Major Dry-Mergers In Early-Type Brightest Cluster Galaxies

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ABSTRACT

We search for ongoing major dry-mergers in a well selected sample of local Brightest Cluster Galaxies (BCGs) from the C4 cluster catalogue. 18 out of 515 early-type BCGs with redshift between 0.03 and 0.12 are found to be in major dry-mergers, which are selected as pairs (or triples) with \(r\)-band magnitude difference \(\delta m_r < 1.5\) and projected separation \(r_p < 30\) kpc, and showing signatures of interaction in the form of significant asymmetry in residual images. We find that the fraction of BCGs in major dry-mergers increases with the richness of the clusters, consistent with the fact that richer clusters usually have more massive (or luminous) BCGs. We estimate that present-day early-type BCGs may have experienced on average \(\sim 0.6 (t_{\text{merge}}/0.3\text{ Gyr})^{-1}\) major dry-mergers and through this process increases their luminosity (mass) by 15\% \((f_{\text{mass}}/0.5)\) on average since \(z = 0.7\), where \(t_{\text{merge}}\) is the merging timescale and \(f_{\text{mass}}\) is the mean mass fraction of companion galaxies added to the central ones. We also find that major dry-mergers do not seem to elevate radio activities in BCGs. Our study shows that major dry-mergers involving BCGs in clusters of galaxies are not rare in the local Universe, and they are an important channel for the formation and evolution of BCGs.

Key words: galaxies: elliptical and lenticular, cD - galaxies: clusters: general - galaxies: photometry

1 INTRODUCTION

The Brightest Cluster Galaxies (BCGs) are at the most luminous and massive end of galaxy population. They are usually located at or close to the centres of dense clusters of galaxies based on the X-ray observations or gravitational lensing observations (e.g., Jones & Forman 1984; Smith et al. 2005). Most of them are dominated by old stars without prominent ongoing star formation. They are much more luminous than other galaxies in the clusters, and have distinct surface brightness profiles from other galaxies (see Vale & Ostriker 2008 and references therein). And yet the luminosities of BCGs appear to have rather small scatters. As a result, they have been proposed as a distance indicator (e.g., Postman & Lauer 1995). Because of the unusual properties of BCGs, their formation and evolution has long attracted particular attention.

Galactic cannibalism as a way to build up the BCGs was proposed more than three decades ago (e.g., Ostriker & Tremaine 1975; White 1976; Vale & Ostriker 2008). However, as pointed out by several authors (e.g., Merritt 1985; Lauer 1988; Tremaine 1990), cannibalism of satellite galaxies may not be enough to account for the luminosity growth of massive BCGs due to the small luminosity ingestion rate. If this is correct, then other mechanisms, such as major mergers may play an important role (Lin & Mohr 2004; Vale & Ostriker 2008). Since most central galaxies in clusters have little cold gas, the mergers are not expected to trigger major episodes of star formation and thus they are likely dry mergers.

Recent studies from both numerical simulations and observations indicate that a large part of stellar mass in luminous early-type galaxies form before redshift \(z \sim 1 - 2\),

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and later dry mergers play an important role in their stellar mass assembly (Gao et al. 2004; De Lucia & Blaizot 2007; van Dokkum et al. 1999; Tran et al. 2005). Ruszkowski & Springel (2009) investigated the effect of dry-mergers on the scaling relations of BCGs in simulations. Observational studies on the properties of luminous early-type galaxies provide evidence that they have experienced dry-mergers (e.g., Lauer et al. 2007; Bernardi et al. 2007; von der Linden et al. 2007; Liu et al. 2008, hereafter Paper I). Theoretical investigations suggest that half the mass of a typical BCG may be assembled via accretion of smaller galaxies, i.e., by minor mergers at $z < 0.5$ (e.g., Gao et al. 2004; De Lucia & Blaizot 2007). Recently, Bernardi (2009) studied their evolutions in the size- and velocity dispersion-stellar mass correlations since $z < 0.3$, and concluded that early-type BCGs grow from many dry minor mergers (see Discussion). However, Whitley et al. (2008) using the ESO Distant Cluster Survey, found little evolution of BCGs since $z \approx 1$, at least within a metric circular aperture of 37 kpc. A consensus about the evolution of BCGs is yet to emerge.

Recent modelling suggests that major dry-mergers play a significant role in forming luminous, intermediate-mass, early-type galaxies (e.g., Naab et al. 2006) at redshift $z \lesssim 0.5$. Whether the same scenario applies to the much more luminous BCGs, and more generally how the occurrence of major dry-mergers depends on the environments, is still somewhat controversial. Merritt (1985) argued that massive major mergers are more likely to occur in large groups than in massive clusters, since the merger rate is a steeply declining function of the velocity dispersions of a virialized system.

However, recent observational studies indicate major dry-mergers do occur in groups and clusters of galaxies. For example, Mulchaey et al. (2006) and Jeltema et al. (2007) reported some examples of dry-mergers involving central galaxies in intermediate-redshift groups. Tran et al. (2008) reported an observational analysis of supergroup SG 1120-1202 at $z \approx 0.37$, which is expected to merge and form a cluster with mass comparable to Coma. They argued that the group environment is critical for the process of major dry-mergers. Rines et al. (2007) reported a very massive cluster (CL0958+4702) at moderate redshift ($z = 0.39$), in which a major dry-merger is ongoing to build up a BCG. Using the Sloan Digital Sky Survey (SDSS) data, McIntosh et al. (2008) identified 38 major mergers of red galaxies from 845 groups of galaxies at $z \leq 0.12$ identified using the halo-based group finder of Yang et al. (2005), and showed that centres of massive groups are the preferred environment for major dry-mergers and mass assembly of massive early-type galaxies.

All these studies show that major dry-mergers are important in the formation of BCGs at moderate redshifts. Our own visual inspections of 249 merging pairs identified from luminous early-type galaxies (Wen, Liu & Han 2009) also hint that some of these mergers involve BCGs. The purpose of this work is to perform a search for major dry-mergers in a well-selected local early-type BCG sample with a quantitative method and then estimate their major dry-merger and luminosity (mass) increase rates. We also investigate the dependence of the merger fraction as a function of the richness of the clusters.

The structure of the paper is as follows. In §2 and §3 we describe our sample and identifications of major dry-mergers involving BCGs. We present our main results in §4 and finish with a summary and discussion in §5. Throughout this paper we adopt a cosmology with a matter density parameter $\Omega_m = 0.3$, a cosmological constant $\Omega_{\Lambda} = 0.7$, and a Hubble constant of $H_0 = \frac{72}{100} \text{ km s}^{-1} \text{ Mpc}^{-1}$, i.e., $h = H_0 / (\frac{72}{100} \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.72$.

2 THE SAMPLE

The C4 cluster catalogue (Miller et al. 2005) was constructed from the SDSS spectroscopic data in the parameter space of position, redshift, and color. The C4 algorithm identifies the BCG from the spectroscopic catalogue within $0.5 h^{-1}\text{Mpc}$ of the central galaxy at the peak of the C4 density field (“mean” galaxy). The early (DR2) version of the C4 catalogue incorporates the SDSS photometric catalogue to select the brightest cluster galaxy within $1 h^{-1}\text{Mpc}$ in order to avoid missing BCGs in spectroscopic data due to fiber collisions. The catalogue is relatively complete in the redshift range $0.03 \leq z \leq 0.12$, including 98% of X-ray-identified clusters and 90% of Abell clusters in the same region (Miller et al. 2005). We thus limit our data within this range of redshift, obtaining 643 clusters after we reject 16 duplicates (Bernardi et al. 2007).

However, as pointed out by several previous works (e.g., Bernardi et al. 2007; von der Linden et al. 2007), some bright stars have been mis-classified as BCGs, and about 1/4 of BCGs show late-type features (e.g., distinct spiral arms, dust features). We thus re-checked each cluster and identified the brightest galaxy within $1 h^{-1}\text{Mpc}$ of the cluster center as the BCG. We then select a sample of early-type BCGs from this catalogue by excluding artifact stars and late-type galaxies. Furthermore we require the BCGs should be in clusters with richness larger than 10, and have colour typical of early-type galaxies, $g - r > 0.7$ (Strateva et al. 2001) in the SDSS model magnitudes. In the end we obtain a sample of 515 early-type BCGs in the local Universe. Figure 1 shows the distributions of redshifts of the clusters and $g - r$ colours of BCGs, which has taken into account the extinction by the SDSS, and k-correction to $z = 0.1$ (Blanton & Roweis 2007). The cluster redshifts range from 0.03 to 0.12, with a maximum around 0.08; the $g - r$ colours of BCGs peak around 0.9 with a small RMS scatter of around 0.06, consistent with their stellar populations being quite old and uniform.

3 IDENTIFICATIONS OF MAJOR DRY-MERGERS INVOLVING BCGS

Dry-mergers between gas-poor early-type galaxies are generally more difficult to identify than those mergers involving late-type galaxies (Naab et al. 2006). The latter often develop prominent tidal tails dotted with star-forming regions. However, dry-mergers have more subtle features, such as broad “fans” due to ejected stars, asymmetries in inner isophotes and/or sometimes diffuse tails (Rix & White 1989; Combes et al. 1995). While major dry-mergers usually...
Major Dry-Mergers In BCGs

Figure 1. The top panel shows the redshift distribution of redshift $z_{cl}$ for the 515 C4 clusters while the bottom panel shows the colour $g - r$ distribution of their early-type BCGs.

Figure 2. The $r$-band residual magnitudes $m_{res}$ versus the asymmetry factor $A$. The black points are the pairs in Wen et al. (2009, Fig. 5 in their paper). The 36 merger candidates with $7 < r_p < 30$ kpc are shown with red circles. Four additional mergers with $r_p < 7$ kpc are shown with red triangles. The horizontal and vertical dotted lines illustrate the criteria of Wen et al. e.g., $m_{res} < 20$ mag and $A > 0.45$ used to select major mergers. The histograms for $A$ and $m_{res}$ for the Wen et al. (2009) sample are shown at the right and bottom for major-mergers with strong interactions (solid histogram) and those classified as weak interactions or due to chance alignment (dashed histogram).

have more prominent morphological signatures than minor dry-mergers (Le Fèvre et al. 2000), they still exhibit much weaker merging features than wet-mergers.

We adopt the following criteria to select candidates of ongoing major dry-mergers involving the BCG in our sample. First, galaxies with projected distance from central BCG must satisfy $r_p < 30$ kpc. We search for close pairs both automatically and visually. In the automated search, a lower limit of the projected distance, 7 kpc, is imposed, which corresponds to a separation of 3″ at $z = 0.12$. This restriction is necessary because the photometry becomes unreliable for galaxies with smaller angular separation (McIntosh et al. 2008; Wen, Liu & Han 2009). Pairs or triples with separations smaller than 7 kpc are searched visually. Second, they should have magnitude difference with their corresponding central BCGs < 2 magnitudes in the SDSS $r$-band model magnitude. The magnitude difference applied here is slightly larger than the value (1.5) that will be eventually used to select major-mergers. The reason is that the SDSS magnitudes for BCGs are somewhat inaccurate due to the problem of sky background subtraction (Paper I). Third, both galaxies in a pair must have $g - r > 0.7$ to ensure the merging galaxies are early-type (Strateva et al. 2001). In total, there are 49 apparent close pair candidates at $7 < r_p < 30$ kpc satisfying these three conditions (pairs with $r_p < 7$ kpc are discussed below).

Most previous studies impose an additional requirement of a small difference in the line-of-sight velocities $\delta v_z$ (e.g., $\delta v_z < 500$ km s$^{-1}$) besides a small projected distance $r_p$ to avoid chance alignment. However, SDSS spectroscopic survey is severely incomplete on very small angular scales due to fiber collision (McIntosh et al. 2008; Wen, Liu & Han 2009). Hence it is not possible to apply this criterion to the SDSS data. An alternative method is needed to identify merging systems from the projected pairs and triples.

Although, as mentioned above, the interaction features (e.g., broad plumes at the outskirts, short tidal tails, bridges or asymmetries in inner isophotes) are weak in mergers of early-type galaxies, they can nevertheless be seen more clearly from the residual image after we subtract a smooth and symmetric model for each galaxy in an image (Bell et al. 2006; McIntosh et al. 2008; Wen, Liu & Han 2009). Such a procedure has been described in detail by Wen, Liu & Han (2009). For completeness, we repeat the essentials of the method below.

First, we extract the SDSS $r$-band images of all 49 close pairs and triples. The sky backgrounds are subtracted precisely from the corrected frames with the method of Paper I. Briefly, the background is subtracted as follows: all the objects including target sources in the corrected frame were firstly masked to obtain a background-only image.
Second-order Legendre polynomials are then used to fit the smoothed background-only image to obtain an accurate sky background model. After background subtraction, the GALFIT package (Peng et al. 2002) is then used to construct a smooth symmetric Sérsic (Sérsic 1968) model for every early-type galaxy in the projected pair or triple. Stars and fainter galaxies with distances closer than 2$R_{90}$ from the centre of BCGs (Here $R_{90}$ is the radius containing 90% of Petrosian flux from the SDSS catalogue) are modelled with a double-Gaussian point-spread-function (Stoughton et al. 2002) and Sérsic function respectively. Objects outside 2$R_{90}$ in the extracted images are masked. All models are convolved with the point-spread-function; we then obtain the best model by minimizing the χ² with the sky-subtracted image of unmasked pixels.

A fitted magnitude for each target galaxy and a residual image for each pair are obtained afterwards. Notice that the fitted magnitude is superior because it can separate the flux in the overlapping region of pairs and correct the overestimate in the sky background in the SDSS pipeline (Paper I). Wen, Liu & Han (2009) improved the method of Conselice et al. (2000) to calculate the asymmetry factor for residual images of galaxy pairs. Essentially it measures the difference between pixels and those symmetric pixels with respect to the centre and major axis of each galaxy (see eqs. 8-10 in their paper). The pixels in overlapping regions are treated separately (see their Figure 4). The asymmetry factor $A \sim 0$ is for a galaxy pair without any interaction feature ideally. A large $A$ means a stronger asymmetric interaction. In order to find an efficient criterion, they compared the asymmetry factors of two test samples of residual images selected through careful visual inspections: a sample with distinct interaction features and another almost without. Both are not contaminated by other objects within 2$R_{90}$ of target galaxies. The test showed that a close pair can be classified efficiently as a merging system with distinct interaction features when the residual images have an $r$-band magnitude $r_{res} < 20$ mag and an asymmetry factor $A > 0.45$. In this work, we performed further extensive tests and find that both the asymmetry parameter $A > 0.5$ and residual magnitude $r_{res} < 19.5$ can select strongly interacting mergers efficiently (see the two histograms in Figure 2). These criteria are only slightly different from those used by Wen, Liu & Han (2009). The criteria of $r_{res} < 19.5$ mag is almost the same as requiring the flux ratio of the residual image to the initial image to be larger than 2% ($f_{res}/f_{ini} > 2\%$, see the last column in Table 1).

If we limit major mergers as having a fitted magnitude difference $\delta m_r < 1.5$, we find that 36 out of 49 close pairs or triples satisfy $7 < r_p < 30$ kpc. Furthermore, 14 out of 36 have residuals $r_{res} < 19.5$ mag and asymmetry factors $A > 0.5$ (see Figure 2). Others may be weak interacting systems or pairs in chance alignment; two examples with small residuals are shown in Figure 2. We added 4 mergers (C1035, C1176, C3150, C3157) with $r_p < 7$ kpc (e.g., mergers with close double nuclei) identified visually – these systems have fiber magnitude difference $\delta m_r < 1.0$, and can be classified as merging systems if we apply the same criteria as mergers at $7 < r_p < 30$ kpc. The $r$-band observational images and corresponding residual images for these 18 mergers involving BCGs are shown in Figure 3. Their corresponding parameters are listed in Table 1.

![Figure 4. Two typical example galaxies which after subtraction show small residuals and small asymmetry factors. They are likely pairs produced by either weakly interacting with each other or chance alignment. Each image is 80″ × 80″.](image)

Bernardi et al. (2003) derived the luminosity function of early-type galaxies. In the $r$-band, the magnitude for an $L_*$ galaxy (derived from a Gaussian fit) is $M_r = -21.09$ (taking $h = 0.72$ instead of their $h = 0.70$). The BCGs in our sample have luminosities ranging from $L_*$ to roughly $\sim 10L_*$, with a mean luminosity of $\sim 5L_*$. For C4 2089, the merging pair has luminosities $11.2L_*$ and $5.6L_*$. Similarly, for C4 1055, the triple merging galaxies have luminosities $7.9L_*, 6.8L_*$ and $0.46L_*$; the two most luminous components have identical radial velocities, and thus there is little doubt that they are physically associated. Mergers appear to occur even among the most luminous galaxies in clusters (see Figure 3). If all the stars coalesce to form a single giant galaxy, then the luminosities will be as high as $16.8L_*$ and $15L_*$; such galaxies are rarely seen. This suggests that a substantial amount of stars of the companion are tidally stripped to form an “envelope” around the central galaxy, a point we return to in § 4.1.

4 RESULTS

4.1 Merger rate and stellar assembly of BCGs

We have identified 18 (∼3.5% of the total) major dry merging pairs (or triples) involving the BCG in 515 C4 clusters at 0.03 < $z$ < 0.12. It has usually been assumed that physically bound pairs will merge due to dynamical friction. The merger timescale is, however, uncertain since it depends on a number of factors, including the separation, relative velocity and mass ratios of galaxies. Kitzbichler & White (2008) noticed that previous studies on merger rates based on pair statistics have yielded a wide variety of results (see their paper for a review). This diversity can be attributed to differences in the pair definition and in the timescales adopted. They thus used the Millennium simulation to calibrate the merging timescale as a function of the stellar mass and projected separation. They find an average merging timescale (appropriate for our stellar mass and the Hubble constant):

$$t_{\text{merge}} = 2.2 \text{ Gyr} \cdot \frac{r_p}{30 \text{ kpc}} \left(\frac{M_r}{5.6 \times 10^{10} M_\odot}\right)^{-0.3} \left(1 + \frac{z}{8}\right),$$

where $M_r$ is the total stellar mass, and $z$ is the (cluster) redshift. We take a mass-to-light ratio of $M_*/L_r \approx 5M_\odot/L_\odot$ (Rines et al. 2007; Patton et al. 2000), yielding a mean total stellar mass of $M_\sim \sim 8.5 \times 10^{11} M_\odot$ for our massive mergers. We estimate the merger timescale for each merger by this formula. We find the merger timescale of our mergers ranges from 0.04 to 0.55 Gyr with a mean value of 0.3 Gyr and a standard deviation of 0.17 Gyr (see Column 11 in Table 1). For comparison, if we apply the formula of Masjedi et
al. (2006) to calculate the dynamical timescale of our mergers, we obtain a similar timescale of $\sim 0.3$ Gyr. However, a somewhat shorter dynamical friction timescale of $\sim 0.1$ Gyr is obtained if we apply the formula of Patton et al. (2000), although the dynamical friction formula may be less applicable to major mergers (Binney & Tremaine 1987). We also note that Bell et al. (2006) obtained a shorter timescale of $\sim 0.15$ Gyr from simulations for massive early-type mergers. It seems that the average merging timescale is likely uncertain by a factor of $\sim 2$.

To evaluate the number of mergers BCGs has experienced since (for example) $z = 0.7$, we need to understand how the dry-merger fraction evolves as a function of redshift. Parameterizing the evolution of pair fraction in the form of $(1 + z)^m$, several previous studies (e.g., Le Fèvre et al. 2000; Patton et al. 2002; Conselice et al. 2003; Lin et al. 2004; De Propris et al. 2005; Kartaltepe et al. 2007; Lotz et al. 2008) derive a positive slope in the range of $m \sim 0 - 3$ for all mergers (including dry or wet mergers). Lin et al. (2008), for the first time, estimated the merger fraction of red galaxies (the majority of them should be dry-mergers) decreases with redshift slightly with $m = -0.92 \pm 0.59$. This suggests that dry-mergers may preferentially occur in the local Universe. In contrast, a recent work by Khochfar & Silk (2008) suggests a nearly constant dry-merger rate at $z \lesssim 1$.

If we adopt an average merger timescale, and assume a constant fraction (18/515 $\sim 3.5\%$) of BCGs are in major dry-mergers over the 6.3 Gyr interval since redshift 0.7, then a present-day early-type BCG will have experienced $6.3/t_{\text{merge}} \times 18/515 \sim 0.7(t_{\text{merge}}/0.3 \text{Gyr})^{-1}$ major dry-mergers. On the other hand, if the fraction evolves as $(1 + z)^{-0.92 \pm 0.59}$ (Lin et al. 2008), then the number of mergers changes to $\sim 0.5(t_{\text{merge}}/0.3 \text{Gyr})^{-1}$. Below we adopt an average number of mergers of these two evolution scenarios, $0.6(t_{\text{merge}}/0.3 \text{Gyr})^{-1}$. In any case, the uncertainty in the merger timescale is much larger than that due to the evolution of the merger rate.

Our merger pairs/triples have an average magnitude difference of $\sim 0.7$, which corresponds to a $\sim 1 : 2$ luminosity ratio. In the merging process, a substantial fraction of the companion galaxy may be tidally stripped, and so not all the mass of the companion galaxy will be added to the main one (Yang et al. 2009). We assume a fraction of $f_{\text{mass}}$ of the companion galaxy is accreted to the primary galaxy. Thus in each merger, the central galaxy increases its luminosity (or mass) by $25\%(f_{\text{mass}}/0.5)$. It follows that a present-day BCG has on average increased its luminosity by $15\%(t_{\text{merge}}/0.3 \text{Gyr})^{-1}(f_{\text{mass}}/0.5)$ from $z = 0.7$ at a rate of $2.5\%(t_{\text{merge}}/0.3 \text{Gyr})^{-1}(f_{\text{mass}}/0.5)$ per Gyr. Thus a non-negligible fraction of the stellar mass of a present-day early-type BCG is assembled via major dry-mergers since $z = 0.7$. 

Figure 3. The colour images and corresponding residual images in the r-band for the 18 identified major mergers. Each image is $80'' \times 80''$. The SDSS-C4 name for the DR2 version is marked at the top left corner of each colour image.
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Table 1. Basic parameters for the 18 identified major dry-mergers involving BCGs

| C4 ID | zmag   | M_{tot} (mag) | R.A.(J2000) | Dec.(J2000) | zsp | r_p (kpc) | δv_r (km s^{-1}) | m_r (mag) | M_r (mag) | t_{merge} (Gyr) | A | m_res (mag) | f_{res/fini} (%) |
|-------|--------|---------------|-------------|-------------|-----|-----------|-----------------|-----------|-----------|----------------|---|------------|----------------|
| 1000  | 0.0864 | -23.36        | 202.543925  | -2.105012   | 0.0866 | 15.42     | -22.62          | 0.32       | 0.75      | 17.98          | 5.2 |
| 1004  | 0.0814 | -23.30        | 149.717402  | 1.059187    | 0.0814 | 14.90     | -22.99          | 0.27       | 0.78      | 19.04          | 2.5 |
| 1011  | 0.0903 | -23.91        | 227.107326  | -0.266266   | 0.0903 | 14.87     | -23.27          | 0.39       | 2.71      | 17.79          | 5.1 |
| 1026  | 0.0908 | -24.16        | 191.926938  | -0.137254   | 0.0908 | 14.50     | -23.65          | 0.28       | 1.15      | 18.36          | 2.3 |
| 1035* | 0.0444 | -22.95        | 175.872249  | -1.667968   | 0.0446 | 16.11     | -23.09          | 0.04       | 0.69      | 18.46          | 2.1 |
| 1055  | 0.0836 | -24.03        | 202.795056  | -1.727285   | 0.0836 | 14.61     | -23.34          | 0.28       | 0.62      | 18.39          | 2.1 |
| 1060  | 0.1170 | -23.29        | 212.497855  | -1.539655   | 0.1170 | 15.87     | -22.91          | 0.17       | 3.49      | 19.09          | 4.2 |
| 1176* | 0.0737 | -23.90        | 189.734808  | 6.158386    | 0.0738 | 17.06     | -23.09          | 0.11       | 1.53      | 17.34          | 3.3 |
| 1304  | 0.0986 | -22.69        | 148.914494  | 1.596777    | 0.0986 | 16.12     | -22.23          | 0.50       | 0.87      | 18.55          | 7.4 |
| 1364  | 0.0708 | -22.75        | 154.700071  | 0.385141    | 0.0708 | 15.06     | -22.49          | 0.50       | 0.82      | 18.54          | 4.9 |
| 2049  | 0.0751 | -23.89        | 16.841087   | 14.273229   | 0.0751 | 14.05     | -23.64          | 0.13       | 0.77      | 18.04          | 2.2 |
| 2089  | 0.0652 | -24.15        | 59.582654   | -5.538873   | 0.0652 | 13.65     | -23.71          | 0.27       | 0.86      | 17.92          | 5.1 |
| 2179  | 0.0938 | -22.24        | 322.027369  | 11.405484   | 0.0938 | 16.71     | -21.53          | 0.47       | 0.57      | 18.43          | 10.6|
| 3059  | 0.0406 | -22.47        | 122.14887   | 38.914504   | 0.0406 | 14.26     | -22.00          | 0.43       | 1.12      | 17.62          | 4.4 |
| 3150* | 0.0456 | -22.05        | 134.299844  | 53.470904   | 0.0456 | 16.43     | -21.32          | 0.06       | 0.71      | 17.72          | 4.8 |
| 3157* | 0.0635 | -24.10        | 176.404931  | 64.511845   | 0.0635 | 16.37     | -23.72          | 0.49       | 0.53      | 19.29          | 3.5 |
| 3166  | 0.1112 | -24.04        | 192.035328  | 64.036916   | 0.1112 | 14.93     | -22.72          | 0.55       | 1.92      | 19.01          | 3.05|
| 3167  | 0.0915 | -23.36        | 256.014668  | 33.872002   | 0.0915 | 15.88     | -22.29          | 0.55       | 1.92      | 19.01          | 3.05|

Note: Col:(1). The C4 cluster ID (DR2) for the Clusters. The four visually-selected ones (indicated by *) have r_p < 7 kpc (see [1]). Col:(2). Redshifts of identified merging pairs (or triples). Col:(3). Total absolute magnitude of mergers in the SDSS r-band. Col:(4). R.A. (J2000) of the component galaxy in a merger. Col:(5). Dec. (J2000) of the component galaxy in a merger. Col:(6). Spectroscopic redshift of the component galaxy in a merger. Col:(7). The projected distance, r_p. Col:(8). The line-of-sight velocity difference, δv_r. Col:(9). Extinction-corrected r-band fitted apparent magnitude of component galaxy in a merger. Col:(10). r-band absolute magnitude of component galaxy in a merger, corrected for extinction (by SDSS) and the k-correction (using the KCORRECT algorithm of Blanton & Roweis 2007). Col:(11). The merger timescale estimated by the formula of Kitzbichler & White (2008). Col:(12). The asymmetry factor for the residual image. Col:(13). r-band apparent magnitude of the residual image. Col:(14). The flux ratio of residual and initial image within 3R_e (Here R_e is the fitted effective radius from our model).

4.2 Dependence on environments

In the hierarchical structure formation model, clusters of galaxies form through mergers of sub-clusters and small groups; in the process central galaxies are expected to grow together with clusters. This scenario suggests that the evolution of BCGs may depend on the environments. We thus examine the relation between the fraction of BCGs involved in major dry-mergers and the richness of the parent clusters.

Figure 5 shows the results. The fraction of merging BCGs appears to increase as the clusters become richer. A simple linear fit in the form of fraction = A log richness + B yields A = 0.11 ± 0.04, B = -0.12 ± 0.05 (shown as the solid line), and so the significance is not very high due to the large error bars. The higher frequency of more massive dry-mergers in richer clusters will lead to more luminous (or
more massive) BCGs. This is empirically seen in observations, as illustrated in the bottom panel of Figure 5.

5 SUMMARY AND DISCUSSION

In this work, we have searched for BCGs involved in major dry-mergers in a sample of early-type BCGs selected carefully from C4 cluster catalogue (Miller et al. 2005). 18 (∼3.5%) major dry-mergers involving BCGs have been identified out of 515 clusters at 0.03 ≤ z ≤ 0.12. These major mergers are selected as pairs (or triples) with r-band magnitude difference δm < 1.5 and projected separation rp < 30 kpc, and showing signatures of interaction in the form of significant asymmetry in residual images.

To double check whether our results are affected by the choice of the cluster (C4) catalogue (based on DR2 of SDSS), we have also searched for major dry-mergers involving BCGs in the sample of 625 clusters refined by von der Linden et al. (2007) from the unpublished DR3 version of C4 clusters. Their sample selects preferentially early-type BCGs and discards clusters with very few member galaxies. For this sample, we find 27 (27/625 = 4.3%) BCGs are involved in major dry-mergers, entirely consistent with the fraction (3.5%) found here for the C4 cluster catalogue. It should be emphasized that the goal of our method is to identify merging pairs with strong interaction features and calculate their true fraction in BCGs. They should be real, physically bound pairs. However, some physical bound pairs may not yet show strong interaction signatures. Our estimated fraction should thus be considered as the lower limit of physical pair fraction in BCGs.

From the identified major-merger candidates, we conclude that a present-day BCG may have experienced 0.6 (tmerge/0.3 Gyr)−1 major dry-mergers and increased their mass by 15% (tmerge/0.3 Gyr)−1 (fmass/0.5) on average from z = 0.7. This fraction is comparable to the mass increase predicted by mostly minor mergers in semi-analytical galaxy formation models of De Lucia & Blaizot (2007), if all mass of companion galaxies are added to BCGs (fmass = 1) as De Lucia & Blaizot (2007) assumed. However, the mass increase we found here is due to major-mergers rather than minor majors. Bernardi (2009) concluded that the evolution of BCGs in the velocity dispersion-stellar mass relation favors the growth of BCGs via many dry minor-mergers. However, the evidence is not very strong (see her Fig. 8). A more detailed comparison between theory and observations is desirable.

The major uncertainties in our estimates arise due to the calibration of the merging timescale and the fraction of the satellite galaxy that will be added to the central host. For the former, we used the calibration of Kitzbichler & White (2008) derived from the Millennium simulation. However, it remains to be seen whether their calibration applies well to the dense environments such as clusters of galaxies. The parameter fmass is also somewhat uncertain. The stellar mass not accreted to the central host may form the envelopes in cD galaxies and/or the intracluster light (Lin & Mohr 2004; Rines et al. 2007; Paper I and reference therein). We notice, however, that if all the mass is assembled into the final BCGs, some of them may be too bright; the resulting luminosity function at the bright end may be inconsistent with the observations which show little evolution at L > 2.5L∗ (e.g., Brown et al. 2007; Cool et al. 2008). We conclude that a substantial fraction of the companion mass must be stripped, consistent with the presence of envelopes in giant cD galaxies (e.g., Paper I).

We have also checked the radio properties of BCGs to investigate whether major mergers trigger the phenomenon of active galactic nuclei. We cross-correlate our sample with the radio data from the FIRST survey (Becker, White & Helfand 1995). There are 94 (∼18.3%) sources with radio emission out of 515 BCGs; these fractions are consistent with the statistics of Best et al. (2007) and Croft, de Vries & Becker (2007). In comparison, there are 3 radio sources
which may explain why their merger fraction (the merger frequency increases as a function of halo mass, and this is confirmed by our studies. In addition, they find that massive mergers tend to appear in richer systems, a conclusion supported by our studies. In other words, we are probing the most massive end of their SDSS “groups” in terms of mass range from $10^{13.5} M_\odot$ to $10^{15} M_\odot$. They find that more massive mergers tend to appear in richer systems, a conclusion confirmed by our studies. In addition, they find that the merger frequency increases as a function of halo mass, which may explain why their merger fraction (~2.1%) is slightly lower than ours (3.5%). The mass increase rate we find for the BCGs is roughly consistent with their results (2%-9% per Gyr under similar assumptions). We conclude that major dry-mergers in BCGs are not rare events in the local Universe and they are an important way to assemble luminous BCGs.

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