Ongoing assembly of massive galaxies by major merging in large groups and clusters from the SDSS

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ABSTRACT

We investigate the incidence of major mergers creating massive (M_{star} > 10^{11} M_{\odot}) galaxies in present-day (z \leq 0.12) groups and clusters. Using a volume-limited sample of 845 groups with dark matter halo masses above 2.5 \times 10^{13} M_{\odot}, we isolate 221 galaxy pairs with \leq 1.5 r-band magnitude differences, \leq 30 kpc projected separations and combined masses above 10^{11} M_{\odot}. We fit the r-band images of each pair as the line-of-sight projection of symmetric models and identify 38 mergers by the presence of residual asymmetric structure associated with both progenitors, such as non-concentric isophotes, broad and diffuse tidal tails and dynamical friction wakes. In other words, at the resolution and sensitivity of the Sloan Digital Sky Survey (SDSS), 16 per cent of massive major pairs in dense environments have mutual tidal interaction signatures; relying on automated searches of major pairs from the SDSS spectroscopic galaxy sample will result in missing 70 per cent of these mergers owing to spectroscopic incompleteness in high-density regions. We find that 90 per cent of these mergers are between two nearly equal-mass progenitors with red-sequence colours and centrally concentrated morphologies, in agreement with numerical simulations that predict that an important mechanism for the formation of massive elliptical galaxies is the dissipationless (gas-poor or so-called dry) major merging of spheroid-dominated galaxies. We identify seven additional massive mergers with disturbed morphologies and semiresolved double nuclei; thus, 1.5 \pm 0.2 per cent of M_{star} \geq 5 \times 10^{10} M_{\odot} galaxies in large groups are involved in the major merger assembly of massive galaxies. Mergers at the centres of these groups are more common than between two satellites, but both types are morphologically indistinguishable and we tentatively conclude that the latter are likely located at the dynamical centres of large subhaloes that have recently been accreted by their host halo. Based on reasonable assumptions, the centres of group and cluster-sized haloes are gaining stellar mass at a rate of 2–9 per cent per Gyr on average. Our results indicate that the massive end of the galaxy population continues to evolve hierarchically at a measurable level, and that massive mergers are more likely to occur in large galaxy groups than in massive clusters.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: formation – galaxies: interactions.

1 INTRODUCTION

Understanding the formation of massive galaxies (M_{star} > 10^{11} M_{\odot}) remains an important challenge in astrophysics. The tip of the stellar mass function is dominated by elliptical galaxies with intrinsically spheroidal mass distributions that are supported by anisotropic stellar motions (Kormendy & Bender 1996; Burstein et al. 1997). Numerical simulations have long demonstrated that ‘major’ mergers between smaller galaxies of comparable mass could produce the observed shapes and dynamics of ellipticals (Toomre 1977; Barnes & Hernquist 1996; Naab & Burkert 2003; Cox et al. 2006). Moreover, massive ellipticals are found in greater abundance in high-density structures like large groups and clusters of galaxies (e.g. Dressler 1980; Postman & Geller 1984; Hashimoto & Oemler 1999; Smith

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et al. 2005), which naturally grow through the hierarchical merging of dark matter haloes over cosmic time as expected in the ΛCDM cosmological model (Blumenthal et al. 1984; Davis et al. 1985; Cole et al. 2000). There is, therefore, a clear expectation for galaxy–galaxy and halo–halo merging to be physically linked (Hopkins et al. 2006; Maller et al. 2006; De Lucia & Blaizot 2007). Indeed, modern galaxy formation models predict that massive ellipticals form by major dissipationless (so-called ‘dry’) merging of likewise spheroidal and gas-poor progenitors (Boylan-Kolchin, Ma & Quataert 2006; Naab, Kohofar & Burkert 2006a), that a large fraction of today’s massive ellipticals had their last major merger since redshift $z = 0.5$ (e.g. De Lucia et al. 2006), and that the most massive systems form at the centres of large dark matter haloes (Aragon-Salamanca, Baugh & Kauffmann 1998; Dubinski 1998). Yet, direct evidence for the major merger assembly of massive galaxies at present times has been lacking, and finding such systems is needed to place constraints on their rates, progenitor properties and environmental dependencies. To this end, we look for close pairs of massive interacting galaxies within a complete and well-defined sample of over 5000 galaxies with $z < 0.12$ and $M_{\text{star}} \geq 5 \times 10^{10} M_\odot$, selected from galaxy groups in the Sloan Digital Sky Survey (SDSS) with dark matter halo masses above $M_{\text{halo}} = 2.5 \times 10^{13} M_\odot$.

Ellipticals galaxies make up the bulk of the massive end of the red-sequence population with optical colours indicative of their non-star forming and old stellar nature. Despite a quiet star formation history over the last 6–8 billion years (Bell et al. 2005), the total stellar mass density on the red sequence has roughly doubled over this interval (Bell et al. 2004b; Borch et al. 2006; Blanton 2006; Brown et al. 2007; Faber et al. 2007) and now accounts for more than half of the present-day budget (Hogg et al. 2002; Bell et al. 2003), providing strong observational evidence for the ongoing hierarchical growth of the massive galaxy population. These results were derived from red galaxy number densities over a wide range of stellar masses above and below $10^{11} M_\odot$. Owing to the scarcity of the highest mass galaxies, cosmic variance and systematic uncertainties in stellar mass estimates, any increase in the number density of $M_{\text{star}} > 10^{11} M_\odot$ galaxies is poorly constrained, resulting in controversy over whether this population has continued to grow slowly (e.g. Brown et al. 2007) or has been effectively static (e.g. Scarlata et al. 2007), since $z \sim 1$.

Besides number density evolution, mergers of sufficiently massive galaxies could provide a more clear indication for some continued stellar mass growth in the high-mass galaxy population. The existence of a handful of massive red mergers over the redshift interval $0.1 < z < 0.9$ (van Dokkum et al. 1999; Tran et al. 2005; Bell et al. 2006a; Rines, Finn & Vikhlinin 2007; Lotz et al. 2008) proves that the growth is non-zero at high stellar masses and implies that this mechanism does contribute to the assembly of galaxies at the top of the food chain. Yet, the importance of this process and the related rate of mass growth are highly uncertain given the tiny samples over this large cosmic time interval. Indirect measures such as the presence of faint tidal debris or shells around many local massive ellipticals (Mihos et al. 2005; van Dokkum 2005), the isophotal properties of giant ellipticals (Kang, van den Bosch & Pasquali 2007), the lack of evolution of the stellar mass–size relation of red spheroids since $z = 1$ (McIntosh et al. 2005) and the lack of morphological evolution on the red sequence since $z = 0.7$ (Bell et al. 2004a) provide a variety of limits to the importance of dissipationless mergers. Perhaps the most powerful method for obtaining estimates for the stellar mass growth rate via major merging is based on small-scale clustering statistics that provide an accurate measurement of close pair frequencies in real space (Bell et al. 2006b; Masjedi et al. 2006; Masjedi, Hogg & Blanton 2008). However, this method likely yields an overestimate of the merger frequency because it assumes that all close pairs will merge. All estimates of merger-driven growth rates are limited by uncertainties in the time interval over which a pair will merge, and over what duration an object could be identified as interacting. Masjedi et al. (2008) find a very small growth rate ($1–2$ per cent per Gyr) at $z \sim 0.25$ for major mergers involving at least one progenitor drawn from the SDSS Luminous Red Galaxy sample (LRG; Eisenstein et al. 2001); LRGs have typical masses of several times $10^{11} M_\odot$. To date there remains no direct evidence of ongoing merger-driven assembly of massive galaxies at $z < 0.1$, and the LRG result implies that this formation process is no longer important. These facts motivate a thorough search for the existence/non-existence of ongoing examples in the present-day Universe.

While the aforementioned statistical method for finding close physical pairs is powerful, it does not isolate actual merging systems and thus provides no information on the progenitor properties of massive merger remnants. Recent numerical simulations and models make a range of predictions regarding the progenitor morphologies at the time of the last major merger (Kochofar & Burkert 2003; Naab et al. 2006a; Kang et al. 2007), yet robust observational constraints are missing for $M_{\text{star}} > 10^{11} M_\odot$ systems. Many studies have identified major merger candidates by either close pairs (Carlberg, Pritchet & Infante 1994; Carlberg et al. 2000; Patton et al. 2000, 2002; Bundy et al. 2004; Lin et al. 2004) or disturbed morphologies (Le Fèvre et al. 2000; Conselice et al. 2003; Jogee et al. 2008; Lotz et al. 2008), but these samples mostly contain major mergers between lower luminosity galaxies that tend to be gas-rich spiral discs. Numerical simulations show that such dissipative merging of disc galaxies will not produce massive pressure-supported ellipticals (e.g. Naab, Jesseit & Burkert 2006b). As mentioned above, only circumstantial evidence and a small number of red galaxy pairs with $z < 0.9$ support the existence of mergers likely to produce massive ellipticals. Our understanding of the progenitors is therefore very limited. Here, we present a thorough census of 38 massive merger pairs from SDSS, providing an order of magnitude increase in the number of such detections at $z < 0.5$ and allowing an improved understanding of their progenitor properties.

While many estimates of major merger rates are found in the literature, to date no measure of the environmental dependence of merger-driven mass growth has been attempted. In the standard cosmological model, there is a trade off between the expansion of the Universe and the gravitational collapse of dark and luminous matter. Therefore, the rate at which stellar mass is assembled at the centres of the largest dark matter haloes over recent cosmic history is a fundamental aspect of the ongoing formation of large-scale structure, and the rate that high-mass galaxies form by mergers as a function of halo mass constrains galaxy formation theories. Some theories predict that the mergers producing massive ellipticals occur preferentially in groups rather than in high-density cluster or low-density field environments because the smaller velocity dispersions allow more galaxy interactions (Cavaliere, Colafrancesco & Menci 1992); also dynamical friction is more efficient in lower mass haloes (e.g. Cooray & Milosavljevic 2005). Others predict that the brightest cluster galaxies (BCGs) grow by hierarchical merging (‘galactic cannibalism’) at the centres of the dark matter potential wells of large clusters (Ostriker & Tremaine 1975; Merritt 1985; Dubinski 1998; Cooray & Milosavljevic 2005). A handful of low-redshift BCGs show multiple nuclei suggesting cannibalism in the form of...
multiple minor mergers (Lauer 1988), but there are no observations of major mergers at the centres of clusters. In this paper we make use of the statistically large SDSS group catalogue (Weinmann et al. 2006; Yang et al. 2005) to show that major mergers occur in present-day dense environments, and to explore the halo-mass dependence and central/satellite identity of merger-driven massive galaxy assembly.

Throughout this paper, we calculate comoving distances in the $\Lambda$CDM concordance cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and assume a Hubble constant of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. SDSS magnitudes are in the AB system.

### 2 SAMPLE SELECTION

We exploit the large number statistics of the SDSS (York et al. 2000) to search for elusive pairs of massive galaxies undergoing major merging in dense group and cluster environments. With large surveys of spectroscopic redshifts and imaging data, astronomers are for the first time able to study galaxies according to their membership and position within dark matter haloes (i.e. galaxy groups). To this end, we make use of the SDSS DR2 group catalogue\(^1\) (Weinmann et al. 2006), which was constructed by applying the Yang et al. (2005) halo-based group finder to the New York University Value-Added Galaxy Catalogue (NYU-VAGC, Blanton et al. 2005). The NYU-VAGC is an improved processing of the spectroscopic main galaxy sample (Strauss et al. 2002), in this case from the SDSS DR2 (Abazajian et al. 2004). As described in detail below, our sample selection consists of (i) a complete and mass-limited set of large haloes drawn from the group catalogue, (ii) the subset of massive galaxy pairs within these groups that meet the stellar mass criteria of $M_1 + M_2 > 10^{13}$ M$_\odot$ and (iii) the identification of merger candidates among the massive pairs.

#### 2.1 Large haloes from the SDSS group catalogue

Weinmann et al. (2006) extracted 53 229 groups from an initial sample of 184 425 NYU-VAGC galaxies with $0.01 < z \leq 0.20$ better than 70 per cent redshift completeness and apparent magnitudes of $r < 17.77$ (extinction corrected). A detailed description of the halo-based group finder is given in Yang et al. (2005). We note that using detailed mock galaxy redshift surveys, the average completeness in terms of true membership of individual groups was found to be $\approx 90$ per cent, with $<20$ per cent contamination by interlopers. The groups span a halo-mass range of $11.8 < \log_{10}(M_{\text{halo}}/M_\odot) < 15.5$ and contain 92 315 galaxies. As described in Weinmann et al. (2006), halo masses for each identified group were estimated by matching the rank ordered group luminosities to the halo-mass function corresponding to a flat $\Lambda$CDM cosmology with $\Omega_m = 0.3$ and $\sigma_8 = 0.9$. This estimation assumes a simple one-to-one relation between group luminosity and mass. According to the tests with mock galaxy surveys, these halo masses have an estimated standard deviation of about 0.3 dex. Moreover, these masses are more reliable than those based on the velocity dispersion of the group members, especially when the number of group members is small.

For our analysis, the group catalogue provides two important environmental measures for every member galaxy: (i) an estimate of the virial mass ($M_{\text{halo}}$) of the host halo and (ii) a distinction between central (CEN) and satellite (SAT) galaxies. Throughout, a CEN galaxy is defined as the brightest member of its group. As discussed in detail in Weinmann et al. (2006), these quantities allow more physically meaningful discussions of the dependencies of galaxy properties on the environment than do on projected number densities.

Owing to the magnitude limit of the galaxy sample, the completeness of the group catalogue depends on both halo mass and redshift. In detail, the catalogue is complete for groups with $\log_{10}(M_{\text{halo}}/M_\odot) > 11.86$ to $z = 0.06$, $\log_{10}(M_{\text{halo}}/M_\odot) > 12.19$ to $z = 0.12$ and $\log_{10}(M_{\text{halo}}/M_\odot) > 13.09$ to $z = 0.20$. We exclude haloes with $0.12 < z \leq 0.20$ to avoid resolution limitations. At $z = 0.12$, the SDSS resolution of 1.4 arcsec corresponds to 3 kpc, thus fairly massive galaxies will be only semiresolved. Moreover, unreliable photometry is known to occur in SDSS for galaxies separated by $<3$ arcsec (Masjedi et al. 2006), which corresponds to 7–10 kpc over the $0.12 < z \leq 0.20$ interval. We find many close pairs with physical separations less than 10 kpc, thus our redshift cut avoids selecting a large fraction of close pairs with poor photometry.

We further limit our selection to haloes that have at least three spectroscopic members to allow for a complete search of massive pairs associated with either CEN or SAT galaxies. This restricts our final sample to all SDSS DR2 groups with masses of $\log_{10}(M_{\text{halo}}/M_\odot) \geq 13.4$ ($0.01 < z \leq 0.06$) and $\log_{10}(M_{\text{halo}}/M_\odot) \geq 13.8$ ($0.06 < z \leq 0.12$). Hence, our selection is halo-mass limited at values significantly larger than the group catalogue completeness limits. We plot the halo mass and redshift distribution of our final sample in Fig. 1, which contains 845 groups with masses ranging from one-tenth to ten times that of the Virgo cluster.

#### 2.2 Massive major pairs of galaxies

The primary goal of our study is to find whether evidence exists for the major merger assembly of massive ($M_{\text{star}} > 10^{11}$ M$_\odot$) galaxies in dense environments. We approach this by first searching the membership of our large group sample for high-mass galaxies that have a major companion (mass ratios between 4:1 and 1:1) with a

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\(^1\) Public access to the group catalogue is at http://www.astro.umass.edu/~xhyang/Group.html.
maximum 30 kpc projected separation. It is important to keep in mind that these companions are neither restricted to be in the SDSS spectroscopic main sample nor in the group catalogue. We then use an image decomposition technique, as described in Section 2.3, to identify the pairs that exhibit signs of tidal interaction associated with an ongoing merger.

We estimate stellar masses \( M_{\text{star}} \) in \( M_\odot \) units for all group members under the assumption of a Kroupa (2001) initial mass function and using the Bell et al. (2003) colour-based stellar M/L ratios as follows:

\[
\log_{10} M_{\text{star}} = -0.456 + 1.097^{0.9}(g-r) - 0.4 \left( 0.9 M_r - 4.67 \right),
\]

where \( g \) and \( r \) are Petrosian magnitudes from the NYU-VAGC (random uncertainties \( < 0.03 \) mag) that were \( K \)-corrected to \( z = 0 \) using the method in Blanton et al. (2003a) and corrected for Milky Way extinction using the Schlegel, Finkbeiner & Davis (1998) dust maps. For galaxies with early-type morphologies, we correct \( M_r \) by \(-0.1 \) mag for missing flux (Blanton et al. 2003b). We use the \( r \)-band central-light concentration \( (R_{50}/R_{90}) \), defined by the ratio of the radii containing 90 and 50 per cent of the Petrosian flux, to coarsely separate early-type \( (R_{50}/R_{90} \geq 2.6); \) spheroid dominated \( R_{50}/R_{90} < 2.6 \); disc-dominated) galaxies as others have with SDSS data (e.g. Strateva et al. 2001; Hogg et al. 2002; Bell et al. 2003; Kauffmann et al. 2003). The Bell et al. stellar M/L ratios have 20 per cent random uncertainties and a 0.10–0.15 dex systematic error caused by a combination of effects including dust, stellar population ages and bursts of star formation. The characteristic stellar mass of the local galaxy mass function from Bell et al. (2003) is \( M^* = 7.24 \times 10^{10} M_\odot \).

To find all major pairs that might be \( > 10^{11} M_\odot \) mergers, we start with the 5376 group members that have \( M_{\text{star}} \geq 5 \times 10^{10} M_\odot \) (hereafter sampM). We plot the colour versus stellar mass distribution of sampM in Fig. 2. The contours represent all SDSS DR2 main galaxies with \( z \leq 0.12 \). The halo-mass limited sample of 845 CEN galaxies from sampM is shown as red and blue circles separated by the red-/blue-sequence boundary adapted from Weinmann et al. (2006). The 4531 SATs from sampM are plotted as black solid points. Not surprising, the vast majority of high-mass galaxies in large groups (both CEN and SAT) have red-sequence colours. We compare the galaxy content of sampM with that of the DR2 within the \( z \leq 0.12 \) volume in Table 1.

We use the SDSS Image List Tool\(^2\) as a virtual observatory to visually examine an \( 80 \times 80 \) kpc region centred on each galaxy in sampM, which allows us to view the full extent of each galaxy in a 30 kpc pair. Although more time-consuming, this method ensures that we find all major companions that could produce a \( \geq 10^{11} M_\odot \) remnant, including those without SDSS spectroscopic data and those that have masses below the sampM cut. In addition, our examination allows the identification of individual (non-pair) sources with highly disturbed morphologies suggestive of ongoing major mergers, which cannot be found with automated pair selection. We find seven morphologically identified mergers that have semiresolved double nuclei with projected separations too close to be accurately deblended by the SDSS (Fig. 3).

We find that 221 galaxies in sampM have a major companion with a projected separation of \( d_{12} \leq 30 \) kpc (centroid-to-centroid). Operationally, we use an apparent \( r \)-band magnitude difference of \( |\Delta M_r| \leq 1.5 \), corresponding to mass ratios \( \leq 4:1 \) assuming a constant M/L ratio, to identify major companions both with and without spectroscopic data. Throughout this paper, we use the following designations for projected pairs: galaxy number 1 is from sampM and galaxy number 2 is its projected companion, regardless of relative brightness or mass. In the cases where both galaxies have spectroscopic redshifts and are massive enough to be included in sampM, galaxy 1 is the primary (i.e. brightest) member and we remove from further analysis the duplicated pair initiated on galaxy number 2. The SDSS spectroscopy is known to be about 8 per cent incomplete overall, independent of galaxy luminosity. The main source of incompleteness results from the 55 arcsec minimum separation for fiber placement (i.e. ‘fiber collisions’) in the mechanical spectrograph (Blanton et al. 2003c). This selection effect leads to a slight systematic under representation in regions of high galaxy number density (Hogg et al. 2004), such as in large groups and clusters. Less than one-third of the 221 pairs have spectra for both galaxies (i.e.

\[
\begin{array}{llllll}
\text{per cent of DR2 total} & 0.1 & 2.3 & 23.7 & 69.7 \\
\text{Satellites in sampM} & 3209 & 1174 & 139 & 5 \\
& 11.3 & 11.0 & 7.2 & 3.0 \\
\end{array}
\]

\(\text{Table 1. Galaxy content in sampM and the } z \leq 0.12 \text{ SDSS DR2 volume.}\)

\(\text{stellar mass bins}\)

\(\text{[10.7,11.0]} \quad [11.0,11.3] \quad [11.3,11.6] \quad [11.6,11.9] \)

\(\text{Total in DR2 volume}\)

\(28377 \quad 10600 \quad 1943 \quad 165 \)

\(\text{Per cent}\)

\(83.4 \quad 92.1 \quad 97.6 \quad 99.4 \)

\(\text{Red sequence}\)

\(23657 \quad 9846 \quad 1897 \quad 164 \)

\(\text{Per cent}\)

\(92.0 \quad 93.9 \quad 97.8 \quad 99.2 \)

\(\text{Total in sampM}\)

\(3238 \quad 1415 \quad 599 \quad 120 \)

\(\text{Red sequence}\)

\(2979 \quad 1329 \quad 586 \quad 119 \)

\(\text{Per cent}\)

\(92.0 \quad 93.9 \quad 97.8 \quad 99.2 \)

\(\text{Centrals in sampM}\)

\(29 \quad 241 \quad 460 \quad 115 \)

\(\text{Per cent}\)

\(92.0 \quad 93.9 \quad 97.8 \quad 99.2 \)

\(\text{Satellites in sampM}\)

\(3209 \quad 1174 \quad 139 \quad 5 \)

\(\text{Per cent}\)

\(92.0 \quad 93.9 \quad 97.8 \quad 99.2 \)

\(\text{Total in sampM}\)

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\(\text{Per cent}\)

\(92.0 \quad 93.9 \quad 97.8 \quad 99.2 \)

\(\text{Note. Bins of stellar mass are in units of } \log_{10}(M_\odot).\)

\(\text{Figure 2. Rest-frame optical colour versus stellar mass plot for our selection of high-mass members (sampM) from a halo mass-limited sample of large SDSS DR2 groups. Grey-scale contours show all SDSS (DR2) galaxies with } 0.01 < z \leq 0.12 \text{; each contour represents a three-fold increase in the number of galaxies. The solid red line is the red-/blue-sequence separation adapted from Weinmann et al. (2006). Blue and red circles denote the subset of 845 CEN galaxies, and black solid points denote the 4531 satellites. The vertical arrow indicates } M^* \text{ from Bell et al. (2003).}\)

redshifts for galaxies number 1 and 2, hereafter spec–spec pairs).

In what follows, we will show that an important fraction of all pair-identified massive mergers have only one spectroscopic progenitor (i.e. spec–spec pairs).

Close pairs of galaxies are used often to infer information about galaxy merging (e.g. Carlin et al. 2000; Patton et al. 2000; Le Fèvre et al. 2000; Patton et al. 2002; Bundy et al. 2004; Lin et al. 2004; Bell et al. 2006b). These studies use a range of definitions, which usually include tight limits on both velocity and projected spatial separations (typically <500 km s$^{-1}$ and 10–50 kpc), and do not use further knowledge such as the halo mass or the position relative to the group centre. Our choice of $d_{12} \leq 30$ kpc separations is rather arbitrary and we have no way of knowing ab initio whether or not it will include all massive pairs that show obvious signs of interaction. Owing to our larger 80 $\times$ 80 kpc field of view, we effectively search within a projected radius of 40 kpc around each galaxy in sampM, which enables us to find three additional wide–separation ($d_{12} > 30$ kpc) pairs that exhibit strong merging signatures. The maximum projected separation of the additional mergers is 37 kpc. The minute frequency of 30 $< d_{12} < 40$ kpc pairs with strong tidal signatures in these groups suggests that wider-separation systems will not be apparent in SDSS-depth imaging data. We include only pairs with $d_{12} \leq 30$ kpc for our projected pair statistics, but include the three additional merger pairs in our progenitor and mass assembly statistics.

Our sample includes three pairs with 2–3 arcsec separations, which are a potential source of systematic bias in our major pair selection. As mentioned above, Masjedi et al. (2006) showed that the SDSS photometric pipeline boosts the recovered flux of individual galaxies in very close pairs. For equal-luminosity galaxies separated by 5–20 arcsec, the excess is only about 5 per cent, but this quickly rises to 20 per cent at 3 arcsec separation. Moreover, the pipeline has trouble deblending very close pairs as is evident in Fig. 3. We do not attempt to separate the progenitors of these mergers, instead we assume that they represent major mergers and we explicitly state where we include them in our analysis.

Finally, the subset of 64 major spectroscopic pairs in sampM allows us the unique opportunity to test the frequency of interlopers in large groups. We find that 25 per cent of the spectroscopic pairs (2 CEN-SAT, 14 SAT–SAT) are comprised of projected galaxies in two separate groups with average absolute velocity separation $\langle|\Delta v_{12}|\rangle = 7550$ km s$^{-1}$. If we limit our analysis to spectroscopic pairs with $d_{12} \leq 30$ kpc and $\langle|\Delta v_{12}|\rangle \leq 500$ km s$^{-1}$, we find 5 per cent contamination from interlopers in basic agreement with Berrier et al. (2006), who used mock galaxy catalogues from cosmological simulations to demonstrate that 10–50 kpc pairs (14–71 kpc in our assumed cosmology) with less than 500 km s$^{-1}$ separation reside in the same halo with a low (5–20 per cent) contamination from projected interlopers. Overall, the spectroscopic pairs from sampM that live in the same group have absolute velocity differences spanning 10 to 1560 km s$^{-1}$ with means of 260 km s$^{-1}$ (CEN-SAT) and 360 km s$^{-1}$ (SAT–SAT). Many of these pairs are likely doomed to merge, yet some may still be chance projections on opposite sides of the same group. We feel that the most conservative approach to locating physically interacting pairs is to look for morphological signs of disturbance, an approach that we adopt and discuss in the next section.

### 2.3 Identifying major mergers

Besides pair statistics, major galaxy mergers are routinely identified by their highly disturbed appearance (e.g. Le Fèvre et al. 2000; Conselice et al. 2003; Jogee et al. 2008; Lotz et al. 2008). Tidal tails and debris, multiple nuclei, strong asymmetries and other morphological peculiarities are common features in both observations and in simulations of galaxy collisions (Toomre & Toomre 1972; Barnes 1988; Barnes & Hernquist 1992; Dubinski, Mihos & Hernquist 1996; Barnes & Hernquist 1996; Mihos 2001). Yet, distinguishing major mergers from lower mass ratio ‘minor’ interactions using morphology alone is fraught with uncertainties. For example, depending on the orbital geometry, a 10:1 gas-rich merger can result in a more disturbed morphology than an encounter between two high-mass ellipticals, which have broad low-surface brightness features (Bell et al. 2006a). We circumvent this issue by selecting major pairs of high-mass galaxies first, and then fitting symmetric models to the light profiles of each galaxy in each major pair and identifying interaction signatures in the residual (data $-$ model) image. Our methodology is similar in spirit to that of Lauer (1986, 1988), who modelled BCGs with multiple nuclei as the line-of-sight superpositions of normal elliptical galaxies.

For each major pair in sampM, we use GALFIT (Peng et al. 2002) to fit the surface photometry of both galaxies and any other close companions in the SDSS r-band image data. For each fit, we use the global background estimate provided in the SDSS image header. The details of our fitting pipeline developed for SDSS imaging will be presented in Guo et al. (in preparation). Asymmetries commonly associated with galaxy mergers (e.g. tails, bridges, plumes, non-concentric isophotes, diffuse excess structure and dynamical friction wakes) are not well fit by symmetric models centred on the galaxy. Therefore, to isolate and highlight asymmetries in the residual image we use either a single-component Sérsic or a two-component Sérsic bulge plus exponential disc model for each source, depending on whether or not disc features such as spiral arms, rings or bars are apparent. We classify any major pair as a merger if there are...
Examples of two galaxy pairs with small projected separations but large physical separations; that is, the two galaxies reside in different groups and are thus not physically associated. Panels: (left-hand side) $r$-band SDSS image in arbitrary false colour, logarithmic scale to highlight low-surface brightness features, (middle) GALFIT symmetric model profile and (right-hand side) data–model residual. We identify merging galaxies by the presence of asymmetric residual flux associated with each individual galaxy (see the text for details). These two examples are among the subset of 16 null (interloper) cases, none of which meet our merger identification criteria. Some interloper pairs have one galaxy with detectable residuals for a variety of reasons other than an interaction between the two galaxies. We show the strongest residual cases here to illustrate the most common cause, which is the spiral structure. Each image is 80 x 80 kpc and we provide the NYU-VAGC DR2 identification number (NYU ID) in the upper left-hand panel.

We find 38 pairs of high-mass galaxies in sampM that we classify as major mergers (35 with $d_{12} \lesssim 30$ kpc). We display the SDSS $r$-band image and corresponding GALFIT residual of each merger in increasing redshift order (left- to right-hand panel) in Fig. 6. These images leave little doubt that the two galaxies in each pair are in the midst of merging. We find a variety of strong tidal features including broad tails (e.g. 311008, 352171 and 274752) such as seen during the period between second close passage and final coalescence in dissipationless merger simulations (Naab et al. 2006a) and observations (see fig. 1, Bell et al. 2006a), and dynamical friction wakes in the outer stellar envelopes (e.g. 367419 and 258681) as predicted by Weinberg (1986) and hinted at in a few BCG systems by (Lauer 1988). In addition, we find bridges (e.g. 301558 and 371303), plumes (e.g. 150206 and 261132), diffuse structure (e.g. 294450 and 9993) and many examples of non-concentric isophotes (e.g. 392792, 222852 and 373137), which present the strongest indications for tidal contact (Lauer 1988). In Fig. 7, we show 10 examples of close (spec–phot) pairs that have no residual asymmetries and are likely the result of chance projections. Comparing these non-interacting examples with the 38 mergers in Fig. 6 clearly demonstrates the fidelity of our merger identification scheme. As the sensitivity of the SDSS imaging may be too low to detect all massive pairs of interacting galaxies, our classifications provide a conservative lower limit. Nevertheless, our sample identifies the strongest cases and serves as an important data set for studying the properties of massive merger progenitors in Section 3.2.

Nearly 70 per cent (26) of these massive mergers have redshift information for only one progenitor (spec–phot pairs) as a result of fiber collisions, which highlights the importance of our thorough approach for identifying such systems. We estimate that we could be missing an additional four (11 per cent) mergers that are photometric–photometric sources based on the 34 per cent (26/76) of progenitor galaxies that have only SDSS photometry. Quantifying the exact number of massive phot–phot mergers in the DR2-based group catalogue is beyond the scope of this paper. An improved understanding of the completeness of pairs of merging galaxies in SDSS groups is one of the aims of our next paper.

3 PROPERTIES OF MASSIVE MERGERS IN GROUPS AND CLUSTERS

In this section, we explore the properties of the $M_{\text{vir}} > 10^{11} M_\odot$ mergers that we identify from a complete sample of $\leq 4:1$ mass ratio pairs residing in large SDSS groups and clusters. We compare the distributions of basic observables for merger pairs and major pairs not classified as mergers, quantify the nature of the merger...
progenitors, make predictions about the remnants, and look for environmental dependencies in this merging population.

### 3.1 Basic observables

In Fig. 8, we plot the normalized distributions of basic observables that describe each massive major pair we selected in Section 2.2. Here, we compare the subsets of 35 mergers \(d_{12} \leq 30 \text{ kpc} \) (bold lines), 16 interlopers (i.e. definite non-interacting; hatched bins) and the remaining 170 we classify as non-interacting (grey bins). It is important to note that a simple selection of massive major pairs in local, dense environments yields only 16 per cent with obvious merger signatures in SDSS imaging. We find that the pairs that we identify as mergers have some minor differences compared to those without interaction signatures. Likewise, merging galaxies obviously residing in the same group are different from projected pairs of galaxies that reside in distinct host haloes.

In general, the merger pairs have a flatter \(\Delta r_{12} \) distribution than non-interacting pairs, with more systems near \(\Delta r_{12} = 0\), the proxy for equal-mass mergers, in contrast to the increasing number of non-mergers towards larger magnitude offsets as expected for a simple projected pair sample. We address the prevalence of near equal-mass mergers in Section 3.2.2. Nevertheless, there is no statistical difference between the \(\Delta r_{12} \) distributions of mergers and the subset of known interlopers. Recall that we select pairs with \(|\Delta r_{12}| \leq 1.5\), but here we show the \(\Delta r_{12} \) distribution to illustrate that some spec–phot pairs have \(\Delta r_{12} > 0\); i.e. the source without SDSS spectroscopy is more massive.

Pairs of merging galaxies have an angular separation \(\theta_{\text{sep}}\) distribution that is skewed a bit more towards smaller separations compared with non-interacting pairs and interlopers. In terms of the colours and concentrations of galaxies in pairs, we find little difference between the merging and non-interacting subsets. Owing to our selection bias for red galaxies (see Fig. 2) and their stronger clustering (e.g. Zehavi et al. 2002), it is not surprising that the colour difference \(\Delta (g - r)_{12} = (g - r)_1 - (g - r)_2\) distributions are narrow and peaked near zero. Likewise, given the broad range of concentrations \((2 < R_{90}/R_{50} < 4)\) found for SDSS main galaxies (e.g. Hogg et al. 2002), the relatively small concentration differences \(\Delta (R_{90}/R_{50})_{12}\) are consistent with matched morphologies of similarly red galaxies. We note a mild difference between the \(\Delta (g - r)_{12}\) and \(\Delta (R_{90}/R_{50})_{12}\) distributions of merging and interloper subsets, such that the physically unassociated pairs have an increased chance of being composed of a red group member with a blue, later type projected companion.

We check whether or not any of the basic pair properties in Fig. 8 depend on the redshift \(z_1\) or stellar mass \(M_1\) of the pair member from sampM. Only \(\theta_{\text{sep}}\) depends on \(z_1\), as expected for a sample...
Figure 6. The full sample of 38 massive major mergers identified in a halo-mass limited subset of SDSS DR2 groups with $z \leq 0.12$ (sampM). The three pairs (301558, 83539 and 284077) have projected separations between $30 < d_{12} < 37$ kpc. We identify these merging systems when both galaxies have asymmetric residual features in excess of 24.5 mag arcsec$^{-2}$. Such asymmetries are associated with tidal signatures (e.g. tails, bridges, plumes, non-concentric isophotes, diffuse excess structure and dynamical friction wakes) of mutual encounters between two galaxies. For each pair, we provide the $r$-band data in false colour (arbitrary scaling) at the left-hand panel, and the data-model residual at the right-hand panel. To highlight low-surface brightness features, we Gaussian smoothed (using a 1 pixel sigma) the residual images of each, except for 301558, 250588, 278870, 352171, 392792, 371303, 44192, 392792, 371303, 11349, 241625 and 274752. All images are $80 \times 80$ kpc with the NYU ID and spectroscopic redshift given.

limited to 30 kpc maximum projected separations. The different subsets (mergers, interlopers, non-interacting) are independent of $z_1$ and $M_1$, and hence we conclude that the initial selection of sampM did not impart biases on our ability to classify mergers in a larger sample of major pairs. Moreover, despite the minor differences we find between the observables of merging and non-interacting galaxy pairs, we cannot distinguish these subsets of major pairs based on these differences alone.

As we mentioned in Section 2.2, a spectroscopic close pair of galaxies that belong to the same host halo may reside on opposite
sides of the group, and thus have a much larger real-space separation than their projected separation implies. On the other hand, merger pairs by definition must be in close physical proximity. As such, for pairs where both galaxies are members of the same group, we compare in Fig. 9 the merging and non-interacting subsets in terms of their magnitude differences, and their projected spatial ($d_{12}$) and velocity ($v_{12}$) separations. We find that the presence/absence of residual asymmetries clearly produces different $d_{12}$ distributions consistent with the non-interacting pairs being drawn from a much broader distribution of real-space separations than the mergers. Moreover, the declining number of mergers with increasing $d_{12}$ suggests that wider separation pairs do not typically include tidal distortions that are apparent in the SDSS imaging. Similarly, we find a more narrow distribution of $v_{12}$ for mergers compared to the non-interacting pairs in a matched group, but the significance of this is unclear owing to the large number of spec–phot mergers without $z_2$ measurements (25 out of 35). There is no substantial difference between $|\Delta r_{12}|$ for the two subsets.

3.2 Nature of progenitors

In the Introduction, we outlined the importance of improving our understanding of the progenitors of massive mergers. Here, we use concentration, rest-frame colour and stellar mass to explore the properties of the progenitor galaxies in our total sample of 38 mergers; we tabulate information for all 76 progenitors in Tables 2 (CEN-SATs) and 3 (SAT–SATs).

Two-thirds of the merger sample have spectroscopic information for only one of the progenitors as a result of fiber collisions (Section 2.3). To obtain rest-frame quantities for these companions, we use $K$-corrections downloaded from the SDSS PhotoZ table, which we then correct to the redshift of the merger; i.e. we
Figure 7. Examples of 10 spec–phot pairs in projection that show no signs of disturbance; the central galaxy of each panel has a spectroscopic redshift. These non-interacting pairs likely have much larger physical separations than their projected < 30 kpc separation suggests, and are either interlopers (separate groups) or well separated within a common halo. All images (r-band data—model, residual with log-scale stretch) are zoomed into 60 × 60 kpc, and are labelled as in Fig. 4.

Figure 8. Normalized distributions of observables for major (≤ 4:1 mass ratio) projected (≤ 30 kpc) pairs split into three subsets: 35 mergers (bold lines), 16 known interlopers (hatched bins) and the remaining 170 pairs without signs of interaction (grey bins). From left to right-hand side, we plot the extinction-corrected r-band Petrosian magnitude difference, angular separation, extinction-corrected (g − r) Petrosian colour difference and r-band concentration difference. All parameter differences are defined \( \Delta p = p_1 - p_2 \) such that one denotes the galaxy from sampM and two denotes the companion.

Assume \( z_2 = z_1 \). For all photometric sources in SDSS, PhotoZ provides photometric redshifts \( z_{\text{phot}} \) and related K-corrections \( K(z_{\text{phot}}) \) to shift quantities to \( z = 0 \). For our subset of merger pairs, we find that \( z_{\text{phot}} \) is systematically larger than \( z_1 \), and thus \( K(z_{\text{phot}}) \) is an overestimate. In the left-hand panel of Fig. 10, we show the g and r band \( K(z_{\text{phot}}) \) bias relative to \( K(z_2) \) for the 12 mergers in our sample where we have spectroscopic information for both galaxies. We estimate the correct K-correction for a given passband

\[
K(z_2) = K(z_{\text{phot}}) \frac{\log_{10}(1 + z_2)}{\log_{10}(1 + z_{\text{phot}})},
\]

(2)
Figure 10. $K$-corrections for $g$ (open triangles) and $r$ (solid triangles) passbands shifted to $z = 0$ for the subset of 12 companion galaxies in major-merger pairs where spectroscopic redshifts are available for both progenitors. We plot the accurate NYU-VAGC $K$-corrections versus those from PhotoZ (left-hand panel), corrected using (2) (middle panel) and the relative difference between the NYU-VAGC and our corrected values (right-hand panel); the error bars show the mean and scatter of the offsets in each passband.

by assuming $K(z) \propto 2.5 \log_{10}(1 + z)$. As we demonstrate in the middle and right-hand panels of Fig. 10, our method provides excellent $K$-correction estimates with a smaller than ±0.02 mag scatter, a −0.03 mag $g$-band offset and no $r$-band offset. In this manner, we obtain $0.0(g - r)$ and $M_{\text{star}}$ estimates for each photometric progenitor from its extinction-corrected colour downloaded from the SDSS PhotoTag table.

Among the SAT–SAT mergers, there are three spec–phot pairs (336039, 364190 and 373137) where the photometric progenitor is more massive than the host group’s central (brightest) galaxy. We, therefore, assume that this galaxy is in fact the CEN and add these pairs to the CEN-SAT merger subset. Our final sample of 38 massive pairs of merging galaxies includes 21 CEN-SAT and 17 SAT–SAT systems. We distinguish between the CEN-SAT and the SAT–SAT mergers in the remaining plots.

3.2.1 Progenitor morphology

We explore the colour and concentration of the progenitor galaxies in massive mergers in Fig. 11. In the left-hand panel, we plot the rest-frame colour of progenitor number 2 relative to the blue-red-sequence boundary shown in Fig. 2 as a function of the colour of progenitor number 1 from sampM for each merger pair. The data points in Fig. 11 are colour coded to distinguish blue- or red-sequence $0.1 (g - r)_1$ colours, and data above the dashed line have red $0.1 (g - r)_2$ colours. We find that $90 \pm 5$ per cent of the massive mergers we identify are comprised of two red progenitors; only one merger is blue–blue and three are mixed pairs. In the centre panel, we show the central-light concentration of progenitor 2 plotted against that of progenitor 1. Consistent with the high fraction of red–red mergers, $92 \pm 4$ per cent of the mergers are comprised of two concentrated progenitors with $R_{90}/R_{50} > 2.6$, the fiducial value for early-type morphologies (see Section 2.2). Three mergers are made up of an early/late mix according to concentration, with one of each red–red, red–blue and blue–blue.

The nature of the progenitors appears to depend little on whether the merger is positioned at the centre of the host group or is between a pair of SAT galaxies. Owing to the small number statistics, the slight decrease in the red–red merger fractions from 95 per cent (CEN-SAT) to 82 per cent (SAT–SAT), and likewise for early–early mergers from 95 per cent (CEN-SAT) to 88 per cent (SAT–SAT), are consistent with no difference. Generally speaking, the major mergers that will produce $M_{\text{star}} > 10^{11} \, M_{\odot}$ remnants in large groups are between two red-sequence spheroids that have little

Figure 11. Colours, concentrations and stellar masses of the progenitors of massive major mergers. CEN-SAT mergers (stars) are distinguished from those involving two SATs (circles). Data points are colour-coded to represent blue-red-sequence colour of the progenitor in sampM (galaxy number 1). Left-hand panel: relative Petrosian $(g - r)$ colour of the companion galaxy (number 2) with respect to the blue/red cut plotted as a function of progenitor number 1 colour. Red points above the dashed line represent red–red mergers. Centre: $r$-band central-light concentrations of progenitor 2 versus progenitor 1. Dashed lines show the crude early/late morphology cut of $R_{90}/R_{50} = 2.6$. Right-hand panel: stellar mass ratios of the progenitors of massive major mergers plotted as a function of the stellar mass of progenitor number 1. This panel shows the results for colour-derived stellar masses based on Petrosian photometry. Similar results are found using Model-derived colours. The dotted lines show 4:1 and 2:1 mass ratio boundaries. Mergers with $M_1/M_2 < 1$ lack a redshift for the more massive primary galaxy; i.e. these mergers are spec–phot pairs with $M_2 > M_1$. Data below the solid diagonal line have $M_2 > 10^{11} \, M_{\odot}$, thus, only three massive major mergers have two $<10^{11} \, M_{\odot}$ progenitors (upper left-hand side region delineated by the dashed lines).
cold gas for star formation and are presumably dissipationless. The properties of these low-redshift mergers match the six $0.1 < z < 0.9$ dissipationless mergers in Bell et al. (2006a).

### 3.2.2 Progenitor mass ratios

The major mergers we have identified are drawn from pairs with $|Δr_{12}| ≤ 1.5$ mag, our proxy for 4:1 to 1:1 mass ratios (Section 2.2). Here, we explore the actual stellar mass ratios of the merger progenitors. Overall, the Petrosian colour derived $M_{\text{star}}$ estimates for sampM are well behaved as demonstrated by the tight red sequence of CEN and SAT members in Fig. 2. We note, however, that there are a handful of extreme outliers in colour–mass space such that some galaxies have very red colours, especially at the massive end of the red sequence. Large systematic errors in colour translate into errors in $M_{\text{star}}$, which is a critical issue when trying to ascertain the progenitor mass ratios. Nevertheless, it is unclear whether the measured colours are the result of an error in the photometric pipeline or simply the intrinsic nature of a rare population.

We attempt to quantify the amplitude of systematic uncertainties in our stellar mass estimates from issues related to the SDSS photometry by recomputing $M_{\text{star}}$ for all 76 merger progenitors using SDSS Model magnitudes in place of Petrosian quantities in (1). In Fig. 12, we plot the relative difference between the masses derived with each type of magnitude as a function of the $0.0M_{\text{r}}$ and $0.0(g − r)$ differences (Petrosian Model), and $\theta_{\text{sep}}$. We find that the bulk (75 per cent) of the progenitors have a small ($<0.15$ dex) but systematic shift towards lower masses, which correlates with fainter $0.0M_{\text{r}}$, when using Model magnitudes. This subset has a tight locus of $Δ[0.0(g − r)]$ comparable to the quoted ~0.04 mag random error for Petrosian colours. The remaining 25 per cent of the progenitors have systematic colour offsets as large as $+0.30(-0.25)$ mag resulting in a greater than a factor of 2 shift in $M_{\text{star}}$, or more than twice as much as the expected $0.10−0.15$ dex systematic uncertainty (Section 2.2). In Tables 2 and 3, we note the progenitors with $>0.3$ dex difference between their Petrosian and Model based $M_{\text{star}}$ estimates. We find no dependence of these mass offsets on CEN versus SAT, nor on the angular separation of the pairs. One possible explanation for the large photometric variances could be related to known pipeline errors for very close pairs (Masjedi et al. 2006), yet very few of our projected pair sample have $\theta_{\text{sep}} < 3$ arcsec and it is difficult to understand how close pairs would have boosted flux in one passband ($r$) but not another ($g$) to account for the very red colours. We choose to use the SDSS Petrosian photometry because it provides a reasonable and model-independent measure of total galaxy flux. We stress that our results are the same whether we adopt Petrosian or Model colours.

In the right-hand panel of Fig. 11, we show the stellar mass ratios of the progenitors in our sample of mergers as a function of the mass $M_1$ of the progenitor drawn from sampM. Both CEN–SAT and SAT–SAT mergers have mass ratios mostly between 2:1 and 1:1, with the primary progenitors in central mergers tending towards higher masses than those in SAT–SAT mergers. It is possible that lower mass ratio interactions, especially between gas-poor systems, may produce weaker tidal signatures that could escape detection at the SDSS sensitivity. Yet, the 12 mergers in Tables 2 and 3 with mass ratios between 2:1 and 4:1 have an average redshift of $z = 0.086$ and values spanning the same range as equal-mass mergers, suggesting that the SDSS is sensitive to the mass ratios we use to define major merging.

As shown in Fig. 11, a majority (70 per cent) of the merger progenitors in large groups and clusters have $M_{\text{star}} > 10^{11}M_\odot$. Indeed, more than half of the major mergers we study here are between two massive progenitors (data points in the lower right region bound by solid lines). These results indicate that (i) some very massive galaxies continue to be assembled in the low-redshift Universe, and (ii) mergers between lower mass ($<10^{11}M_\odot$) galaxies are uncommon at the group scales that we study. The selection of sampM creates a bias insofar as the portion of the DR2 $z ≤ 0.12$ galaxy population that resides in large groups decreases significantly with decreasing stellar mass (see Table 1). In other words, our large group selection (see Fig. 1) misses vast numbers of galaxies with $5 × 10^{10} < M_{\text{star}}/M_\odot < 10^{11}$ that live in smaller haloes. Major mergers between lower mass galaxies are predicted to be more common in smaller groups (Hopkins et al. 2008), as such, these could produce an important portion of massive galaxies and provide a source for the strong mass growth observed on the red sequence below $M^*$ (Bell et al. 2004b; Blanton 2006; Borch et al. 2006; Brown et al. 2007; Faber et al. 2007). The importance of major mergers between $M_{\text{star}} < 10^{11}$ galaxies in lower mass haloes will be the subject of a forthcoming paper.

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3 In addition to standard Petrosian magnitudes, the SDSS photometry includes measures of galaxy flux from the best-fitting model, either a de Vaucouleurs or an exponential, to the $r$-band image profile.
Table 2. Progenitors of massive CEN-SAT merger systems.

<table>
<thead>
<tr>
<th>Group ID</th>
<th>$M_{\text{halo}}$</th>
<th>Flag</th>
<th>NYU ID</th>
<th>RA (5)</th>
<th>Dec. (6)</th>
<th>$z$ (7)</th>
<th>$M_{\text{star}}$ (8)</th>
<th>$0.0,(g-r)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>121</td>
<td>13.74</td>
<td>CEN</td>
<td>150206</td>
<td>14:14:32.6</td>
<td>+0:43:53.6</td>
<td>0.053</td>
<td>11.21 (11.28)</td>
<td>0.82 (0.84)</td>
</tr>
<tr>
<td>830</td>
<td>13.55</td>
<td>CEN</td>
<td>249473</td>
<td>08:54:38.9</td>
<td>+49:08:32.4</td>
<td>0.052</td>
<td>11.31 (11.47)</td>
<td>0.86 (0.93)</td>
</tr>
<tr>
<td>419</td>
<td>14.41</td>
<td>CEN</td>
<td>99993</td>
<td>12:27:37.1</td>
<td>-00:23:02.4</td>
<td>0.115</td>
<td>11.54 (11.72)</td>
<td>0.78 (0.85)</td>
</tr>
<tr>
<td>54</td>
<td>14.62</td>
<td>CEN</td>
<td>11349</td>
<td>15:08:25.8</td>
<td>-00:15:58.6</td>
<td>0.090</td>
<td>11.63 (11.65)</td>
<td>0.81 (0.80)</td>
</tr>
<tr>
<td>614</td>
<td>13.82</td>
<td>CEN</td>
<td>124158</td>
<td>13:52:02.2</td>
<td>+66:50:20.1</td>
<td>0.068</td>
<td>11.31 (11.37)</td>
<td>0.82 (0.85)</td>
</tr>
<tr>
<td>163</td>
<td>14.47</td>
<td>CEN</td>
<td>175344</td>
<td>15:09:59.4</td>
<td>+03:00:11.1</td>
<td>0.092</td>
<td>11.51 (11.58)</td>
<td>0.81 (0.84)</td>
</tr>
<tr>
<td>539</td>
<td>14.30</td>
<td>CEN</td>
<td>228252</td>
<td>00:56:20.1</td>
<td>-09:36:29.7</td>
<td>0.103</td>
<td>11.51 (11.51)</td>
<td>0.77 (0.77)</td>
</tr>
<tr>
<td>393</td>
<td>14.26</td>
<td>CEN</td>
<td>261132</td>
<td>10:04:39.4</td>
<td>+02:57:42.8</td>
<td>0.104</td>
<td>11.37 (11.41)</td>
<td>0.80 (0.79)</td>
</tr>
<tr>
<td>398</td>
<td>14.29</td>
<td>CEN</td>
<td>293645</td>
<td>10:37:29.8</td>
<td>-00:40:40.5</td>
<td>0.096</td>
<td>11.33 (11.37)</td>
<td>0.75 (0.79)</td>
</tr>
<tr>
<td>214</td>
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<td>311008</td>
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<td>+55:58:39.8</td>
<td>0.068</td>
<td>11.31 (11.30)</td>
<td>0.89 (0.87)</td>
</tr>
<tr>
<td>291</td>
<td>14.07</td>
<td>CEN</td>
<td>392792</td>
<td>22:28:25.5</td>
<td>-09:37:22.3</td>
<td>0.083</td>
<td>11.35 (11.42)</td>
<td>0.76 (0.71)</td>
</tr>
<tr>
<td>5</td>
<td>14.24</td>
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<td>301558</td>
<td>14:40:42.8</td>
<td>+03:27:55.5</td>
<td>0.027</td>
<td>11.39 (11.48)</td>
<td>0.84 (0.81)</td>
</tr>
<tr>
<td>102</td>
<td>14.32</td>
<td>CEN</td>
<td>44192</td>
<td>09:58:52.2</td>
<td>-01:03:33.1</td>
<td>0.081</td>
<td>11.26 (11.33)</td>
<td>0.67 (0.74)</td>
</tr>
<tr>
<td>759</td>
<td>14.13</td>
<td>CEN</td>
<td>88664</td>
<td>08:46:13.1</td>
<td>+53:26:38.1</td>
<td>0.113</td>
<td>11.73 (11.43)</td>
<td>1.13 (0.92)</td>
</tr>
<tr>
<td>74</td>
<td>14.27</td>
<td>CEN</td>
<td>258681</td>
<td>11:45:37.2</td>
<td>+64:30:41.4</td>
<td>0.063</td>
<td>11.42 (11.46)</td>
<td>0.84 (0.85)</td>
</tr>
<tr>
<td>847</td>
<td>13.91</td>
<td>CEN</td>
<td>274752</td>
<td>10:34:09.7</td>
<td>+04:21:29.8</td>
<td>0.100</td>
<td>11.42 (11.52)</td>
<td>0.82 (0.84)</td>
</tr>
<tr>
<td>572</td>
<td>13.92</td>
<td>CEN</td>
<td>371303</td>
<td>13:30:10.3</td>
<td>-02:06:18.0</td>
<td>0.087</td>
<td>11.35 (11.38)</td>
<td>0.81 (0.79)</td>
</tr>
<tr>
<td>1775</td>
<td>13.98</td>
<td>CEN</td>
<td>92509</td>
<td>17:20:36.1</td>
<td>+56:39:42.5</td>
<td>0.120</td>
<td>11.40 (11.42)</td>
<td>0.82 (0.83)</td>
</tr>
<tr>
<td>1545</td>
<td>13.43</td>
<td>SAT</td>
<td>364190</td>
<td>13:36:43.6</td>
<td>-03:29:57.0</td>
<td>0.053</td>
<td>10.91 (10.79)</td>
<td>1.01 (0.93)</td>
</tr>
<tr>
<td>261</td>
<td>14.26</td>
<td>SAT</td>
<td>336039</td>
<td>17:01:52.2</td>
<td>+35:02:54.9</td>
<td>0.107</td>
<td>11.01 (11.06)</td>
<td>0.67 (0.74)</td>
</tr>
<tr>
<td>479</td>
<td>14.28</td>
<td>SAT</td>
<td>373137</td>
<td>14:09:59.4</td>
<td>-01:32:18.9</td>
<td>0.117</td>
<td>11.64 (11.24)</td>
<td>1.17 (0.90)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NO(^{\dagger})</td>
<td>NA</td>
<td>14:09:59.5</td>
<td>-01:32:22.8</td>
<td>NA</td>
<td>NA</td>
<td>0.71 (0.74)</td>
</tr>
</tbody>
</table>

Notes. For each merger pair, the progenitor properties are listed on two separate lines with the following columns: group ID number (1) and dark matter halo mass estimate in units of log$_{10}$(M$_{\odot}$) (2) from the public SDSS DR2 group catalogue of Yang et al.; flag (3) for whether galaxy was identified in group catalogue as a central (CEN), satellite (SAT), or not identified (NO) owing to no spectroscopic redshift; ID number (4), epoch J2000.0 celestial coordinates (5 and 6), and spectroscopic redshift (7) from the NYU-VAGC; stellar mass estimates in units of log$_{10}$(M$_{\odot}$) (8) based on SDSS Petrosian (Model) photometry and Bell et al. (2003) M/L ratios; rest-frame K-corrected to $z = 0.0$ colour (9) from SDSS Petrosian (Model) photometry. \(^{\dagger}\)Estimated stellar mass of the companion exceeds that of the spectroscopic CEN galaxy of the host; the merger is added to the CEN-SAT subset in the analysis.

More than factor of 2 difference (0.3 dex) between Petrosian and model-based $M_{\text{star}}$ estimates.

3.2.3 The predicted colour–mass distribution of massive remnants

Recall that besides the sample of 38 merger pairs, we have also identified seven massive mergers based on their disturbed morphologies (Section 2.2; Fig. 3). Under the assumption that these morphologically identified mergers are examples of an advanced evolutionary stage between massive pairs of interacting galaxies and the final coalesced remnant,\(^{4}\) it is worthwhile to compare their positions in the colour–stellar–mass plane with the predicted locations for the remnants of the merger pairs. For each pair of progenitors, we calculate the remnant’s final mass $M_{\text{rem}} = M_p + f M_s$ and its mass-weighted colour:

$$\begin{align*}
(g-r)_{\text{rem}} &= -2.5 \log_{10}\left[ \frac{M_p}{M_{\text{rem}}} \right] \\
&\quad - 2.5 \log_{10}\left[ \frac{M_{\text{rem}}}{M_p} \right] \times 10^{0.4(g-r)_p}
\end{align*}$$

where the primary progenitor is more massive than the secondary by definition (i.e. $M_p \geq M_s$). The factor $f$ allows us to adjust the

\(^{4}\)This is a fair assumption given that all seven morphologically disturbed mergers have stellar masses in excess of 10$^{11}$ M$_{\odot}$.
Table 3. Progenitors of massive SAT–SAT merger systems.

<table>
<thead>
<tr>
<th>Group ID</th>
<th>$M_{\text{halo}}$ (2)</th>
<th>Flag</th>
<th>NYU ID</th>
<th>RA (5)</th>
<th>Dec. (6)</th>
<th>$z$ (7)</th>
<th>$M_{\text{star}}$ (8)</th>
<th>$0.0(g - r)$ (9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>126</td>
<td>13.55</td>
<td>SAT</td>
<td>367419</td>
<td>13:59:25.2</td>
<td>$-03:12:29.0$</td>
<td>0.025</td>
<td>10.73 (10.58)</td>
<td>0.95 (0.86)</td>
</tr>
<tr>
<td>37</td>
<td>14.72</td>
<td>SAT††</td>
<td>35684</td>
<td>15:11:20.3</td>
<td>$-00:07:20.1$</td>
<td>0.089</td>
<td>11.02 (11.10)</td>
<td>0.74 (0.77)</td>
</tr>
<tr>
<td>72</td>
<td>14.79</td>
<td>SAT</td>
<td>83539</td>
<td>08:54:48.7</td>
<td>$+00:51:02.6$</td>
<td>0.107</td>
<td>11.11 (11.15)</td>
<td>0.62 (0.67)</td>
</tr>
<tr>
<td>2955</td>
<td>13.81</td>
<td>SAT</td>
<td>206506</td>
<td>20:45:09.4</td>
<td>$+06:17:05.5$</td>
<td>0.112</td>
<td>10.88 (10.87)</td>
<td>0.79 (0.80)</td>
</tr>
<tr>
<td>81</td>
<td>14.37</td>
<td>SAT</td>
<td>218908</td>
<td>23:37:05.4</td>
<td>$+15:55:58.5$</td>
<td>0.066</td>
<td>10.94 (11.14)</td>
<td>0.68 (0.74)</td>
</tr>
<tr>
<td>219</td>
<td>14.20</td>
<td>SAT††</td>
<td>223211</td>
<td>23:54:59.6</td>
<td>$-09:14:49.4$</td>
<td>0.074</td>
<td>11.03 (11.00)</td>
<td>0.84 (0.81)</td>
</tr>
<tr>
<td>14</td>
<td>14.83</td>
<td>SAT</td>
<td>278870</td>
<td>10:39:39.0</td>
<td>$+05:10:31.3$</td>
<td>0.068</td>
<td>10.73 (10.86)</td>
<td>0.52 (0.64)</td>
</tr>
<tr>
<td>1786</td>
<td>13.99</td>
<td>SAT</td>
<td>284077</td>
<td>14:31:09.6</td>
<td>$+06:41:18.4$</td>
<td>0.113</td>
<td>10.74 (10.72)</td>
<td>0.81 (0.79)</td>
</tr>
<tr>
<td>344</td>
<td>13.92</td>
<td>SAT</td>
<td>333778</td>
<td>12:40:30.2</td>
<td>$+05:52:21.5$</td>
<td>0.075</td>
<td>11.59 (11.36)</td>
<td>1.36 (1.15)</td>
</tr>
<tr>
<td>75</td>
<td>14.85</td>
<td>SAT</td>
<td>346478</td>
<td>14:27:56.7</td>
<td>$+62:36:27.6$</td>
<td>0.107</td>
<td>11.33 (11.28)</td>
<td>0.90 (0.85)</td>
</tr>
<tr>
<td>170</td>
<td>13.88</td>
<td>SAT††</td>
<td>352171</td>
<td>13:33:03.2</td>
<td>$+06:07:00.0$</td>
<td>0.072</td>
<td>11.37 (11.06)</td>
<td>1.13 (0.94)</td>
</tr>
<tr>
<td>1047</td>
<td>13.97</td>
<td>SAT††</td>
<td>395494</td>
<td>22:22:48.8</td>
<td>$-09:02:14.4$</td>
<td>0.084</td>
<td>11.15 (11.23)</td>
<td>0.81 (0.80)</td>
</tr>
<tr>
<td>462</td>
<td>13.91</td>
<td>SAT</td>
<td>250588</td>
<td>08:36:45.9</td>
<td>$+47:22:10.2$</td>
<td>0.053</td>
<td>11.13 (11.15)</td>
<td>0.81 (0.81)</td>
</tr>
<tr>
<td>714</td>
<td>13.60</td>
<td>SAT</td>
<td>604118</td>
<td>15:28:12.7</td>
<td>$+42:55:47.7$</td>
<td>0.019</td>
<td>10.90 (10.94)</td>
<td>0.82 (0.87)</td>
</tr>
<tr>
<td>460</td>
<td>14.24</td>
<td>SAT</td>
<td>241625</td>
<td>09:55:39.5</td>
<td>$+01:35:48.4$</td>
<td>0.099</td>
<td>11.24 (11.20)</td>
<td>0.80 (0.76)</td>
</tr>
<tr>
<td>465</td>
<td>14.13</td>
<td>SAT††</td>
<td>294450</td>
<td>10:50:25.4</td>
<td>$-00:20:11.1$</td>
<td>0.096</td>
<td>11.20 (11.30)</td>
<td>0.80 (0.84)</td>
</tr>
<tr>
<td>337</td>
<td>14.12</td>
<td>SAT††</td>
<td>269340</td>
<td>09:22:22.2</td>
<td>$+02:35:09.3$</td>
<td>0.088</td>
<td>11.19 (11.22)</td>
<td>0.83 (0.82)</td>
</tr>
</tbody>
</table>

Notes. Columns are as in Table 2. Dark matter halo mass (2) and stellar mass (8) are in units of log($M_\odot$).

†† Total estimated stellar mass of the two SATs ($M_1 + M_2$) exceeds that of the spectroscopic CEN galaxy of the host; including/excluding the merger to the CEN-SAT subset is analysed.

‡ More than factor of 2 difference (0.3 dex) between Petrosian and model-based $M_{\text{star}}$ estimates.

Zibetti et al. (2005) found that the intracluster light (ICL) within 100 kpc of the group or cluster centre makes up as much as 40 per cent of the total cluster luminosity (galaxies + ICL), and they showed that the stars making up the ICL have the same red colours as high-mass galaxies in the intracluster environment. Therefore, it is conceivable that some stellar mass from the massive, red, CEN-SAT mergers deep in the potential wells of large groups and clusters winds up in the ICL rather than as part of the central remnant galaxy. Various groups have argued that disruption of SAT galaxies through tidal stripping and heating can remove 10–80 per cent of their stellar mass and account for the ICL (Monaco et al. 2006; Conroy, Wechsler & Kravtsov 2007; White et al. 2007). These theories provide a way to reconcile the predicted merger-driven mass growth above $10^{11} M_\odot$ in a $\Lambda$CDM cosmology with the little growth that is observed in the stellar mass function (e.g. Wake et al. 2006; Brown et al. 2007). In the right-hand panel of Fig. 13, we try a highly conservative test of the latter scenario by assuming $f = 0.5$ for CEN-SAT remnants, but $f = 1$ for SAT–SAT mergers. This assumption implies that each high-mass SAT merging with the centre of its host potential well would lose 50 per cent of its present stellar mass.
Assembly of massive galaxies in SDSS groups

Figure 13. Predicted stellar masses and mass-weighted colours of massive-merger remnants compared with observations of disturbed-morphology mergers presumed to be nearing final coalescence. Small grey circles show all sampM galaxies with $M_{\text{star}} = M^*$. White (CEN) and black (SAT) squares represent the seven mergers shown in Fig. 3; stars (from CEN-SAT mergers) and circles (from SAT–SAT mergers) represent the predicted remnants of the 38 merger pairs. Left-hand panel: the simple assumption that all of the mass from both progenitors is added to the final remnant. Right-hand panel: the assumption that 50 per cent of the SAT progenitor mass is added to the ICL if the merger is at the group centre. The blue/red galaxy division is as in Fig. 2. All data are based on Petrosian quantities.

by the time it coalesced from an average projected group-centric distance of 15 kpc. In the previous section, we show that these CEN-SAT mergers have mass ratios typically within a factor of 2 of unity, and these systems are clearly separated by distances much less than the ICL half-light radius. These facts suggest either (i) a much lower SAT mass loss than our conservative assumption, or (ii) the SAT masses at the ICL half-light radius were in excess of the CEN with which they will eventually merge. Another possibility is that the CEN-SAT masses are much more disparate as a result of the standard SDSS photometry systematically underestimating the CEN luminosities (Lauer et al. 2007). Resolving these issues is beyond the scope of this paper. Instead we simply point out that in terms of relative stellar mass from SDSS photometry, we see better agreement between the observed mergers and the predicted remnants at the centres of large groups if we assume that only half of the SAT mass ends up in the remnant, which suggests that major mergers at the bottom of the potential well in groups and clusters could be an important source for the ICL.

3.3 Environmental dependencies

One of the key goals of our study is to quantify the environmental dependencies, if any, of massive mergers. Here, we use the host’s halo mass, and the distinction between CEN (brightest) and SAT members, to explore the environments of the mergers that we have identified in large SDSS groups and clusters from the local Universe. In what follows, we consider the combined sample of 45 massive mergers: 38 close pairs identified by residual asymmetric structure plus seven single sources identified by their morphologically disturbed appearance.

3.3.1 Preference for central merging

We find that the centres of large groups and clusters appear to be the preferred environment for the major merger assembly of present-day $M_{\text{star}} > 10^{11} \text{M}_\odot$ galaxies. More than half of the mergers we identify involve the central (most luminous) member of the host halo, yet there are five times less CENs than SATs to merge with in sampM. Thus, on average, $3.0 \pm 0.6$ per cent of large groups with $z \leq 0.12$ have a major merger at their centre, while $1.5 \pm 0.2$ per cent of $M_{\text{star}} \geq 5 \times 10^{10} \text{M}_\odot$ galaxies within these groups are involved in a massive merger.

In Fig. 14, we compare the group-centric properties of the CEN and SAT mergers. We find that mergers involving a CEN are significantly closer to the luminosity-weighted centre of their host group than mergers between SAT galaxies. The average projected group-centric distance of CEN mergers is 210 kpc, compared to 490 kpc for SATs. Moreover, relative to the luminosity-weighted group redshifts, the CEN mergers have a narrower distribution of velocity offsets ($\sigma = 200 \text{ km s}^{-1}$) than the SAT mergers ($\sigma = 370 \text{ km s}^{-1}$).
The small group-centric offsets of the CEN mergers are consistent with them residing at the bottom of their halo’s potential well, where dynamical friction is maximum. In contrast, most merging SATs have large group-centric offsets as expected given their rank within their host group. At face value, these results indicate that mergers between high-mass SATS do occur, yet in terms of their morphologies and mass ratios (Fig. 11) there are no clear differences between CEN-SAT and SAT–SAT merger progenitors.

Massive mergers likely occur at the dynamical centre of a common halo. If the merger is between two SATs, then we may be witnessing a merger at the centre of a subhalo that merged with the larger host halo.5 Another possibility is that the SAT merger represents the true dynamical centre of the host halo. Indeed, we find that 20 per cent (4/20) of the SAT mergers reside closer to the centre of the group’s projected galaxy distribution than the spectroscopic CEN galaxy identified by the group catalogue, and these systems have a total stellar mass estimate \( M_1 + M_2 \) that is greater than the mass of the CEN (\( M_{CEN} \)). We identify these four pairs in Table 3 and explore their inclusion/exclusion in the CEN-SAT merger subset in our analyses of central merger frequencies and mass accretion rates in the following sections.

It is also possible that a significant fraction of the SAT mergers are at the centre of a distinct halo seen in projection along the line of sight to the host halo. This explanation would explain the group-centric differences in Fig. 14, and the similar colours, concentrations and mass ratios shown in Fig. 11. We note that 6/20 SAT mergers have \( M_1 + M_2 \geq M_{CEN} \) and large projected group-centric distances, providing circumstantial evidence for membership in a separate group from the host of the CEN galaxy. Yet, a simple calculation shows that there is only a 10 per cent chance for a line-of-sight projection of a distinct group with \( M_{halo} \geq 10^{13} \, M_\odot \) within 1 Mpc radius and \( \pm 400 \, \text{km s}^{-1} \) depth (following the group-centric properties of the SAT–SAT mergers in Fig. 14). This estimate is an upper limit based on the mean number density of groups that typically host a \( 10^{11} \, M_\odot \) CEN galaxy (10–3.5 Mpc\(^{-3}\), Mo & White 2002), and the assumption that the correlation strength between groups increases the local density relative to the mean by a factor of 10. Therefore, the observed frequency of 3 per cent of groups with central mergers implies that we should find only three SAT–SAT mergers that are misidentified CEN-SAT systems from a projected group. We find 16–20 SAT–SAT mergers in 845 groups (1.9–2.4 per cent depending on whether or not we include the four cases at the centre of their host discussed in the previous paragraph), indicating that most are correctly identified as SAT–SAT interactions. Given the large velocity dispersions of high-density environments, true SAT–SAT mergers are not expected. While we do find large group-centric velocity offsets for SAT–SAT mergers (Fig. 14), for the subset of 12 spec–spec mergers we find no significant difference between the small velocity separations (\( v_{12} \), see Fig. 9) of CEN-SAT and SAT–SAT mergers. Therefore, we tentatively conclude that massive SAT–SAT mergers identify the centres of large subhaloes that have recently accreted on to their host.

### 3.3.2 Merging dependence on halo mass

By identifying the massive galaxy mergers in a halo-mass limited selection of large groups, we can for the first time constrain their importance as a function of halo mass. In the left-hand panel of Fig. 15, we plot the halo-mass dependence for the frequency of groups that have merger-driven assembly of \( M_{\text{sat}} > 10^{11} \, M_\odot \) galaxies restricted to their centres. We find that the fraction of groups that have a massive merger at their centre (bold red line) is statistically constant at 3 per cent over the interval 13.4 < \( \log_{10}(M_{\text{halo}}/M_\odot) \) < 14.9; we note that including the four morphologically identified CEN mergers, plus the four mergers at their host’s dynamical centre that are likely misclassified SAT–SAT, result in a minor increase in this frequency (thin red line, open diamonds). We contrast our estimate for the merger frequency dependence on halo mass, based solely on galaxies exhibiting obvious tidal features, to that obtained from simple close projected pairs of high-mass galaxies (dashed

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5 The halo-based group finder of Yang et al. (2005) used to produce the SDSS group catalogue does not have the ability to distinguish subhaloes within the halo defining each galaxy group.
black line), which grows steadily with halo mass as a result of the increased projected number density of high-mass galaxies in dense environments. The increased chance of projection with increasing \(M_{\text{halo}}\) also occurs for the subset of spec–spec pairs that are found in the same host group (solid black line), but the amplitude is diminished owing to the high spectroscopic incompleteness in the pairs that we study. At \(\log_{10}(M_{\text{halo}}/M_\odot) < 14.6\), the number of spec–spec projected pairs in matched haloes is less than that of all mergers, which by definition must reside in the same host halo, because the latter include spec–phot pairs.

In the right-hand panel of Fig. 15, we repeat our analysis of merger and projected pair frequencies as a function of halo mass using the combined CEN-SAT plus SAT–SAT sample. When considering all possible mergers that will produce high-mass remnants (red lines), the frequency is roughly constant at 5 per cent for \(13.4 < \log_{10}(M_{\text{halo}}/M_\odot) < 14.9\). Including/excluding the seven non-pair (morphologically identified) mergers does not change these frequencies significantly. The issues with using simple projected pair statistics (black lines) to estimate merger frequencies grow rapidly out of hand for massive groups that contain large numbers of \(M_{\text{star}} \geq 5 \times 10^{10}M_\odot\) galaxies; for example, on average nearly half of all \(\log_{10}(M_{\text{halo}}/M_\odot) = 14.5\) groups have one major pair of high-mass galaxies that appear close in projection.

Besides merger frequency per group, we can approach massive mergers from a different perspective and calculate the frequency of \(M_{\text{star}} \geq 5 \times 10^{10}M_\odot\) SATs that are currently involved in a massive merger that can be identified as such with the technique that we use here. We calculate separate frequencies for merging with a CEN or another high-mass SAT galaxy and plot them as a function of \(M_{\text{halo}}\) in Fig. 16. The SAT merging frequencies decrease from a few per cent for our lowest mass groups, to \(\lesssim 1\) per cent for groups larger than \(M_{\text{halo}} = 5 \times 10^{13}M_\odot\). Both CEN-SAT and SAT–SAT merging follow a very similar trend of decreasing frequency with increasing \(M_{\text{halo}}\). This result indicates that a high-mass SAT is more likely to experience a major merger in a group than in a larger cluster. This behaviour is qualitatively consistent with a simple model (Hopkins et al. 2008) based on empirical halo occupation models, theoretically well-constrained halo-mass functions and merger time-scale estimates from dynamical friction considerations. Moreover, the frequency dependence on \(M_{\text{halo}}\) is consistent with the \(M^{-1}\) scaling of dynamical friction and provides more circumstantial evidence that SAT–SAT mergers are occurring at the dynamical centres of recently accreted subhaloes.

4 DISCUSSION

We find the first direct observational evidence for an important population of galaxy–galaxy mergers with total stellar masses above \(10^{11}M_\odot\) in the local Universe. These objects provide an unprecedented census of the progenitor properties for the merger-driven assembly of massive galaxies, which we compare to recent predictions from numerical models of galaxy formation and evolution. Moreover, the existence of these mergers proves that a measurable amount of stellar mass growth continues in the massive galaxy population at present times, and we compare estimates based on this sample with other estimates in the literature. Finally, we have identified mergers restricted to reside in large SDSS groups and clusters with \(z \leq 0.12\), thus allowing the first constraints on the halo-mass dependencies of recent massive merger activity. While it is well established that massive galaxies are more common in such high-density environments, these groups contain much less than 50 per cent of the \(M_{\text{star}} < 4 \times 10^{11}M_\odot\) galaxy population in the local volume, as Table 1 shows. Therefore, we must keep this caveat in mind when interpreting the conditions for which our results hold. In an upcoming study, we will examine the role of major mergers as a function of stellar mass over the full range of environments hosting \(M_{\text{star}} \geq 5 \times 10^{10}M_\odot\) galaxies.

4.1 Massive merger progenitors: observations meet theories

Establishing the luminosity dependence of elliptical (E) galaxy properties (Davies et al. 1983; Bender 1988; Bender, Burstein & Faber 1992) set the stage for theories regarding the types of merger progenitors that would produce the characteristics of low- and high-mass early-type galaxies (ETGs)\(^6\) (Kormendy & Bender 1996; Faber et al. 1997). We concentrate on modern numerical simulations and semi-analytic models that attempt to reproduce the kinematic, photometric and structural properties observed in massive Es through major merging (Naab, Burkert & Hernquist 1999; Khocharf & Burkert 2003; Naab & Burkert 2003; Khochfar & Burkert 2005; Boylan-Kolchin, Ma & Quataert 2006; Naab, Khocharf & Burkert 2006a; Kang, van den Bosch & Pasquali 2007). For this discussion, we make the straightforward assumption that the major mergers that we have identified will produce remnants that are not unlike the \(M_{\text{star}} > 10^{11}M_\odot\) galaxy population already in place. We can only guess at remnant properties (see Fig. 13), but, in general, massive galaxies on the red sequence are typically early type.

As we show in Fig. 11, the progenitor masses are comparable for the most part, and quantitatively consistent with the LRG–LRG merger mass spectrum from Masjedi et al. (2008) under the assumption that companions merge on dynamical friction time-scales. N-body simulations (e.g. Naab et al. 1999) have long shown that

\[^6\] The distinction between elliptical and ETGs is often blurred in the literature. We consider Es to be a morphological subset of ETGs, which are concentrated and spheroid-dominated systems including Es, lenticulars (S0s) and Sa spirals. When referencing other authors we remain faithful to their choice of nomenclature.
$M_1/M_2 \approx 1$ is necessary to produce the lack of significant rotation observed in massive Es. Yet, a near unity mass ratio alone is not sufficient to produce the predominance of boxy and anisotropic Es found at high luminosity (Naab & Burkert 2003; Naab et al. 2006a). To match the decreasing fraction of rotational support and increasing fraction of boxiness in more luminous Es, the role of gas dissipation must be significantly reduced at high masses (Bender et al. 1992; Khochfar & Burkert 2005; Naab et al. 2006b; Kang et al. 2007), and recent ETG–ETG merger simulations have demonstrated this numerically (Naab et al. 2006a). Fig. 11 shows that 90 per cent of the progenitors in this study have concentrated light profiles and red-sequence colours, both common attributes of ETGs with little or no cold gas content. In addition, the tidal signatures of the bulk of these massive mergers (see Fig. 6) match those of observed (Bell et al. 2006a) and simulated (Naab et al. 2006a) major dissipationless (or gas-poor) mergers of ETGs. Thus, our sample represents a more than order of magnitude increase in the number of such known systems with $z < 0.2$ and demonstrates that dissipationless merging is indeed an important channel for the formation of massive galaxies.

Finally, we compare the observed high fraction of ETG–ETG mergers ($f_{\text{ETG–ETG}} = 0.9$) with several semi-analytic predictions. Recall that we have looked for signs of interaction in 221 major pairs from a total sample of 5376 high-mass galaxies (i.e. sampM), yet only 10 per cent of the 38 mergers we identify could possibly form a $M_{\text{star}} > 10^{11} M_{\odot}$ remnant by other than an ETG–ETG merger. The progenitor morphologies of this study best match the predictions of Khochfar & Burkert (2003), who find $f_{\text{ETG–ETG}} = 0.75$ for the last major merger of 4L$^*$ remnants, independent of environment. We find much larger ETG–ETG fractions than Naab et al. (2006a) who predict only 20–35 per cent (also independent of environment) over the estimated mass range of our merger remnants [$11.1 < \log_{10}(M_{\text{star}}/M_{\odot}) < 11.7$, and Kang et al. (2007) who predict $f_{\text{ETG–ETG}} < 0.1$ for $\log_{10}(M_{\text{star}}/M_{\odot}) > 11$. We note that these predicted progenitor morphologies for present-day Es are based on the final major mergers that could occur over a large redshift range out to $z < 1$, which could be different in nature to those that occur in the short time interval that we observe. Moreover, we focus on high-density environments known to have very few luminous late-type (blue) galaxies (Butcher & Oemler 1978), which might explain the low number of ‘mixed’ (early late or elliptical spiral) mergers that we find. Hence, for these models to be consistent with our data, either (i) the $f_{\text{ETG–ETG}}$ of present day major mergers depends on halo mass (i.e. environment) or (ii) the relative importance of major mixed mergers has decreased significantly since $z = 1$.

### 4.2 Estimating stellar mass accretion rates

The existence of massive dissipationless mergers at low redshift is direct observational evidence that the growth of $M_{\text{star}} > 10^{11} M_{\odot}$ galaxies continues at present times in agreement with many cosmologically motivated simulations (Khochfar & Burkert 2005; De Lucia et al. 2006; Kang et al. 2007; Kaviraj et al. 2008). Moreover, even under conservative assumptions that limit the amount of companion mass that is added to CEN galaxies in massive mergers, our entire sample will still result in remnants with $M_{\text{star}} > 10^{11} M_{\odot}$. Previously, the observational evidence for recent merger-based assembly of $z \sim 0$ massive Es was limited to luminous/massive galaxy clustering statistics (Bell et al. 2006b; Masjedi et al. 2006, 2008) or post-merger signatures that cannot distinguish between minor and major merging; for example, tidal shells (Malin & Carter 1983), fine structure (Schweizer & Seitzer 1992), faint tidal features (Mihos et al. 2005; van Dokkum 2005) or kinematic/photometric properties (e.g. Kang et al. 2007). With the merger sample presented here, we can quantify directly the amount of growth, occurring in dense environments, at the high-mass end of the stellar mass function.

Going from the observed merger frequency to an inferred merger rate is limited mostly by the uncertainty in the time-scale ($t_{\text{merg}}$) that a merger is recognizable in a given set of observations. Numerical models show that the time interval for two galaxies to interact and finally merge into a single remnant depends critically on the orbital parameters, mass ratio and structure of the progenitors, and the degree to which the merger is dissipationless. We find that 90 per cent of the massive mergers in dense environments appear to be dissipationless and nearly equal mass. Bell et al. (2006a) analysed a set of $N$-body merger simulations and found that the morphological signatures of such mergers are visible for about 0.2 Gyr in imaging of similar resolution and sensitivity when the merger redshift is accounted for. In addition, a number of different time-scales for close pairs of high-mass galaxies to merge have been put forth in the literature based on simple orbital time-scale arguments. For example, Masjedi et al. (2006) derived a reasonable lower limit of 0.2 Gyr for a close ($d_{1,2} = 10$ kpc) pair of LRG galaxies with a velocity dispersion of $\sigma = 200$ km s$^{-1}$. Naturally, bound pairs with $d_{1,2} > 10$ kpc separation will take longer to merge. Bell et al. (2006b) made a similar calculation for somewhat less massive galaxies typically separated by $d_{1,2} = 15$ kpc and estimated 0.4 Gyr and argued for at least a factor of 2 uncertainty in this time. The mergers in this study have an average projected separation of 15.5 kpc (see Fig. 9). In what follows, we adopt a conservative estimate of $t_{\text{merg}} = 0.4^{-0.2}$ Gyr to encompass the range of timescales discussed above.

Owing to the progenitor nature of the majority of the massive mergers in this paper, we note that they are likely to tend towards the lower limit of our $t_{\text{merg}}$ estimate.

Here, we compute the rate of stellar mass accretion by major merging on to high-mass galaxies in large groups. First, we find that the total mass accreted on to the centres of the $N_{\text{CEN}} = 845$ haloes that we study is $\sum f M_{\text{star}} = 3.9(3.5) \times 10^{12} M_{\odot}$, if we include (exclude) the four SAT–SAT mergers at their host’s dynamical centre (see Section 3.3.1). $M_{\text{star}}$ is the stellar mass of the secondary (SAT) galaxy in the $i^{\text{th}}$ CEN-SAT merger, and $f$ is the fraction of $M_{\text{star}}$ that winds up as part of the CEN galaxy. Therefore, the rate of stellar mass buildup per CEN galaxy in these large groups is

$$M_{\text{CEN}} = \frac{\sum f M_{\text{star}} + M_{\text{sat}}}{N_{\text{CEN}} + N_{\text{SAT}} - N_{\text{CEN,SAT}}} \times \frac{1}{t_{\text{merg}}},$$

or between $1.0^{+0.9}_{-0.5} \times 10^{10} M_{\odot}$ Gyr$^{-1}$ and $1.2^{+1.1}_{-0.6} \times 10^{10} M_{\odot}$ Gyr$^{-1}$, depending on which sample of CEN-SAT mergers that we consider. The lopsided error bars result from the range of accretion rates for $t_{\text{merg}} = 0.4^{-0.2}$ Gyr, as described above. If we divide all of these accretion rates by $2.69 \times 10^{13} M_{\odot}$, the average stellar mass of the 845 CEN galaxies in this study, we find that each CEN is growing by 2–9 per cent per Gyr. Finally, these values can be decreased by assuming $f < 1$ in (4), but as we discuss in Section 3.2.3, $f = 0.5$ represents a likely lower limit.

Likewise, the total stellar mass accreted on to all galaxies in sampM is $\sum f M_{\text{star}} = \sum M_{\text{star}} = 5.1 \times 10^{12} M_{\odot}$, where $M_{\text{star}}$ is the mass of the secondary (SAT) galaxy in the $i^{\text{th}}$ SAT–SAT merger. Therefore, the growth per $M_{\text{star}} \geq 5 \times 10^{10} M_{\odot}$ galaxy in large groups is

$$M_{\text{CEN}} = \frac{\sum f M_{\text{star}} + N_{\text{sat}}M_{\text{star}}}{N_{\text{CEN}} + N_{\text{SAT}} - N_{\text{CEN,SAT}}} \times \frac{1}{t_{\text{merg}}},$$

where $N_{\text{CEN}} = 12$ is the number of secondary SAT galaxies in...
 sampM that are involved in major mergers (i.e. those with a spectroscopic redshift) and must be subtracted to avoid double counting. We find $M_{\text{sampM}} = 2.4^{+1.2}_{-1.7} \times 10^9 M_{\odot} \text{ Gyr}^{-1}$; if we assume $f = 0.5$ for CEN-SAT mergers only we find $M_{\text{sampM}} = 1.6^{+0.7}_{-0.5} \times 10^9 M_{\odot} \text{ Gyr}^{-1}$.

Given that the average stellar mass of sampM galaxies is $1.04 \times 10^{11} M_{\odot}$, we find that every sampM galaxy is growing by $1-5$ per cent per Gyr. Even though SAT–SAT mergers may occur as frequently as CEN-SAT mergers in these large groups, the centres are where much of the mass growth takes place.

Rather than mass growth rates we can use the same line of reasoning to estimate massive merger rates of $38 \times (7 +)/845 + 4531 - 12)/f_{\text{merg}} = 0.021^{+0.031}_{-0.011} \text{ Gyr}^{-1}$ overall, and $(21 + 4)/845/ f_{\text{merg}} = 0.074^{+0.074}_{-0.037} \text{ Gyr}^{-1}$ for CEN-SAT systems. For these estimates, we included the seven additional major mergers (four CEN, three SAT) identified by their highly disturbed appearance. Masjedi et al. (2006) found a strict upper limit to the LRG–LRG rate of only $0.006 \text{ Gyr}^{-1}$. We estimate that LRGs have a stellar mass range of $11.4 < \log_{10}(M_{\text{star}}/M_{\odot}) < 12.0$, based on typical red-sequence colours and luminosities between $4L^*$ and $25L^*$. Within these mass limits, we find five LRG–LRG mergers in our sample and calculate a rate of $5/462/f_{\text{merg}} = 0.027^{+0.032}_{-0.014} \text{ Gyr}^{-1}$, or two to nine times the published rate. In Table 1, we show that the large groups that we study contain $>70$ per cent of the very massive, red-galaxy population in the $z < 0.12$ volume of DR2, with the vast majority being CENs. Yet, the same group selection contains only 30 per cent of the population of $11.3 < \log_{10}(M_{\text{star}}/M_{\odot}) < 11.6$ systems. These numbers show that a significant portion of the local counterparts to LRGs is in groups with $M_{\text{halo}} > 6.3 \times 10^{13} M_{\odot}$ (see Fig. 1). Keeping the small numbers in mind, our results suggest that LRG–LRG merging occurs more frequently in large groups and clusters in agreement with the theoretical predictions of Hopkins et al. (2008).

5 SUMMARY

Using the SDSS DR2 group catalogue, we search a volume-limited sample of $M_{\text{halo}} > 2.5 \times 10^{13} M_{\odot}$ groups for major mergers that will produce $M_{\text{star}} > 10^{11} M_{\odot}$ galaxies. From a complete sample of 5376 group members with $M_{\text{star}} > 5 \times 10^{10} M_{\odot}$, we identify 38 major pairs of merging galaxies such that both systems exhibit asymmetric features consistent with mutual tidal interactions, and another seven massive mergers that have disturbed morphologies and semiresolved double nuclei. Thus, $1.5 \pm 0.2$ per cent of the high-mass membership of large groups are merging. This work provides the first direct evidence for the present day, hierarchical formation of massive galaxies. With this sample, we provide new empirical constraints on the progenitor nature, the environmental dependence and the stellar mass growth rate of merger-driven assembly of massive galaxies. We summarize our results as follows:

(i) Massive mergers, as defined here from SDSS data, make up only 16 per cent of the major pairs ($\leq 30$ kpc projected separations) of high-mass galaxies in dense environments.

(ii) An important percentage (70 per cent) of these mergers would be lost in an automated search of SDSS spectroscopic galaxy pairs as a result of the spectroscopic incompleteness in regions of high projected number density.

(iii) 90 per cent of massive mergers are between two redsequence galaxies with concentrated (spheroid-dominated) morphologies and broad tidal asymmetries like those seen in observations and in simulations of major dissipationless mergers of spheroidal galaxies (Bell et al. 2006a; Naab et al. 2006a).

(iv) Two-thirds of massive mergers have progenitor mass ratios of 1:1 to 2:1, despite a complete search of major pairs down to 4:1, indicating that near equal-mass merging is preferred in high-density environments.

(v) Massive mergers at the centres of large groups are more common than between two SAT galaxies, but the latter are also identified and morphologically indistinguishable from CEN-SAT mergers. We argue that SAT–SAT mergers could identify the dynamical centres of large subhaloes that have recently been accreted by their host halo, rather than the centres of distinct haloes seen in projection.

(vi) Moderately massive ($M_{\text{star}} > 5 \times 10^{10} M_{\odot}$) SATs are more likely to be involved in a major merger that will produce a massive galaxy in a large group rather than in a massive cluster.

(vii) Based on reasonable assumptions, the centres of large groups and clusters at $z \leq 0.12$ are growing in stellar mass by $1-5$ per cent per Gyr. Even though SAT–SAT mergers may occur as frequently as CEN-SAT mergers in these large groups, the centres are where much of the mass growth takes place.

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