The Astronomical Journal, 139:794–802, 2010 February
doi:10.1088/0004-6256/139/2/794


# AN UPPER LIMIT TO THE DRY MERGER RATE AT $\langle z \rangle \sim 0.55$

Roberto De Propris[1], Simon P. Driver[2], Matthew Colless[3], Michael J. Drinkwater[4], Jon Loveday[5], Nicholas P. Ross[6,7], Joss Bland-Hawthorn[3,8], Donald G. York[9], and Kevin Pimbblet[4]
[1] Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile
[2] School of Physics and Astronomy, University of St. Andrews, North Haugh, St Andrews, Fife KY16 9SS, UK
[3] Anglo-Australian Observatory, P.O. Box 296, Epping, NSW 1710, Australia
[4] Department of Physics, University of Queensland, Brisbane, Queensland 4072, Australia
[5] Astronomy Centre, University of Sussex, Falmer, Brighton, BN1 9QJ, UK
[6] Physics Department, Durham University, South Road, Durham, DH1 3LE, UK
[7] Department of Astronomy and Astrophysics, The Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802, USA
[8] Institute of Astronomy, School of Physics, University of Sydney, NSW 2006, Australia
[9] Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA
*Received 2008 September 16; accepted 2009 December 27; published 2010 January 14*

## ABSTRACT

We measure the fraction of luminous red galaxies (LRGs) in dynamically close pairs (with projected separation less than 20 $h^{-1}$ kpc and velocity difference less than 500 km s$^{-1}$) to estimate the dry merger rate for galaxies with $-23 < M(r)_{k+e,z=0.2} + 5\log h < -21.5$ and $0.45 < z < 0.65$ in the 2dF-SDSS LRG and QSO (2SLAQ) redshift survey. For galaxies with a luminosity ratio of 1:4 or greater we determine a $5\sigma$ upper limit to the merger fraction of 1.1% and a merger rate of $<0.8 \times 10^{-5}$ Mpc$^{-3}$ Gyr$^{-1}$ (assuming that all pairs merge on the shortest possible timescale set by dynamical friction). This is significantly smaller than predicted by theoretical models and suggests that major dry mergers do not contribute to the formation of the red sequence at $z < 0.7$.

*Key words:* galaxies: evolution – galaxies: formation – galaxies: interactions

*Online-only material:* color figure

## 1. INTRODUCTION

In the standard $\Lambda$ cold dark matter ($\Lambda$CDM) picture, galaxies are assembled via the progressive (hierarchical) merger of increasingly more massive subunits (see, e.g., Cole et al. 2008; Neistein & Dekel 2008 for recent reviews). About half of the stellar mass in present-day massive ($L > L^*$) galaxies is expected to be accreted via major mergers at $z < 1$ (e.g., De Lucia et al. 2006; De Lucia & Blaizot 2007). Mergers should therefore be a common occurrence in the life of galaxies and have a profound influence on their properties (such as star formation, morphology, and nuclear activity among others).

Observational and theoretical evidence suggest that an increasing fraction of mergers at lower redshifts should take place between spheroidal or gas-poor galaxies ("dry" mergers). In their study of the morphology of merging pairs in a CDM universe, Khochfar & Burkert (2003, 2005) found that elliptical galaxies brighter than $L^*$ were mainly formed via major dry mergers and that gas-rich mergers were only important at lower luminosities. Above a "threshold" mass of $\sim 6.3 \times 10^{10}\, M_\odot$, galaxies are not expected to grow their stellar mass by (induced) star formation, but their primary mode of mass accretion at $z < 1$ is via gas-poor (stellar-dominated) mergers (De Lucia et al. 2006; Khochfar & Silk 2009). Unlike gas-rich mergers, dry mergers are not expected to disturb the observed tight scaling relations for early-type galaxies (Boylan-Kolchin et al. 2005, 2006) and to better reproduce the internal structure of local ellipticals (Naab et al. 2006, 2007).

The first examples of dry mergers, in significant numbers, were observed as close pairs of galaxies on the red sequence in deep images of high-redshift clusters (van Dokkum et al. 1999, 2001), where approximately 50% of galaxies were expected to have undergone a dry merger to the present epoch. In the local universe, van Dokkum (2005) estimated that $\sim$30% of $z < 0.1$ bright ellipticals in the MUSYC and NDFWS surveys showed residual structural features indicative of a dry merger in the "recent" past.

Bell et al. (2006a) used close pairs in the Combo-17 survey having similar photometric redshifts *and* showing evidence of interactions to infer an integrated merger rate of $\sim$80% since $z < 0.8$ for red galaxies with $M_B < -20.5 + 5\log h$, while Lin et al. (2008) used dynamically close pairs in the DEEP2 survey to derive an integrated dry merger rate of 24% at $z < 1.2$ for galaxies with $-21 < M_B - 5\log h < -19$. However, Hsieh et al. (2008) identify close pairs in the RCS survey and derive an integrated merger rate of only 6% per Gyr since $z = 0.8$ for galaxies with $-25 < M_r - 5\log h < -20$, and Wen et al. (2008) use the same approach as Bell et al. (2006a) on luminous red galaxies (LRGs) in the Sloan Digital Sky Survey (SDSS) to determine a merger rate of 0.8% per Gyr at $z < 0.12$ for galaxies with $M_r < -21.2 + 5\log h$. Bundy et al. (2009) find evidence of few to zero pairs of red galaxies at $z < 1.2$ in the GOODS data.

The small-scale correlation function of LRGs in SDSS at $z < 0.36$ analyzed by Masjedi et al. (2006, 2008) is consistent with an upper limit of $<$1.7% per Gyr to the dry merger rate for galaxies with $M_i < -22.75 + 5\log h$ at $0.16 < z < 0.30$. Bell et al. (2006b) used this method to derive a merger rate of 4% per Gyr for $M_B < -20.5 + 5\log h$ galaxies at $0.4 < z < 0.8$. White et al. (2007) obtain an integrated merger rate of $\sim$30% for LRGs at $0.5 < z < 0.9$ in the NDFWS survey. Finally, Wake et al. (2008) apply the correlation function method to galaxies the 2SLAQ survey to derive a merger rate of 2.4% per Gyr at $0.19 < z < 0.55$.

The galaxy merger rate has been usually measured via the fraction of galaxies in close pairs, often with the added requirement of closeness in velocity space to cull interlopers (e.g., Patton et al. 2000, 2002, hereafter P00, P02), and the fraction of galaxies showing significant asymmetries in their light distribution (e.g., Conselice 2003; Conselice et al. 2003).

The rationale behind the former approach is that if a merger is to occur, a companion must be present, and therefore the close pair fraction is related to the *future* merger rate for the galaxies being considered. The latter method relies on the observation that if a galaxy has undergone a recent merger, it is likely to be morphologically disturbed, and therefore an asymmetric light distribution would be a signpost of a recent merger. A critical discussion of these approaches may be found in De Propris et al. (2007) and Genel et al. (2009).

In this paper, we derive the dynamically close pair fraction for galaxies in the 2SLAQ survey and determine an upper limit to their merger rate. The benefit of using close pairs is that we are able to select major merger candidates between galaxies in a specified mass range (by appropriately choosing the luminosity and magnitude difference between participating galaxies), to derive a merger rate within a specified timescale (dependent on the chosen projected and velocity separations for the pair members and theoretical simulations), and to identify ongoing merger candidates for later study. Galaxy asymmetries tend to be more difficult to interpret in this fashion and usually require better quality imaging than we have available in our survey, especially for dry mergers (Bell et al. 2006a; Wen et al. 2008), to which the 2SLAQ survey is most sensitive. Unlike asymmetries, galaxy pairs are sensitive to the merger fraction of "progenitor" halos, and this quantity may be more directly compared to theoretical models (Genel et al. 2009).

The structure of this paper is as follows: in the following section, we present the data, describe the methodology, and derive the pair fraction and an upper limit to the dry merger rate at the intermediate redshifts sampled by the 2SLAQ survey. We then discuss and compare our results in the context of galaxy formation models and recent work on the dry merger rate. We adopt the latest cosmological parameters with $\Omega_M = 0.27, \Omega_\Lambda = 0.73$, and $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$. Unless otherwise stated, all absolute magnitudes quoted in the following are intended as including a term of +5 log $h$, and all distance measures need to be referred to $h$ (to the appropriate power).

## 2. THE 2SLAQ SURVEY DATA

The data used in the 2SLAQ survey consist of LRGs with $i < 19.8$ mag. from the original sample of Eisenstein et al. (2001), selected by their $g - r$ and $r - i$ colors to lie at $0.45 < z < 0.65$ (see Fukugita et al. 1996 for a description of the SDSS filter system). Photometry and astrometry for the target LRGs are derived from the SDSS Data Release 1 (York et al. 2000; Abazajian et al. 2003) with improvements from the latest release available at the time of the spectroscopic observations (DR4; Adelman-McCarthy et al. 2006). The objects lie in two long strips on the celestial equator, divided into several disconnected patches, each of which is between 10 and 30 deg$^2$ in area, for a total survey coverage of 182 deg$^2$.

Spectroscopy for candidate LRGs was carried out at the Anglo-Australian Telescope using the Two-Degree Field (2dF) facility (Lewis et al. 2002). For objects in the main sample (Sample 8), it was found that most galaxies are within the specified redshift limits and were observed with high spectroscopic completeness (typically 87%). A complete description of the data can be found in the general survey paper by Cannon et al. (2006; hereafter C06). Because we have highly complete spectroscopy, we can confirm that at least 90% of our galaxies have K-type or LRG spectra, with no sign of star formation, while less than 1% of the sample show emission lines (Roseboom et al. 2006). We can therefore use this sample to measure the dry merger rate.

Following Wake et al. (2006), we computed the absolute magnitude for objects with reliable redshifts, *k+e* corrected to the SDSS $r$ band at $z = 0.2$. This facilitates comparison with previous work on galaxy evolution and the merger rate from SDSS (e.g., Masjedi et al. 2006, 2008). Note that no correction for internal extinction was applied to these galaxies.

## 3. METHODOLOGY

We calculate close pair statistics following the formalism developed by P00 and P02 for the SSRS2 and CNOC2 surveys. Here, we give an "algorithmic" description of the procedures used, and show how we apply weights to correct for sources of incompleteness and the flux-limited nature of the 2SLAQ survey. A fuller description of the method can be found in P00 and P02.

### *3.1. Luminosity of the Pair Sample*

Let us consider a sample of $N_1$ primary galaxies brighter than a limiting absolute magnitude $M_1$ in some volume of space, and, in the same volume, a sample of $N_2$ secondary galaxies brighter than a limiting absolute magnitude $M_2$. The two samples may coincide (i.e., $M_1 = M_2$), as is often the case for redshift surveys: we then study "major" mergers between galaxies of approximately similar luminosity. We are interested in knowing the fraction of galaxies in the secondary sample that are dynamically close to galaxies in the primary sample. We define two galaxies to be dynamically close if they have a projected separation $r_p < 20\,h^{-1}$ kpc and a velocity difference of <500 km s$^{-1}$, as used by P00, P02, and in subsequent work.

Of course, pair statistics are usually computed from redshift surveys, which are flux limited rather than volume limited. We therefore need to account for the dependence of pair counts on the clustering properties and the mean density of galaxies in the sample, and to correct for sources of spatial and spectroscopic incompleteness. Because clustering is luminosity dependent (e.g., Norberg et al. 2002) we follow P00 and restrict the analysis to a fixed range in luminosity, within which clustering properties are not expected to vary significantly, by imposing additional bright ($M_{\rm bright}$) and faint ($M_{\rm faint}$) limits on the sample. This means that we derive a pair fraction (and merger rate) for galaxies within a specified range and ratio in luminosity.

In our case, we select galaxies with $0.45 < z < 0.65$ (where the survey is most complete) and with $M_{\rm bright} = -23$ and $M_{\rm faint} = -21.5$ mag. Because the range of luminosities we survey is small, we let $M_{\rm faint}$ coincide with $M_2$. We also let the primary and secondary samples coincide, to select major mergers between galaxies of approximately equal luminosities (and make full use of the spectroscopic sample). Figure 1 shows the distribution of 2SLAQ galaxies in absolute magnitude versus redshift, together with selection lines in magnitude and redshift (see below for details).

The faint limit allows us to include most 2SLAQ galaxies at $z > 0.45$ and reaches slightly below the luminosity of normal $L^*$ galaxies at the mean survey redshift (or, similarly, below the turnover in the 2SLAQ LRG luminosity function of Wake et al. 2006). We choose the bright limit of $M_r = -23$ to avoid the rarer and most luminous galaxies in 2SLAQ, which are likely to be more biased, and to mitigate the effects of luminosity-dependent clustering (as described above). With these choices, we study major mergers, with luminosity ratio $\geqslant$1:4, where the

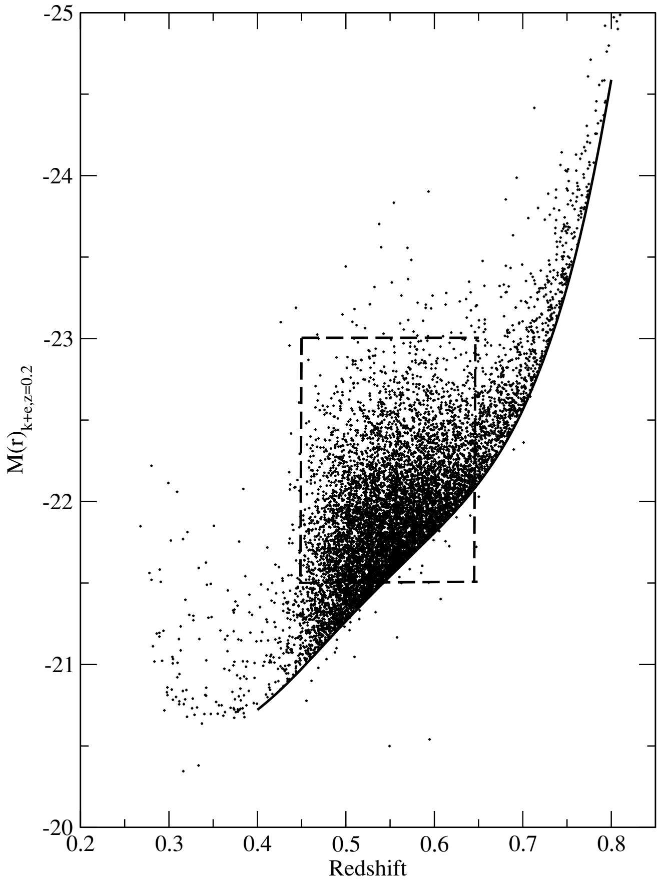


**Figure 1.** Distribution of absolute magnitudes for 2SLAQ galaxies vs. redshift. The thick solid line is the redshift-dependent absolute magnitude limit for selection $M_{\rm lim}(z)$ (see Equation(1) and related explanation in the text). The thick dashed lines mark the ideal volume-limited box to which the observed sample is corrected using the weights described in Equations (2)–(9).

secondary is at least four times less luminous than the primary galaxy,[10] for $M_r < -21.5$.

We can translate our luminosity range into a stellar mass range using the conversion between $r$-band absolute magnitude and stellar mass by Baldry et al. (2006), for typical LRG colors ($u - r > 3$) and with assumptions as to stellar populations as in Baldry et al. (2006). With these choices, our $-23 < M_r < -21.5$ luminosity range corresponds to a stellar mass range of $(16\text{–}5) \times 10^{10}\, M_\odot$.

### *3.2. Density Weighting S(z)*

The pair fraction that we actually measure needs to be corrected to the value that would be observed in an ideal volume-limited survey. In a flux-limited sample, primary galaxies at lower redshifts will have a greater likelihood of having a secondary companion within the survey than galaxies at higher redshift. We correct for this bias by assigning a greater weight to the rarer companions found at the high-redshift end of the survey. This is carried out by computing for each galaxy a weight that renormalizes the sample to the density corresponding to a volume-limited sample within $M_{\rm bright} < M < M_2$. The weight is calculated by integrating the luminosity function over the appropriate ranges in absolute magnitude.

[10] Note that of course no sample can be made complete for a given luminosity ratio without discarding a large fraction of the data (e.g., Patton & Atfield 2008), so theoretical comparisons need to take into account the observational limitations of this technique.

At each redshift, we then search for pairs of galaxies within $M_{\rm bright}$ and a redshift-dependent absolute magnitude limit $M_{\rm lim}(z)$, which is defined as

$$M_{\rm lim}(z) = \max[M_{\rm faint},\ 19.8 - 5\log d_L(z) - 25 - k(z) - e(z)], \quad (1)$$

where $i = 19.8$ mag is the apparent magnitude limit of the survey, $d_L(z)$ is the luminosity distance, and $k(z)$ and $e(z)$ are the $k$ and evolutionary corrections. Recall that here $M_{\rm faint}$ is set to coincide with $M_2$. The $k+e$ corrections are taken to be the maximal corrections for a galaxy formed at high redshift and undergoing pure passive evolution, as other choices would allow galaxies to fall in and out of the sample according to their star formation histories (P00, P02). Note that here max means "the brightest of" rather than the (arithmetically) larger quantity. Figure 1 shows this selection limit as applied to 2SLAQ data.

Each secondary galaxy is weighted by the inverse of a selection function $S(z)$ defined as the ratio of densities in volume-limited versus flux-limited samples:

$$S_N(z) = \frac{\int_{M_{\rm bright}}^{M_{\rm lim}(z)} \Phi(M)dM}{\int_{M_{\rm bright}}^{M_2} \Phi(M)dM} \quad (2)$$

$$S_L(z) = \frac{\int_{M_{\rm bright}}^{M_{\rm lim}(z)} \Phi(M)L(M)dM}{\int_{M_{\rm bright}}^{M_2} \Phi(M)L(M)dM}, \quad (3)$$

where $L(M) = 10^{0.4(M-M_\odot)} L_\odot$ and $\Phi(M)$ is the LRG luminosity function from Wake et al. (2006). The integrals run from $M_{\rm bright}$ to either the faint absolute limit $M_2$ (in the denominator) or to the redshift-dependent absolute magnitude limit $M_{\rm lim}(z)$ (in the numerator) set by the apparent magnitude limit of the survey.

Galaxies in the primary sample at low redshift will also have the largest number of observed companions, while primaries at higher redshifts will have fewer observed companions. This effect is corrected in a similar fashion as for galaxies in the secondary sample, by applying the inverse of the secondaries' weight to primaries, i.e., $S_N(z)$ and $S_L(z)$.

### *3.3. Spatial Incompleteness $w_b$, $w_v$*

We need to account for pairs missed because one of the galaxies falls outside of the survey footprint. A potential companion may lie beyond the survey limits on the sky or be hidden in the "shadow" of a bright star, where galaxies cannot be detected or the spectra are contaminated.[11] For each primary galaxy we compute the fraction $1 - f_b$ of the $\pi r_p^2$ area that may lie outside of the effective survey area. The weight to be applied to the secondary galaxies is then $w_{b_2} = 1/f_b$. Primary galaxies may similarly be lost in the survey boundaries and the appropriate weight to be applied to the primary sample is $w_{b_1} = f_b = w_{b_2}^{-1}$.

For objects with small separations, the SDSS photometric pipeline tends to merge pairs into a single galaxy. For the LRG sample studied by Masjedi et al. (2006), the pipeline becomes unreliable for $r_p < 3''$. The 20 $h^{-1}$ kpc search radius we use corresponds to angular separations of 4$''$.91–4$''$.07 at $0.45 < z < 0.65$. We inspected all our 7889 images to verify whether the SDSS pipeline correctly identifies photometric

[11] This is calculated using a formula developed by I. Strateva (unpublished) for the SDSS survey.

companions, using the SDSS "Image List/Navigate" tools. The results are that the pipeline certainly finds all targets with projected separations between 3″ and 5″. For smaller separations the pipeline is more erratic, especially for fainter systems. We therefore exclude an area of 3″ around each target from our search for companions and correct for the missed region via the $w_b$ weight, where we assume that the distribution of pairs is uniform with projected separation over these small scales. The size of the added factor lies between 37% and 54% depending on redshift.

The SDSS pipeline also tends to "double count" light for close pairs, making these galaxies brighter than they would otherwise be. Because fainter galaxies have more mergers and minor mergers are more common (Patton & Atfield 2008), this has the effect of artificially raising the pair fraction. Masjedi et al. (2006) estimate that this should decrease the actual merger rate for galaxies with $r_p < 5''$ by a factor of about 5. Since this is an uncertain correction and we are interested in an upper limit to the merger rate, we do not consider this effect here (the effect cannot be well modeled for our sample, as the SDSS pipeline cannot be run locally).

We also correct for possible companions missed by the redshift "cuts" we apply to the survey. If the primary lies within 500 km s$^{-1}$ of the redshift boundaries, we ignore all companions between the primary and the borders, and apply a weight $w_{v_2} = 2$ to all other companions in the opposite "direction." We also need to apply a similar weight to account for potential primaries lost in the redshift boundary. This weight is the reciprocal of the weight applied to the secondaries, i.e., $w_{v_1} = 1/2$.

### *3.4. Spectroscopic Incompleteness $w_\theta$*

As all redshift surveys, 2SLAQ is not complete to its flux limit. Our success rate is 87% for all galaxies within Sample 8 of C06 but the spectroscopic incompleteness may be dependent on the separation between galaxies. Fibers in the 2dF positioner cannot be placed closer than about 25″ from each other in every single configuration. However, this effect is compensated by the overlap between individual 2SLAQ tiles and by the fact that fiber configurations were generally retouched halfway through each (typically 4 hr) exposure to place fibers assigned to galaxies for which a reliable redshift had already been obtained on to a nearby target (see C06 for a description of the observations).

In order to correct for this source of bias, we need to estimate the relative incompleteness for close pairs over the range of separations of interest (corresponding to 20 $h^{-1}$ kpc) and compare it with the incompleteness at large separations, where fiber interactions are not important. We follow P02 and estimate this weight by computing the ratio between the number of pairs between galaxies with redshift information ($N_{zz}$) *within the redshift range of interest* and the number of pairs in the input photometric sample ($N_{pp}$), which is by definition complete, as a function of angular separation $\theta$. The weight to be applied is the ratio between the spectroscopic and photometric pair completeness at each separation normalized to the value at large separations.

In 2SLAQ, we have higher overall completeness than CNOC2 (by about a factor of 2) but sample a smaller range of projected separations (because of our higher mean redshift). We plot $N_{zz}(\theta)/N_{pp}(\theta)$ versus $\theta$ in Figure 2 for Sample 8 targets; the error bars are assumed to be Poissonian. Although the data are noisy (because there are relatively few potential pairs to start with), the value of $N_{zz}/N_{pp}$ at $\theta < 6''$ is consistent with the value of this ratio at $\theta > 100''$, arguing that we are not systematically more incomplete at small separations than at large ones where we are not affected by fiber collisions.

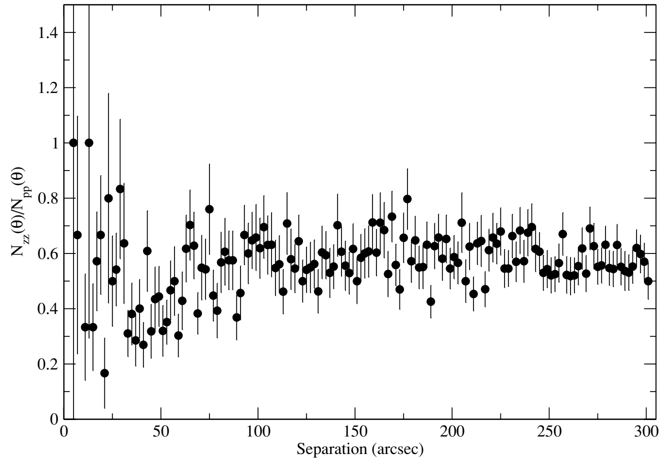


**Figure 2.** Ratio of galaxies in pairs between galaxies with redshifts and galaxies in pairs in the photometric sample, as a function of pair separation $\theta$.

P02 model the incompleteness in the CNOC2 survey by fitting a polynomial to the ratio $N_{zz}(\theta)/N_{pp}(\theta)$ as a function of projected separation $\theta$. Given the small number statistics and noisier nature of our data, it is not fully justified to model the completeness as a function of $\theta$ with a polynomial as done in P02. We therefore adopt a uniform weight of 1 for 2SLAQ galaxies over the separation of interest, as we do not appear to be systematically more incomplete than at larger separations. Although pair completeness drops at 30″–60″ separations, because of fiber collisions, these large separations are not relevant to our study (as pairs with $r_p > 50\ h^{-1}$ kpc or $\Delta v < 1000$ km $s^{-1}$ are largely spurious; P00; De Propris et al. 2007).

Given the small number statistics, and the fact we are ultimately deriving an upper limit, we eventually decided to follow the approach by De Propris et al. (2005) to estimate the contribution from close pairs missed because of fiber collisions. *We do not apply the $w_\theta$ weight to our sample*. We search around each of our main targets (Sample 8 galaxies with $-23.0 < M(r) < -21.5$ and $0.45 < z < 0.65$) for a companion (lying within $r_p$) in the sample of galaxies (from the input photometric sample) for which we did not obtain a valid redshift. If such a companion exists, we assign to it the same redshift as the primary galaxy and require that the companion lies within the selection lines in Figure 1. This identifies all pairs (a total of 3) which are potentially missed because of redshift incompleteness. Pairs, where both members are missed by the spectroscopic survey, will share in the general 2SLAQ incompleteness, without a bias for incompleteness at small angular separations. We can assume that all these three "extra" pairs are real and treat them as a source of systematic error on our determination of the pair fraction and the merger rate. Figure 3 shows postage stamp images of the two dynamical pairs we find and of the three possible pairs.

P02 also use a weight $w_s$ which accounts for the local magnitude incompleteness around each galaxy, a geometric effect due to slit placement and limiting filters in the CNOC2 survey, a color term, and a term that depends on the evolution of the galaxy luminosity function over the redshifts covered by the survey. This weight is specific to the methods employed by the CNOC2 survey (Yee et al. 2000). In our case, we have a very

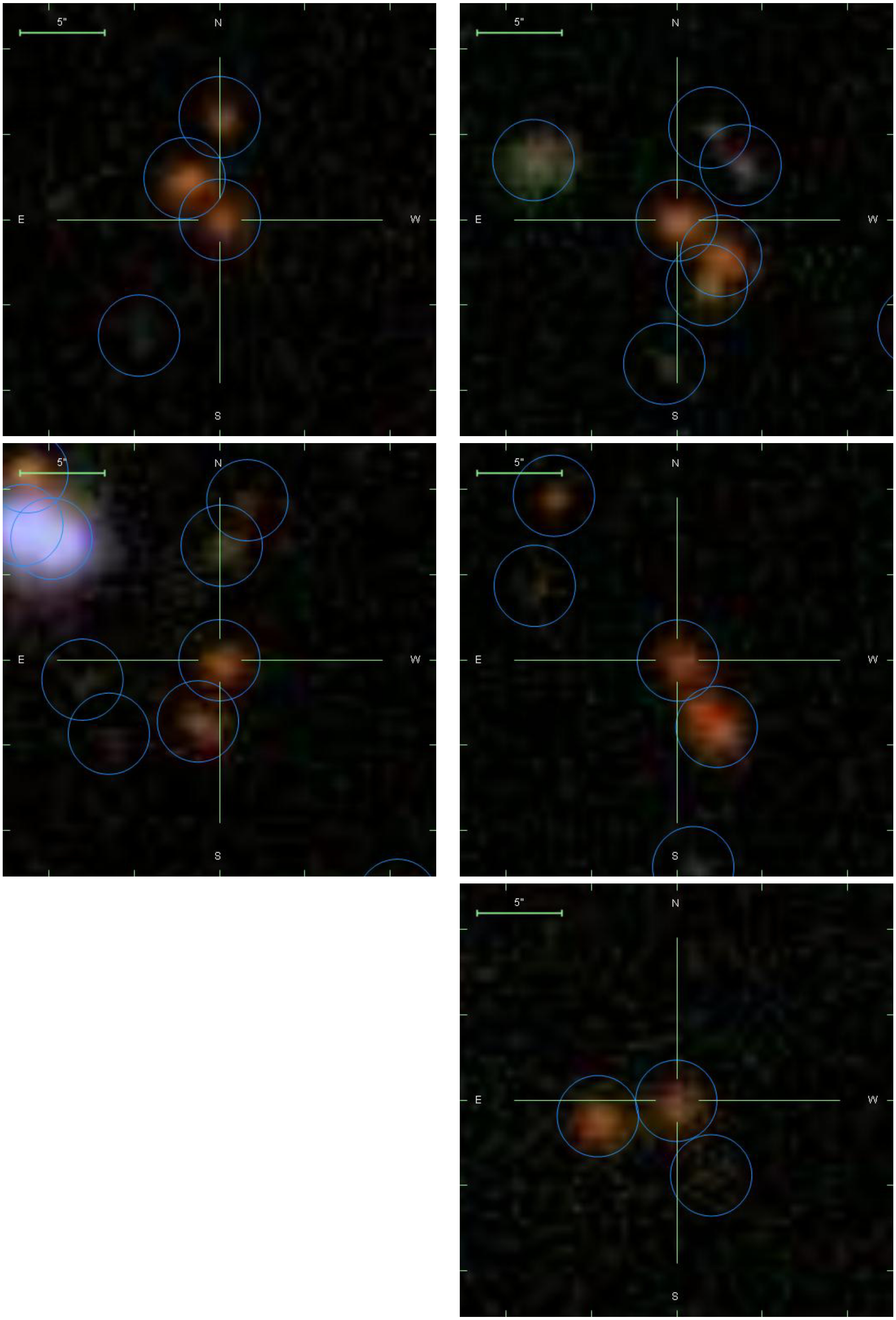


**Figure 3.** Images (from SDSS) of pairs found in our survey. The two panels on the left are the real ones, while the three images on the right show the "possible" pairs. (A color version of this figure is available in the online journal.)

homogeneous sample, there is no geometric effect (other than the one corrected by $w_\theta$), all galaxies have similar colors, and the color selection is very efficient in selecting galaxies of the appropriate magnitude and redshift. Even in the CNOC2 survey, most of these weights are equal to 1 (Yee et al. 2000) for most galaxies. For these reasons, we do not adopt this weight in our study.

### 3.5. *Calculation of Pair Fraction*

Following P00, the number of close companions per galaxy in a flux-limited sample can be expressed as

$$N_c = \frac{\sum_i^{N_1} w^i_{N_1} N_{c_i}}{\sum_i^{N_1} w^i_{N_1}} \tag{4}$$

and the total companion luminosity

$$L_c = \frac{\sum_i^{L_1} w^i_{L_1} L_{c_i}}{\sum_i^{L_1} w^i_{L_1}} L_\odot. \tag{5}$$

The sums run over the $i = 1, \ldots, N_1$, primary galaxies: $N_{c_i}$ and $L_{c_i}$ are the number and summed luminosity of galaxies from the secondary sample that are dynamically close (as defined above) to the $i$th primary galaxy and are expressed as

$$N_{c_i} = \sum_j w^j_{N_2} = \frac{\sum_j w^j_{b_2} w^j_{v_2}}{S_N(z_j)} \tag{6}$$

$$L_{c_i} = \sum_j w^j_{N_2} L_j = \sum_j \frac{w^j_{b_2} w^j_{v_2}}{S_L(z_j)} L_j, \tag{7}$$

where the sums run over those $j = 1, \ldots, N_2$, galaxies in the secondary sample that fulfill the criteria for being dynamically close to the $i$th galaxy in the primary sample.

The weights to be applied to the secondary sample correct for spatial incompleteness ($w^j_b$,$w^j_v$) and the flux-limit of the survey ($S(z_j)$) for each $j$th companion. We do not apply the spectroscopic incompleteness weight $w_\theta$ because we use the alternate method described above to calculate the contribution from missed close pairs. The weights are defined in the previous subsections. Similar weights also need to be applied to the primary sample, to correct for spatial incompleteness and the mean density:

$$w^i_{N_1} = w^i_{b_1} w^i_{v_1} S_N(z_i) \tag{8}$$

$$w^i_{L_1} = w^i_{b_1} w^i_{v_1} S_L(z_i), \tag{9}$$

where $w^i_{b_1} = f^i_b$ and $w^i_{v_1} = 1/2$ (i.e., the reciprocals of the weights applied to the secondary sample). No spectroscopic completeness weight is needed for the primary sample.

### 3.6. *Merger Timescales*

In order to convert a pair fraction into a merger rate, the timescale for the merger event needs to be estimated. Merger timescales are difficult to determine and depend on the poorly known details of the merger process and how the potential of the individual galaxies reacts to the merger episode. The more commonly used timescales in previous work and semianalytic models are based on dynamical friction arguments. The dynamical friction timescale can be calculated as (Patton et al. 2000)

$$T_{\rm fric} = \frac{2.64 \times 10^5\, r^2\, v_c}{M \ln \Lambda}, \tag{10}$$

where $r$ is initial physical pair separation in kpc, $v_c$ is the circular velocity in km s$^{-1}$, $M$ is the mass, and $\Lambda$ is the Coulomb logarithm. Assuming $r = 20\,h^{-1}1$ kpc, $v_c = 260$ km s$^{-1}$, and $\ln \Lambda = 2$ for equal mass mergers, we get a typical dynamical friction timescale between 0.1 and 0.3 Gyr over the range of masses we sample.

The calibration by Kitzbichler & White (2009) for the merger timescale of pairs in $N$-body simulations with $M > 5 \times 10^9\, M_\odot$ and a velocity separation of 300 km s$^{-1}$ yields 0.9 Gyr, while the estimated merger timescale from the $N$-body simulations of Boylan-Kolchin et al. (2008) is $\sim$0.8 Gyr for the mass ratios we consider. A comparison between merger timescale by dynamical friction and in $N$-body simulations by Boylan-Kolchin et al. (2008) shows that the dynamical friction formula underestimates the merger timescale by a factor between 1.7 and 3.3 for mergers of mass ratio from 1:3 to 1:10, respectively, and leads to a 40% overestimate of the mass accretion rate (mainly via minor mergers).

## 4. DISCUSSION

### 4.1. *Results*

We can now apply the above procedure to the 2SLAQ sample. Out of 7889 galaxies, we find a total of one dynamically close pair (we find a second pair, but it lies within the 3″ exclusion circle). This yields a pair fraction $N_c = 0.047\%$ and a luminosity accretion rate $L_c = 2.5 \times 10^7\, L_\odot$. For galaxies within $z < 0.55$ this is $N_c = 0.041\%$. Normally, errors on these quantities can be estimated by bootstrap resampling or jack-knifing, but this is not feasible with a sample of only two objects. We then proceed to estimate an upper limit to the pair fraction and the merger rate.

In order to derive an upper limit to the merger rate, we take the observed detections and use the binomial distribution. For large samples ($N > 100$), the error distribution is given by Burgasser et al. (2003):

$$\left(\epsilon^U_b - \epsilon_b\right)/\epsilon_b = \left(\epsilon_b - \epsilon^L_b\right)/\epsilon_b = \sqrt{1/n + 1/N}, \tag{11}$$

where $\epsilon_b$ is the pair fraction, $n$ is the number of pairs, $N$ is the number of objects in the sample, $\epsilon^U_b$ is the upper 1$\sigma$ probability limit to the pair fraction, and $\epsilon^L_b$ is the lower 1$\sigma$ probability limit to the pair fraction. The region between $\epsilon^U_b$ and $\epsilon^L_b$ corresponds to the 68% confidence interval for $\epsilon_b$ for a Gaussian distribution. In order to obtain a conservative upper limit, we decide to use both pairs that we actually find (even though one of these is not within the valid range of separations).

For $n = 2$ and $N = 7889$, this yields $N_c = 0.094\% \pm 0.066\%$. The systematic error due to the three possible extra pairs is $0.14\% \pm 0.08\%$. We can therefore quote a 5$\sigma$ upper limit to the pair fraction of 0.44% (random) plus 0.54% (systematic), for a total of 1.0%.

As a check, we estimate the pair fraction in each of the separate 2SLAQ survey patches: while most regions have no pairs, in one area, we find a pair fraction of 0.30%, which is consistent with the upper limit we derived above. Finally, we can also consider pairs with wider separation in both projected distance and velocity: $r_p < 50\,h^{-1}$ kpc and

$\Delta v < 1000$ km s$^{-1}$. This considerably increases the number of contaminants (unphysical pairs), as shown by P00 and De Propris et al. (2007). However, this pair fraction may provide a further interesting constraint. For the 2SLAQ sample we find $N_c = 0.13\%$.

Our upper limit to the pair fraction can be translated into a 5$\sigma$ upper limit to the dry merger rate using the expression

$$R_{\rm mg} = N_c\, n(z)\, 0.5\, p_{\rm merg}\, T_{\rm mg}^{-1}, \qquad (12)$$

where $n(z)$ is the space density of galaxies in our sample, 0.5 is a factor introduced to avoid double counting galaxies (one pair contains two galaxies), $p_{\rm merg}$ is the probability that pairs will merge (assumed to be 1 here) and $T_{\rm mg}$ is the merger timescale, for which we take the shortest possible timescale set by dynamical friction. We find that a robust 5$\sigma$ upper limit to the merger rate is $< 0.8 \times 10^{-5}$ Mpc$^{-3}$ $h^{-3}$ Gyr$^{-1}$ (including the systematic contribution due to the three extra photometric pairs) for galaxies with $-23 < M_r < -21.5$ at $0.45 < z < 0.65$ (a period of 1.4 Gyr in the history of the universe). A more realistic merger timescale and merger fraction may decrease this estimate by more than one order of magnitude.

### 4.2. Comparison with Previous Measurements

The low dry merger rate we measured here is in good agreement with a number of other estimates: locally, Masjedi et al. (2006, 2008) obtain an upper limit of <1.7% per Gyr for the dry merger rate of SDSS LRGs with $M_i < -22.75$ and $z < 0.36$, a value which is consistent with ours, albeit for more luminous (massive) galaxies. This is also similar to the dry merger rate of 0.8% measured by Wen et al. (2008) for SDSS LRGs with $M_r < -21.5$ and $z < 0.12$. The integrated dry merger rate for galaxies in the Red Sequence Survey is ∼6% since $z = 0.8$ over $-25 < M_r < -20$, while Bundy et al. (2009) find very low to zero likely dry mergers in GOODS data at $z < 1.2$.

Nevertheless, there are some discrepant estimates in the literature. Apparently, the most worrying is the value of 2.4% per Gyr for $0.19 < z < 0.55$ LRGs from 2SLAQ derived by Wake et al. (2008) using the small-scale correlation function. However, Wake et al. (2008) use LRGs over the entire range of absolute luminosities in the 2SLAQ survey, and their sample therefore includes both minor mergers (luminosity ratio greater than 1:4) and less luminous objects. As shown by Patton & Atfield (2008) and de Ravel et al. (2009), the merger rate increases significantly for minor mergers and less luminous galaxies. Therefore, the larger value derived by Wake et al. (2008) is not necessarily in disagreement with ours.

Lin et al. (2008) apply the same method as we do (dynamically close pairs) to galaxies in the DEEP2 survey and derive an integrated merger rate of 24% since $z < 1.2$ for galaxies with $-21 < M_B < -19$. Assuming a flat evolution of the merger rate (Lin et al. 2008), this is equivalent to ∼6% per Gyr. Here, the different luminosity ranges sampled, the bandpass difference, and the fact that dry mergers were selected by morphology, rather than by colors and spectral features as we do, may play a role in explaining the difference.

Bell et al. (2006a) obtain an integrated dry merger rate of ∼80% since $z = 0.8$ for galaxies in the Combo-17 survey with $M_B < -20.5$, while applying the small-scale correlation function to the same data, Bell et al. (2006b) derive a merger rate of 4% per Gyr at $0.4 < z < 0.8$. As noted by Wake et al. (2008), the space density of objects in these surveys is 20 times greater than ours, and therefore Bell et al. (2006a, 2006b) sample considerably less luminous objects than we do. Given the dependence of the merger rate on luminosity (Patton & Atfield 2008; de Ravel et al. 2009) this does not mean that our results are in disagreement. In addition, Khochfar & Silk (2009) show that the above sample includes both wet and dry mergers, unlike ours where we confirm by spectroscopy that the vast majority of the sample has LRG-type spectra (Roseboom et al. 2006).

Finally, White et al. (2007) measure an integrated dry merger rate of 30% for LRGs in the NDFWS survey between $0.5 < z < 0.9$. This is equivalent to a merger rate of 3.4% per Gyr, but needs to be corrected for the higher mean redshift and different space density than the 2SLAQ sample. Wake et al. (2008) estimate that this downward revision is about a factor of 10, which places the result by White et al. (2007) in good agreement with ours.

In addition, there are several estimates of the merger rate for all galaxies using asymmetries for the DEEP2 (Lotz et al. 2008) and COSMOS surveys (Kampczyk et al. 2007), as well as galaxies in the GOODS fields (Lopez-Sanjuan et al. 2009), and pairs in the COSMOS survey (Kartaltepe et al. 2007). The measured merger rate is approximately 2%–4% per Gyr for the entire population of $L > L^*$ galaxies, of which dry mergers are only a subset, which is in agreement with our measurement.

Our result is also consistent with the more indirect merger fraction derived from the evolution of the red galaxy luminosity function. Note that, in this case, "growth" may take place via the transformation of blue galaxies into quiescent objects, moving on to the red sequence, but without (necessarily) any major merging. Wake et al. (2006) used the 2SLAQ data to show that the LRG luminosity function evolves passively at $z < 0.6$, a result confirmed by several other studies (Bundy et al. 2006; Caputi et al. 2006; Cimatti et al. 2006; Scarlata et al. 2007). For ∼$4L^*$ LRGs, Brown et al. (2007, 2008) and Cool et al. (2008) show that these galaxies evolve essentially passively at $z < 1$.

Some massive red mergers are observed in distant clusters and groups (e.g., van Dokkum et al. 1999, 2001). Using the pair fraction, van Dokkum et al. (1999) estimated that ∼50% of massive red galaxies in the cluster MS1054-0321 at $z = 0.82$ have undergone a merger to the present epoch. McIntosh et al. (2008) calculate that, for groups and clusters in SDSS at $z < 0.12$, the merger rate for massive red galaxies is 2%–9% per Gyr. These are much higher merger rates than we measure, albeit in a much denser environment. Assuming that the merger rate scales with density, and since clusters are about 100 times denser than the field, the values derived by van Dokkum et al. (1999, 2001) and McIntosh et al. (2008) are probably not fully inconsistent with our ∼0.3% upper limit for field LRGs.

### 4.3. Implications for Galaxy Formation

At face value, our results are in considerable tension with models of galaxy formation in ΛCDM cosmologies where most massive red galaxies grow via dry mergers (Khochfar & Burkert 2003; De Lucia et al. 2006; Khochfar & Silk 2009). Khochfar & Silk (2009) use a semianalytic model to model the quenching of star formation and a standard merger tree, to predict the dry merger rate for galaxies above a characteristic mass (the mass for which star formation is shut off) at $z < 1$. For galaxies with $M > 6.3 \times 10^{10}\, M_{\odot}$, Khochfar & Silk (2009) predict a dry merger rate of $6 \times 10^{-5}$ Mpc$^{-3}$ $h^{-3}$ Gyr$^{-1}$, and a typical merger fraction of about 10%–20% per Gyr, almost independent of redshift.

Our luminosity range of $-23 < M_r < -21.5$ translates into a mass range of (16–5) $\times 10^{10}\, M_{\odot}$. The upper limit to the merger rate we derive ($< 0.8 \times 10^{-5}$ Mpc$^{-3}$ $h^{-3}$ Gyr$^{-1}$, including the "worst case scenario" for systematic errors and assuming all pairs merge on the shortest possible timescale) is at least a factor of 5 below these predictions. It is therefore unlikely that dry mergers at $z < 0.7$ are important in the buildup of the red sequence (Bundy et al. 2007, 2009; Genel et al. 2008)

On the other hand, the mass fraction in $\leqslant L^*$ galaxies on the red sequence appears to grow by about 50% since $z = 1$ (Bell et al. 2004; Borch et al. 2006; Faber et al. 2007; Cool et al. 2008). Scarlata et al. (2007) also note a deficit of fainter early-type galaxies in their COSMOS data at $z = 0.7$. The main mode of growth of the red sequence at $z < 1$ may be via cessation of star formation and morphological evolution in lower mass galaxies (Bell et al. 2004; Faber et al. 2007).

We therefore favor a scenario where most massive galaxies are formed quasi-monolithically at high redshift and major mergers are relatively unimportant at $z < 1$ (e.g., Bower et al. 2006; Naab et al. 2007, cf., Conselice 2006 for an observational perspective). This is consistent with recent CDM simulations, that downplay the role of major mergers in galaxy formation over the past half of the Hubble time and favor minor mergers and internal processes as drivers of galaxy evolution in the last ~8 Gyr (e.g., Cattaneo et al. 2008; Guo & White 2008; Parry et al. 2009). However, even in these models the more massive LRGs should grow primarily by major dry mergers, a result that appears to be in some conflict with the slow growth observed for these galaxies (Brown et al. 2007, 2008; Cool et al. 2008).

It is important to distinguish between the merger rate of dark matter halos and that of their galaxy tracers. Strictly speaking, theory can only predict the former, while the latter depends, at least in part, on complex details of baryonic physics and dynamical friction (cf. Berrier et al. 2006). Although our results appear to favor a particular realization of ΛCDM models, interpretation must await more detailed and realistic simulations of the stellar components of galaxies and their fate during mergers and interactions.

We thank Robert C. Nichol for some valuable comments on this paper.

We warmly thank all the present and former staff of the Anglo-Australian Observatory for their work in building and operating the 2dF facility. The 2SLAQ Survey is based on the observations made with the Anglo-Australian Telescope and for SDSS. Funding for SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web site is http://www.sdss.org/.

SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

*Facilities:* AAT (2dF), Sloan

## REFERENCES

Abazajian, K., et al. 2003, AJ, 126, 2081
Adelman-McCarthy, J. K., et al. 2006, ApJS, 162, 38
Baldry, I. K., Balogh, M. L., Bower, R. G., Glazebrook, K., Nichol, R. C., Bamford, S. P., & Budavari, T. 2006, MNRAS, 373, 469
Bell, E. F., Phleps, S., Somerville, R. S., Wolf, C., Borch, A., & Meisenheimer, K. 2006a, ApJ, 652, 270
Bell, E. F., et al. 2004, ApJ, 608, 752
Bell, E. F., et al. 2006b, ApJ, 640, 241
Berrier, J. C., Bullock, J. S., Barton, E. J., Guenther, H. D., Zentner, A. R., & Wechsler, R. H. 2006, ApJ, 652, 56
Borch, A., et al. 2006, A&A, 453, 869
Bower, R. G., Benson, A. J., Malbon, R., Helly, J. C., Frenk, C. S., Baugh, C. M., Cole, S., & Lacey, C. G. 2006, MNRAS, 370, 645
Boylan-Kolchin, M., Ma, C.-P., & Quataert, E. 2005, MNRAS, 362, 184
Boylan-Kolchin, M., Ma, C.-P., & Quataert, E. 2006, MNRAS, 369, 1081
Boylan-Kolchin, M., Ma, C.-P., & Quataert, E. 2008, MNRAS, 383, 93
Brown, M. J. I., Dey, A., Jannuzi, B. T., Brand, K., Benson, A. J., Brodwin, M., Croton, D. J., & Eisenhardt, P. R. 2007, ApJ, 634, 858
Brown, M. J. I., et al. 2008, ApJ, 682, 937
Bundy, K. A., Fukugita, M., Ellis, R. S., Targett, T. A., Belli, S., & Kodama, T. 2009, ApJ, 697, 1369
Bundy, K. A., Treu, T., & Ellis, R. S. 2007, ApJ, 665, L5
Bundy, K. A., et al. 2006, ApJ, 651, 120
Burgasser, A. J., Kirkpatrick, J. D., Reid, I. N., Brown, M. E., Miskey, C. L., & Gizis, J. E. 2003, ApJ, 586, 512
Cannon, R. D., et al. 2006, MNRAS, 372, 425
Caputi, K., et al. 2006, MNRAS, 366, 609
Cattaneo, A., Dekel, A., Faber, S. M., & Guiderdoni, B. 2008, MNRAS, 389, 567
Cimatti, A., Daddi, E., & Renzini, A. 2006, A&A, 453, L29
Cole, S., Helly, J., Frenk, C. S., & Parkinson, H. 2008, MNRAS, 383, 546
Conselice, C. J. 2003, ApJS, 147, 1
Conselice, C. J. 2006, ApJ, 638, 686
Conselice, C. J., Bershady, M. A., Dickinson, M., & Papovich, C. 2003, AJ, 126, 1183
Cool, R. J., et al. 2008, ApJ, 682, 919
De Lucia, G., & Blaizot, J. 2007, MNRAS, 375, 2
De Lucia, G., Springel, V., White, S. D. M., Croton, D., & Kauffmann, G. 2006, MNRAS, 366, 499
De Propris, R., Conselice, C. J., Liske, J., Driver, S. P., Patton, D. R., Graham, A. W., & Allen, P. D. 2007, ApJ, 666, 212
De Propris, R., Liske, J., Driver, S. P., Allen, P. D., & Cross, N. J. G. 2005, AJ, 130, 1516
de Ravel, L., et al. 2009, A&A, 498, 379
Eisenstein, D. J., et al. 2001, AJ, 122, 2267
Faber, S. M., et al. 2007, ApJ, 665, 265
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1748
Genel, S., Genzel, R., Bouché, N., Naab, T., & Sternberg, A. 2009, ApJ, 701, 2002
Genel, S., et al. 2008, ApJ, 688, 789
Guo, Q., & White, S. D. M. 2008, MNRAS, 384, 2
Hsieh, B. C., Yee, H. K. C., Lin, H., Gladders, M. D., & Gilbank, D. G. 2008, ApJ, 683, 33
Kampczyk, P., et al. 2007, ApJS, 172, 329
Kartaltepe, J. S., et al. 2007, ApJS, 172, 320
Khochfar, S., & Burkert, A. 2003, ApJ, 597, L117
Khochfar, S., & Burkert, A. 2005, MNRAS, 359, 1379
Khochfar, S., & Silk, J. 2009, MNRAS, 397, 506
Kitzbichler, M. G., & White, S. D. M. 2009, MNRAS, 391, 1489
Lewis, I. J., et al. 2002, MNRAS, 333, 279
Lin, L., et al. 2008, ApJ, 681, 232
Lpez-Sanjuan, C., Balcells, M., Pèrez-González, P. G., Barro, G., Garca-Dabó, C. E., Gallego, J., & Zamorano, J. 2009, A&A, 501, 505
Lotz, J. M., et al. 2008, ApJ, 672, 177
Masjedi, M., Hogg, D. W., & Blanton, M. R. 2008, ApJ, 679, 260
Masjedi, M., et al. 2006, ApJ, 644, 54

McIntosh, D. H., Guo, Y., Hertzberg, J., Katz, N., Mo, H. J., van den Bosch, F. C., & Yang, X. 2008, MNRAS, 388, 1537
Naab, T., Johansson, P. T., Ostriker, J. H., & Efstathiou, G. 2007, ApJ, 658, 710
Naab, T., Khochfar, S., & Burkert, A. 2006, ApJ, 636, L81
Neistein, E., & Dekel, A. 2008, MNRAS, 388, 1792
Norberg, P., et al. 2002, MNRAS, 332, 827
Parry, O. H., Eke, V. R., & Frenk, C. S. 2009, MNRAS, 396, 1972
Patton, D. R., & Atfield, J. E. 2008, ApJ, 685, 235
Patton, D. R., Carlberg, R. G., Marzke, R. O., Pritchet, C. J., da Costa, L. N., & Pellegrini, P. S. 2000, ApJ, 536, 153
Patton, D. R., et al. 2002, ApJ, 565, 208
Roseboom, I. G., et al. 2006, MNRAS, 373, 349
Scarlata, C., et al. 2007, ApJS, 172, 494
van Dokkum, P. G. 2005, AJ, 130, 2647
van Dokkum, P. G., Franx, M., Fabricant, D., Kelson, D. D., & Illingworth, G. 1999, ApJ, 520, L95
van Dokkum, P. G., Stanford, S. A., Holden, B. P., Eisenhardt, P. R., Dickinson, M., & Elston, R. 2001, ApJ, 552, L101
Wake, D. A., et al. 2006, MNRAS, 372, 537
Wake, D. A., et al. 2008, MNRAS, 387, 1045
Wen, Z. L., Liu, F. S., & Han, J. L. 2009, ApJ, 692, 511
White, M., Zheng, Z., Brown, M. J. I., Dey, A., & Jannuzi, B. T. 2007, ApJ, 655, L69
Yee, H. K. C., et al. 2000, ApJS, 129, 475
York, D. G., et al. 2000, AJ, 120, 1579