 \times 10^9 h_{70}^{-2} M_\odot$, we estimate the real-space number densities $n_i$ from Equation (35). So we measured $n_i$, $\rho_i$, and $w_{si}(r_p)$ separately. But at stellar masses $M_i < 6 \times 10^9 h_{70}^{-2} M_\odot$, it is impossible to precisely measure the
real-space number densities $n_i$, such that we cannot disentangle the clustering power from the number density for these small-mass galaxies from the imaging sample, and we only measure the products $n_i w_i(r_{p})$ and $\rho_i w_i(r_{p})$ but neither $n_i$, $\rho_i$, nor $w_i(r_{p})$ separately.

The second limitation is removing galaxies from imaging sample with apparent magnitudes $r > 21.5$ mag because of the limitation of lacking of imaging information on the galaxies of SDSS (see Figure 5). This cut of apparent magnitudes $r > 21.5$ mag will affect the minor mergers with mass ratio between 1:30 and 1:100 for the small stellar-mass galaxies from spectroscopic samples red1 $\sim 4$ and blue1 $\sim 4$ at redshift $z \gtrsim 0.10$, and the number densities of the galaxies in these spectroscopic samples decrease sharply at redshift $z \gtrsim 0.10$ (see Figures 3 and 4), which will sharply reduce the effect of this cut. This cut will cause less than 5% error because the contribution of the minor mergers with mass ratio between 1:30 and 1:100 is only $< 5\%$. This assumption is good to take because it will cause far below 5% error. In order to not affect the minor mergers with mass ratio between 1:30 and 1:100 at all, we need our imaging sample to be $\sim 1$ mag fainter than what we use now.

We can see “valleys” at the third to fifth data points ($37.6 h_{70}^{-1} Mpc < r_{p} < 94.4 h_{70}^{-1} kpc$) of the two minor-merger curves ($10^{-1.5} < M_{i}/M_{t} < 10^{-1.0}$ and $10^{-2} < M_{i}/M_{t} < 10^{-1.5}$) in each plot of Figures 10–13, which seems like the type of issue that is caused by photometric biases or bad deblending. However we do not think so, because the photometric biases and bad deblending are very small at separations large than 15 arcsec (see Table 1) and at “valleys” (the third to fifth data points $37.6 < r_{p} < 94.4 h_{70}^{-1} kpc$), the photometry correction is nearly zero (below 5%). Also, we do not think that the “valleys” will make our conclusions invalid even if that is an issue in minor

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Figure 24. Comparison of our $f_{\text{pair}}$ at $0.03 < z < 0.15$ with the $f_{\text{pair}}$ of three recent results (Patton & Atfield 2008; Kitzbichler & White 2008; Bundy et al. 2009) at $0.4 < z < 0.7$. The open diamonds on the thick solid lines are the results of Bundy et al. (2009), and the open triangles on the thick dashed lines are our results. The thin horizontal solid lines show the results of Patton & Atfield (2008), and the thin dashed lines are the results of Kitzbichler & White (2008). Please note that the $f_{\text{pair}}$ of Patton & Atfield (2008) and Kitzbichler & White (2008) are calculated by $f_{\text{pair}} = R_{\text{mag}} \times T_{\text{mag}}/C_{\text{mag}}$.

Figure 25. Comparison of our merger rates (per galaxy $h_{70}^{-1}$ Gyr$^{-1}$) under assumption of $t_{\text{merge}} = t_{KW,i}$ at $0.03 < z < 0.15$ with the merger rates of Maller et al. (2006) at $0 < z < 0.5$. The open triangles on the dashed lines are our results, and the thin dotted lines are the best-fit result calculated from Equation (5) of Maller et al. (2006). Both of our mass ratios are $m/M > 0.5$. Please note that the results of Maller et al. (2006) are estimated from a flat $\Omega_{m} = 0.4$ cosmology with $\sigma = 0.8$, a Hubble constant $H_{0} = 100 h$ km s$^{-1}$ Mpc$^{-1}$ with $h = 0.65$, a baryon content $\Omega_{b} = 0.047$, and a spectral index $n = 0.93$. This difference of the two assumptions might lead to the difference of the two slopes.

Figure 26. Comparison of our merger rates (per galaxy $h_{70}^{-1}$ Gyr$^{-1}$) under assumption of $t_{\text{merge}} = t_{KW,i}$ at $0.03 < z < 0.15$ with the estimated merger rates calculated by the “merger rate fitting function” of Stewart et al. (2009) at $z = 0.1$. The open diamonds on the thick lines are our results, and the horizontal thin lines are the best-fit results calculated from Table 1 of Stewart et al. (2009). The dashed lines show the results with mass ratios $m/M > 3.0$, and the solid lines show the results with mass ratios $m/M > 0.6$. Note that the results of Stewart et al. (2009) are estimated from a flat $\Omega_{m} = 1 - \Omega_{\Lambda} = 0.3$ cosmology with a Hubble constant $H_{0} = 100 h$ km s$^{-1}$ Mpc$^{-1}$ and $h = 0.7$. The Astrophysical Journal, 759:140 (21pp), 2012 November 10
mergers, because from the above paragraph we know that only less than 15% of the total fractional accretion rates are from minor mergers with mass ratio between 1:10 and 1:100. If we assume that the growth happens at a non-evolving rate from redshift \( z = 1 \) to now (a period of \( \approx 8 \, h^{-1} \) Gyr), we expect the red galaxies to grow by about \( [10\% \pm 5\%] \) to \([28\% \pm 14\%]\) depending on stellar mass under assumption of \( \tau_{\text{merge}} = t_{\text{KW}},i \), and the red \( L^* \) galaxies (around red7 and red8) grow by about \( [20\% \pm 10\%] \). The merger rate may have been different in the past, of course—both higher and lower (Lin et al. 2008; Chou et al. 2011). If we assume that the growth of massive red galaxies (\( L^* \) galaxies and above) is mainly from galaxy mergers, and also assume that the evolution of the galaxy merger rate per galaxy is proportional to \( (1+z)^{3.0 \pm 1.1} \) (Lotz et al. 2011) from redshift \( z = 1 \) to now, we expect that the stellar-mass density of the red massive galaxies (\( L^* \) galaxies and above) increased about \( \sim 75\% \) under the assumption of \( \tau_{\text{merge}} = t_{\text{KW}},i \), or about \( \sim 40\% \) under the assumption of \( \tau_{\text{merge}} = t_{\text{BT},i} \) (see Table 3), which are consistent with recent studies on the high-redshift universe that find that the red sequence appears to grow in stellar mass over time by a factor of 50%–100% from redshift \( z = 1 \) to now (Bell et al. 2004; Willmer et al. 2006; Blanton 2006; Faber et al. 2007; Conselice et al. 2007; Ciuricu et al. 2008; van Dokkum et al. 2008; Saracco et al. 2009).  

According to Section 4, our results are consistent with the previous clustering results of Zehavi et al. (2011). Our estimated merger rates are consistent with the merger rates estimated by counting of close pairs (Masjedi et al. 2008; Patton & Athfield 2008; Kitzbichler & White 2008; Bundy et al. 2009; De Propris et al. 2010; Robaina et al. 2010). Our estimated merger rates are also consistent with the merger rates predicted in theories of galaxy formation in a cosmological context (Maller et al. 2006; Stewart et al. 2009; A. Wetzel & J. Tinker 2013, in preparation). However, we found that not all merger studies find such low values when we compared our results with the studies at higher redshift. The morphological derivations of the merger fraction (e.g., De Propris et al. 2007; Conselice et al. 2007, 2009; Lotz et al. 2006, 2008) tend to find values of \( f_{\text{pair}} \approx 0.1 \) at \( 0.4 < z < 1.4 \), about two times higher than the results of our pair analysis (see Figure 24). The discrepancy can be resolved easily if either (1) morphological signatures of merging last for many dynamical times (e.g., tidal tails), (2) the very minor mergers (\( m/M < 0.25 \)) inflate the merger rates (note that our pair analysis in Figure 24 are only estimated from major mergers at mass ratio \( m/M > 0.25 \)), (3) morphological tools for finding mergers maybe find some systems that are not involved in mergers, or (4) merger rates at high redshift may be larger than those at low redshift.

The total fractional accretion rates shown in the solid lines in Figure 19 are upper limits on the true fractional mass growth. There are two reasons: (1) we assume \( t_{\text{merge}} = t_{\text{KW},i} \), for every pair. However, this is not true for close pairs in high-velocity dispersion, for which (2) we assume that the stellar-mass growth of the central galaxies from the spectroscopic sample is equal to the stellar mass of the galaxy from the imaging sample, see Equation (30). However Lin et al. (2004) found that up to 50% of the stars in the galaxies from the imaging sample could be stripped off before the merger with LRGs is complete. So our mass growth rate under the assumption of \( t_{\text{merge}} = t_{\text{KW},i} \) is an upper limit on the growth by merging.

We find that the accretion onto red and massive blue galaxies is dominated by mergers with red companions, and that onto small-mass blue galaxies, red and blue companions make comparable contributions; this is shown by Table 2 and Figures 17 and 18. So, most of the mass brought into red galaxies by merging is brought by “dry mergers” (Bell et al. 2006a; van Dokkum 2005; Masjedi et al. 2008). We find that all the contributions to growth decrease with decreasing stellar mass at the small-mass end for all of 18 spectroscopic subsamples. The contribution to growth decreases with decreasing \( M_i/M_i \) since \( M_i/M_i < 0.4 \). For all 18 subsamples, the curves essentially decrease to zero by \( M_i/M_i < 0.01 \) for \( t_{\text{merge}} = t_{\text{KW},i} \) and by \( M_i/M_i < 0.01 \) for \( t_{\text{merge}} = t_{\text{BT},i} \), so calculation of the total amount of mass brought in by merger activities does not require consideration of galaxies from the imaging sample with \( M_i/M_i < 0.01 \).

From Figures 10–13 and Figure 20, we find a sharp break at \( r_p \approx 2.5 \, h^{-1} \) Mpc and a less-sharp transition at \( r_p \approx 0.43 \, h^{-1} \) Mpc. These two transitions are also found in LRGs by Masjedi et al. (2008), which can be explained in the context of the “halo occupation” picture of galaxy clustering (Peacock & Smith 2000; Scoccimarro et al. 2001; Berlind & Weinberg 2002; Cooray & Sheth 2002; Zheng et al. 2005; Watson et al. 2010, 2012): (1) the mergers at \( r_p < 0.43 \, h^{-1} \) Mpc are the one-halo mergers (both of the two merging galaxies are inside one halo); (2) the mergers at \( r_p > 2.5 \, h^{-1} \) Mpc are the two-halo mergers (the two merging galaxies are separately inside two nearby halos); and (3) the mergers at \( 0.43 \, h^{-1} \) Mpc to \( 2.5 \, h^{-1} \) Mpc are the mixed-halo mergers (some of the mergers are the one-halo mergers, the others are the two-halo mergers). So at \( r_p \approx 0.43 \, h^{-1} \) Mpc the mergers transfer from the one-halo mergers to the mixed-halo mergers, and at \( r_p \approx 2.5 \, h^{-1} \) Mpc the mergers transfer from the mixed-halo mergers to the two-halo mergers. These two transitions of mergers between two red galaxies are clearer in Figure 10 than in the other three figures.

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**Table 3**

| Subsample | \( d(\ln M)/d \tau \) | \( d(\ln M)/d t \) |
|-----------|-----------------|-----------------|
| red7      | \( 31.8 \pm 15.9 \) | \( 52.6 \pm 26.3 \) |
| red8      | \( 33.8 \pm 16.9 \) | \( 58.1 \pm 29.1 \) |
| red9      | \( 40.5 \pm 20.3 \) | \( 83.1 \pm 41.6 \) |
| \( \geq L^* \) red7–9 | \( 37.0 \pm 18.5 \) | \( 70.5 \pm 35.3 \) |
| \( \geq L^* \) red8–9 | \( 38.3 \pm 19.1 \) | \( 74.9 \pm 37.4 \) |
| LRG red9  | \( 40.5 \pm 20.3 \) | \( 83.1 \pm 41.6 \) |

**Notes.** Fractional mass growth measurements for massive red galaxies (\( L^* \) galaxies and above) under assumption of merger rates \( (1+z)^{3.0 \pm 1.1} \), split by spectroscopic subsample.

| \( m/M > 0.4 \) | \( m/M \geq 0.4 \) |
|-----------------|-----------------|
| \( \geq 10\% \)  | \( \approx 10\% \) |
| \( \geq 20\% \)  | \( \approx 20\% \) |
| \( \geq 40\% \)  | \( \approx 40\% \) |

- \( \geq 25 \) inflate the merger rates (note this is shown by Table 2 and Figures 17 and 18).
