Ongoing growth of the brightest cluster galaxies via major dry mergers in the last ~6 Gyr

F. S. Liu,1,2* F. J. Lei,2,3 X. M. Meng3 and D. F. Jiang2

1 Center for Theoretical Physics and Astrophysics, Shenyang Normal University, Shenyang 110034, China
2 College of Physical Science and Technology, Shenyang Normal University, Shenyang 110034, China
3 National Astronomical Observatories, Chinese Academy of Sciences, A20 Datun Road, Beijing 100012, China

Accepted 2014 November 28. Received 2014 November 18; in original form 2014 August 1

ABSTRACT
Brightest cluster galaxies (BCGs) might have been assembled relatively late (z < 1) via mergers. By exploiting the high-resolution HST/ACS imaging, we find four BCGs (COSMOS-P 125516, 102810, 036694 and 089357) in major dry merging in 29 X-ray clusters at 0.3 ≤ z ≤ 0.6 in the Cosmological Evolutionary Survey (COSMOS). These BCGs show prominent but quiescent double nuclei with a magnitude difference of δm < 1.5 and a projected separation of r_p < 10 kpc. Clear signatures of interaction such as extended plumes and/or significant asymmetries are also observed in their residual images. We infer a major merger rate of 0.55 ± 0.27 merger per Gyr at z ~ 0.43 assuming the merger time-scale estimate of Kitzbichler & White. This inferred rate is significantly higher than the rate in the local Universe (0.12 ± 0.03 at z ~ 0.07) presented by Liu et al. We estimate that present-day BCGs increase their luminosity (mass) by ∼35 ± 15 percent (f_{mass}/0.5) via major dry mergers since z = 0.6, where f_{mass} is the mean mass fraction of companion galaxies accreted on to the central ones. Although the statistical uncertainty due to our small sample size is relatively large, our finding is consistent with both recent observational and theoretical results. Furthermore, in conjunction with our previous findings by Liu et al., the discovery of these intermediate-redshift merging BCGs is clear evidence of ongoing assembly of BCGs via major dry mergers over the last ~6 Gyr.

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

1 INTRODUCTION
Brightest cluster galaxies (BCGs) are among the most luminous and most massive galaxies in the Universe. They are usually located close to the centres of dense clusters of galaxies as witnessed in the X-ray or gravitational lensing observations (e.g. Jones & Forman 1984; Smith et al. 2005). Except in strong cooling flows, they are dominated by old stars and they lack prominent ongoing star formation (von der Linden et al. 2007; Liu et al. 2012a,b). It was noted very early on that some BCGs show excess of light (‘envelopes’) relative to the de Vaucouleurs (r^{1/4}) profile at large radii (Matthews, Morgan & Schmidt 1964; Schombert 1988; Graham et al. 1996) and were thus termed as cD galaxies. Recent studies have identified cD galaxies using improved Petrosian (Petrosian 1976) parameter profiles (Brough et al. 2005; Patel et al. 2006; Liu et al. 2008). A large fraction of massive nearby BCGs can be classified as cD galaxies (Liu et al. 2008).

*E-mail: fengshan.liu@yahoo.com

In order to understand the formation and evolution of BCGs/cDs, several formation mechanisms including galactic cannibalism (White 1976; Ostriker & Hausman 1977), tidal stripping of stars from interacting galaxies in clusters (Gallagher & Ostriker 1972; Richstone 1976; Merritt 1985) and star formation by cooling flows onto BCGs (Fabian 1994) have been proposed in early studies. Recent numerical simulations and semi-analytic models of galaxy formation suggested that BCGs form in a two-phase process: an initial collapse with rapid cooling and star formation at high redshift is followed by later (z < 1) growth through multiple dissipationless (dry) mergers of pre-existing progenitors (e.g. De Lucia & Blaizot 2007; Ruszkowski & Springel 2009; Naab, Johansson & Ostriker 2009; Laporte et al. 2012, 2013). These studies, however, differ in their predictions of stellar mass growth rates and/or the role of mergers. For instance, De Lucia & Blaizot (2007) predict that the stellar mass of BCGs increase by a factor of ~4 between redshift z = 1 and z = 0 via accretion of smaller galaxies (minor mergers). More recent simulations in a Λ cold dark matter universe in Laporte et al. (2013) show that BCGs can form through dissipationless mergers of quiescent massive z = 2 galaxies and predict a lower stellar mass growth for BCGs by both major and minor

© 2014 The Authors
Published by Oxford University Press on behalf of the Royal Astronomical Society
mergers, with mass growth of a factor of 2.1 over the redshift interval $z \sim 1.0–0.3$ and a further factor of $\sim 1.4$ between $z = 0.3$ and the present day.

Observationally, a vast number of studies over the last few years provide evidence that BCGs have experienced dry mergers (e.g. Bernardi et al. 2007; Lauer et al. 2007; von der Linden et al. 2007; Liu et al. 2008) and have built up a large part of their stellar mass via mergers at $z < 1$ (e.g. Liu et al. 2009, 2013; Edwards & Patton 2012; Lidman et al. 2012; Tsviannian & Andernach 2012). The estimated mass growth factors in these studies (Burke & Collins 2013; Lidman et al. 2013; Ascaso et al. 2014) range from $\sim 1.8$ to $\sim 2.5$, suggesting major mergers as the primary formation mechanism.

However, contrary to the above observations and the most recent simulations (e.g. Laporte et al. 2013), there are other studies that advocate for little change in stellar masses and sizes of BCGs since $z = 1$ (e.g. Collins et al. 2009; Stott et al. 2010, 2011). These studies compared high- redshift BCGs in X-ray clusters to their counterparts in present-day clusters of the same X-ray luminosity. They claimed that the X-ray selected systems at $z \sim 1$ already have more than 90 per cent of their final stellar mass and $\sim 70$ per cent of their final sizes. A possible interpretation of this discrepancy could be a selection bias (Lidman et al. 2013), or an early relaxation of high-redshift BCGs in X-ray clusters, which would therefore imply that they change little in their subsequent evolution.

Direct observational evidence for dry merging has indeed been found in low-redshift ($z < 0.3$) central galaxies in groups and clusters by a number of researchers (e.g. Lauer 1988; McIntosh et al. 2008; Liu et al. 2009; Rasmussen et al. 2010; Brough et al. 2011; Edwards & Patton 2012). Some evidence has also been presented at higher redshift ($z > 0.3$). 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 a observational analysis of supergroup SG 1120–1202 at $z \sim 0.37$, which is expected to merge and form a cluster as massive as to Coma cluster. They argued that group environment is critical for the process of major dry merging. Rines, Finn & Vikhlinin (2007) reported a very massive cluster (CL0958+44702) at $z = 0.39$, in which a major dry merger is ongoing to build up the more massive BCG. They argued that major mergers might be fairly common in deep images of galaxy clusters at intermediate redshifts, and BCGs may be assembled through late major mergers. Lidman et al. (2013) identified three merging pairs in their high-redshift cluster sample, only the pair in RDCX 1252 ($z = 1.238$) shows evidence for a merger.

In the local Universe, it is known that the incidence rate of major mergers involving central galaxies in clusters (Liu et al. 2009) is higher than that in groups (McIntosh et al. 2008). In this work, we perform a search for ongoing major mergers in a homogeneous sample of intermediate-redshift clusters. We find four BCGs (COSMOS-P 125516, 102810, 036694 and 089357) in major dry merging in 29 X-ray-selected clusters at $0.3 \leq z \leq 0.6$ in the Cosmological Evolutionary Survey (COSMOS) catalog (Finoguenov et al. 2007). The high-resolution $HST/ACS F814W$ band imaging data reveal the prominent morphological signatures of dry mergers (close and comparable multiple nuclei, broad surrounding plumes and/or significant asymmetries in the isophotes) in these systems. We studied their stellar population, investigated possible connection of mergers with the formation of BCG envelopes, and discussed the stellar assembly of BCGs in the last $\sim 6$ Gyr. Throughout the paper, we adopt a cosmology with a matter density parameter $\Omega_m = 0.3$, a cosmological constant $\Omega_L = 0.7$ and a Hubble constant of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2 IDENTIFICATIONS OF BCGs AND MAJOR MERGERS

We searched for BCGs involved in major mergers in a catalogue of X-ray clusters published by Finoguenov et al. (2007, hereafter F07), which includes 72 X-ray clusters at $z_f < 1.3$ identified from the first 36 $XMM$–$Newton$ pointings on the $\sim 1.7$ deg$^2$ COSMOS field. We restricted our search in 29 X-ray clusters in the redshift interval of $z = 0.3–0.6$. It is difficult to identify dry merger features, such as broad stellar ‘fans’ and diffuse tails (Rix & White 1989; Combes et al. 1995), at higher redshift with $HST/ACS F814w$-band images in COSMOS because of the significant effects of cosmic surface brightness dimming and bandpass shifting. Despite the small size of this sample, it is a more statistically homogeneous sample compared to other samples collected from many small $HST$ snapshot programmes, since COSMOS is the largest contiguous field ever imaged with $HST$.

The F07 X-ray cluster catalogue provides the centre and the photometric redshift of each cluster candidate, but it does not provide the BCG candidate in each cluster. The cluster centre is defined by the peak of X-ray emission. The majority of photometric redshifts are estimated using the early photo-$z$ catalogue of galaxies in COSMOS (Mobasher et al. 2007) and the rest of the photometric redshifts are from other sources (see F07 for details). The accuracy of photo-$z$ in the catalogue of Mobasher et al. (2007) is $\sigma_{\Delta z}/(1+z) \sim 0.027$. Subsequently, Ilbert et al. (2009) improved the photo-$z$ accuracy by using 30-band photometric data and provided absolute magnitudes in the Subaru $V_j$ band for galaxies in the $\sim 2$ deg$^2$ COSMOS field. The accuracy of photo-$z$ is improved to $\sigma_{\Delta z}/(1+z) \sim 0.012$. Since the used photometric redshifts in F07 have larger uncertainties, in order to select reliable BCG candidates, we first selected galaxies within the radius of 1 Mpc from the cluster centre and a photo-$z$ gap of $z \pm 3\sigma_{\Delta z}$ as temporary member candidates in a cluster. We re-calculated the cluster redshift to be the median value of photometric redshifts of the recognized ‘members’ using the more accurate photo-$z$ values in Ilbert et al. (2009). We then applied this newly-derived cluster redshift to re-select member candidates within the radius of 1 Mpc from a given cluster centre and a photo-$z$ gap of $z \pm 1.44\sigma_{\Delta z}$, and re-calculated the absolute magnitudes of these member galaxies. In this step, we used the spectroscopic redshifts instead of photo-$z$ if they were available from the $z$COSMOS redshift survey (Lilly et al. 2009). We also supplemented the photometric redshifts for X-ray sources from Salvato et al. (2009). The brightest one in the member galaxies in a cluster is finally selected as our BCG candidate.

We then extracted the imaging data of 29 sample BCGs from COSMOS Archive website1 and performed visual inspection. Four BCGs (COSMOS-P 125516, 102810, 036694 and 089357) in the corresponding clusters with ID of 52, 64, 120, 80 in the F07 catalogue caught our high attention due to significant merging features, such as close multiple nuclei and extended surrounding plumes, shown in the high-resolution $HST/ACS F814W$-band images. Their composite pseudo-colour images made with the Subaru $B_j$, $V_j$, $i^\prime$-band images (top panels) and $HST/ACS F814W$-band images (middle panels) are shown in the Fig. 1, respectively. Some characteristics of these candidates are listed as follows, ordered in increasing redshift (hereafter the same ordering will be adopted). Note that there are the spectroscopic redshifts available for COSMOS-P.

\begin{enumerate}
  \item \cite{http://irsa.ipac.caltech.edu/data/COSMOS/}
\end{enumerate}
Ongoing growth of BCGs via major dry mergers

The composite pseudo-colour images made with the Subaru $B_J$, $V_J$, $i^+$-band images (top), HST/ACS $F814W$-band images (middle) and corresponding residual images (bottom) for four identified BCGs in major merging, respectively. The small black boxes (3 arcsec × 3 arcsec) in each pseudo-colour image mark the central and outer plume regions analysed in Section 3. The masked regions (green) in the HST/ACS $F814W$-band images during our modelling procedure are also shown. The central region (3 arcsec × 3 arcsec box) are shown in logarithmic min/max scale on the bottom-right corner of the HST/ACS $F814W$-band images, which can reveal the spectacular multiple nuclei more clearly. The centres are determined by averaging the outer isophotes between the measured $R_e$ and $2R_e$ (see Section 4). In each image, north is up and east is to the left.

We further quantified our visual inspection with a method used in previous studies (Liu et al. 2009; Wen, Liu & Han 2009) to efficiently identify merging signatures in the absence of spectroscopic information for merging members. We applied the GALFIT package (Peng et al. 2002) to construct a smooth symmetric Sérsic (Sérsic 1968) model for every target member in the projected merging list. The modelling procedure gives a fitted magnitude for each target member and a residual image for each candidate. All these candidates have at least a pair of members (nuclei) with the magnitude difference $\delta m_{fit} < 1.5$, which can be classified as major mergers (Bell et al. 2006). All of them have significant residuals and merging signatures, which are seen more clearly in their residual images (see the bottom panels of Fig. 1). The magnitudes of the four residual images are 19.49, 19.34, 19.99 and 19.94, which correspond to 16.1, 18.6, 16.4 and 19.9 percent of their initial images, respectively. The asymmetric factor ($A$) for each residual can be calculated following the method of Wen et al. (2009). This factor measures the brightness difference between pixels and those of symmetric pixels with respect to centres of target

125516 and 036694 only. We used the photometric redshifts available in Ilbert et al. (2009) for the other two candidates.

COSMOS-P 125516 is a typical pair of early-type galaxies with a projected separation of 1.77 arcsec ($\sim$8.75 kpc). The merging features (e.g. bridges and plumes) are obvious.

COSMOS-P 102810 looks such as a merging ‘pair’ of early-type galaxies, but the high-resolution HST/ACS imaging reveals spectacular double nuclei in one of members, which have a projected separation of only 0.12 arcsec ($\sim$0.63 kpc). Broad surrounding plumes to the north-west of its image can be seen clearly, extending to $>9$ arcsec ($\sim$47 kpc, also see Section 4).

COSMOS-P 036694 is a triple system. The two closest nuclei have a projected separation of only 0.45 arcsec ($\sim$2.74 kpc). Broad surrounding plumes, extending to $>10$ arcsec ($\sim$60 kpc), is also obvious on the north-west of the BCG.

COSMOS-P 089357 has close double nuclei with a projected separation of 1.06 arcsec ($\sim$6.51 kpc). It has very broad and symmetric stellar plumes extending to $>10$ arcsec ($\sim$61 kpc) along the semimajor axis.
members. The derived \(A\) values for COSMOS-P 125516, 102810, 036694 and 089357 are 2.71, 2.97, 2.87 and 1.56 for their inner regions within 3 arcsec aperture (1.5 arcsec radius), respectively. The \(A\) values become 1.35, 1.56, 1.42 and 0.25 for the regions within twice measured effective radius (2\(R_e\)). It shows that these candidates have significant asymmetry in their inner and/or outer isophotes (e.g. \(A > 0.45\), Wen et al. 2009). Note that the outer isophotes of COSMOS-P 089357 are relatively symmetric, indicating this merging system has been well relaxed in its outskirts and a perfect structure resembling cD galaxy has formed (see Section 4). Some derived parameters for four candidates are listed in Table 1.

### 3 STELLAR POPULATION ANALYSIS

We investigated stellar population of four major mergers by fitting their spectral energy distributions (SEDs) in optical and near-infrared broad-bands measured from multiwavelength imaging data available in COSMOS survey. We used the CFHT \((u^\prime-, i^\prime-\text{ and } K_s\)-band), Subaru \((B_J-, V_J-, g^\prime-, r^\prime-\text{ and } z^\prime\)-band) and UKIRT \((J\text{-band})\) observations because they are also deep and with high spatial resolution (0.15 arcsec/pixel). Since it has been shown that the evolutionary composite stellar populations (CSPs) can more exactly describe the evolutionary history of COSMOS galaxies (Bolzonella et al. 2010), we followed Bolzonella et al. (2010) to construct a series of evolutionary CSP templates from the libraries of simple stellar populations (SSPs) of Bruzual & Charlot (2003, hereafter BC03) with exponentially declining star formation histories (SFHs), with e-folding times \(\tau = 0.1, 0.2, 0.3, 0.5, 1\) and 2 Gyr. We used an updated version of the code HYPERZ (Bolzonella, Miralles & Pelló 2000), kindly made available to us by M. Bolzonella, which performs SED fitting at a fixed redshift. We performed the best fittings on the observed SEDs in the regions of centres and outer plumes within 3 arcsec boxes (marked on the top panels of Fig. 1) with the fixed solar metallicity and Chabrier initial mass function (Chabrier 2003). The dust extinction was modelled using the Calzetti extinction law (Calzetti et al. 2000). The results (see Fig. 2) show the SEDs of both centres and outer plumes of four systems can be well described by an exponentially declining SFH with a very short e-folding time (0.1–0.3 Gyr) and with extremely low specific star formation rates \((\text{sSFRs} < 10^{-2} \text{ Gyr}^{-1})\). The results from the SED fitting indicate that the SFH of these four BCGs is consistent with that of typical quiescent elliptical galaxies.

The Sloan Digital Sky Survey has spectroscopic data available for COSMOS-P 125516 and 036694, which have the signal-to-noise ratio (S/N) of 12.27 and 10.88, respectively. Since their SFHs can be well modelled by an exponentially declining SFH with very short e-folding time-scale (\(\tau \leq 0.3\)) that is close to an instantaneous burst (\(\tau = 0\)). We follow Liu, Mao & Meng (2012b) to adopt a serial of spectral templates of SSP with the fixed solar metallicity but different ages to estimate the light and mass percentage ratios of their stellar populations at different ages (Fig. 3). We show that the light-to-mass ratio among young \((\tau < 0.5 \text{ Gyr})\), intermediate-age \((0.5 < \tau < 2.5 \text{ Gyr})\) and old \((\tau > 2.5 \text{ Gyr})\) stellar population is 3.37 : 25.95 : 70.68 and 0.29 : 4.51 : 95.20 for COSMOS-P 125516, and 16.73 : 0 : 83.27 and 0.18 : 0 : 99.82 for COSMOS-P 036694, respectively. It shows that recent star formation only contributes a very small (even negligible) percentage to their stellar mass. This result is roughly consistent with the finding in our early study of low-redshift BCGs (Liu et al. 2012b).

### Table 1. Basic parameters for four identified BCGs in major dry merging.

| Cluster ID | L_{0-2.4 keV} | BCG ID | R_{e} | M_{*} | f_{\text{res}} | f_{\text{res}}/f_{\text{peak}} | \text{merger time-scale (Gyr)} | \text{projected separation of members within }2e\text{ (kpc)} | \text{merger age (Gyr)} | \text{residual flux (mag)} | \text{residual flux (mag)} |
|------------|---------------|--------|-------|------|---------------|------------------------|-------------------------------|---------------------------------|-----------------------------|--------------------------|--------------------------|
| 036694     | 110.2 ± 10    | COSMOS-P 089357 | 150.1 ± 12 | 102810 | 0.17 ± 0.02 | 0.23 ± 0.04 | 1.81 ± 0.06 | 19.1 ± 0.3 | 7.3 ± 2.0 | 0.02 ± 0.01 | 0.02 ± 0.01 |
| 125516     | 150.3 ± 12    | COSMOS-P 102810 | 150.3 ± 12 | 036694 | 0.18 ± 0.02 | 0.24 ± 0.04 | 1.91 ± 0.06 | 19.2 ± 0.3 | 7.4 ± 2.0 | 0.02 ± 0.01 | 0.02 ± 0.01 |
| 102810     | 150.4 ± 12    | COSMOS-P 036694 | 150.4 ± 12 | 036694 | 0.19 ± 0.02 | 0.25 ± 0.04 | 2.01 ± 0.06 | 19.3 ± 0.3 | 7.5 ± 2.0 | 0.02 ± 0.01 | 0.02 ± 0.01 |
| 089357     | 150.5 ± 12    | COSMOS-P 125516 | 150.5 ± 12 | 036694 | 0.20 ± 0.02 | 0.26 ± 0.04 | 2.11 ± 0.06 | 19.4 ± 0.3 | 7.6 ± 2.0 | 0.02 ± 0.01 | 0.02 ± 0.01 |
Ongoing growth of BCGs via major dry mergers

The best fittings on the observed SEDs in the regions of centres (left-hand panels) and outer plumes (right-hand panels) of COSMOS-P 125516, 102810, 036694 and 089357 (from top to bottom), respectively. Red dots are the observed data. The best-fitting spectra are from a series of evolutionary CSPs models constructed following Bolzonella et al. (2010). The e-folding time (τ) shown on bottom-right corner of each panel is the closest value that the target region has in the exponentially declining SFHs. The derived sSFR and A^V for each region are also presented. The sizes of observed data dots are larger than their error bars.

### 4 ENVELOPES AND MERGING PROCESS

The surface brightness profiles of a large fraction of local BCGs show strong deviation from a perfect de Vaucouleurs (de Vaucouleurs 1948) or Sérsic (Sérsic 1968) profile since these BCGs are embedded in extensive luminous stellar haloes. The envelopes (haloes) in BCGs can be recognized more clearly by identifying the signatures of plateau in the Petrosian η(r) profiles and valley in the γ(r) = dη(r)/dlog (r) profiles (Liu et al. 2008). We have presented evidence that the formation of extended stellar envelopes in local BCGs are closely connected with dry merger process by analysing the gradient of their Petrosian profiles (see Liu et al. 2008, for details). Here we investigate if such envelopes are observed in these merging systems at intermediate redshift. We performed the surface photometry on these four systems following the method used in Liu et al. (2008). Fig. 4 shows their surface brightness profiles to 26 mag arcsec^−2 in HST/ACS F814W band, corresponding Petrosian η(r) profiles and γ(r) profiles from top to bottom, respectively. It can be seen that these parameter profiles fluctuate significantly in inner regions (within the radius marked with red vertical dashed lines in Fig. 4) due to the existence of multiple nuclei. However, their light profiles at large radii are relatively smooth. There are obvious plateaus in the η(r) profiles and valleys in the γ(r) profiles of all four mergers. The D_{min} values derived in the dη(r)/dlog (r) profiles of four systems (COSMOS-P 125516, 102810, 036694 and 089357) are 0.91, 1.89, 1.81 and 1.90 (see the bottom panels in Fig. 4), respectively. These values are larger than the median D_{min} value (∼0.8) for local BCG sample in Liu et al. (2008). It shows that they have extended envelopes in their outskirts and are likely forming cD galaxies; moreover, the broad stellar fans can also be seen clearly on their images (see the bottom panels of Fig. 1). The signatures of cD galaxies in both intermediate-redshift and local merging BCGs (Liu et al. 2009) and the fans corresponding to cD galaxy envelopes suggest that the extended stellar haloes of BCGs are likely due to major mergers and they appear shortly after merger takes place.

### 5 MAJOR MERGER RATE AND STELLAR ASSEMBLY OF BCGS

We have identified four BCGs in major dry merging in 29 X-ray clusters at 0.3 ≤ z ≤ 0.6 (with a median value of z ≈ 0.43). We estimate the merger time-scale for each merger by the equation 1 in Liu et al. (2009), which is derived from the Millennium Simulation by Kitzbichler & White (2008). We find that the merger time-scale of our mergers ranges from 0.22 to 0.32 Gyr with a mean value of 0.25 Gyr. (see Column 11 in Table 1). Thus, we obtain a major dry...
Figure 4. The HST/ACS F814W band surface brightness profiles, Petrosian $\eta(r)$ profiles and $d\eta(r)/d\log(r)$ profiles for four merging BCGs, respectively. The surface brightness profiles have been corrected for cosmic dimming. The equivalent radius of an ellipse, $r_{\text{ab}} \equiv \sqrt{a^2 + b^2}$, is used, where $a$ and $b$ are the lengths of semimajor and semiminor axes of the best-fitting ellipse. The red horizontal lines in the first rows show the surface brightness of 26 mag arcsec$^{-2}$. The red vertical line in each panel marks the radius, within which the profiles fluctuate significantly due to the existence of multiple nuclei. The depths of valleys in $d\eta(r)/d\log(r)$ profiles are indicated with red horizontal dotted lines and corresponding $D_{\text{min}}$ values are presented.

merger rate of $0.55 \pm 0.27$ merger per Gyr at $z \sim 0.43$, where the error is assumed to be a Poisson error. In our previous work (Liu et al. 2009), we used a broader criterion to select 18 ($\sim 3.5$ per cent of the total) major dry merging pairs (or triples) involving the BCG in 515 C4 clusters at $0.03 \leq z \leq 0.12$ (with a median value of $z \sim 0.07$). The time-scale of those local mergers ranges from 0.04 to 0.55 Gyr with a mean value of 0.3 Gyr (see Liu et al. 2009, for details). A major merger rate of $0.12 \pm 0.03$ at $z \sim 0.07$ can thus be determined as well. Parameterizing the evolution of major merger rate in the form of $(1 + z)^m$, we find that $m = 5.2 \pm 2.4$ at $z \leq 0.6$. Here, we stress that the number of BCGs in our intermediate-redshift sample is small and the resulting statistical uncertainty is relatively large. The two predominant members (nuclei) in our intermediate-redshift mergers have an average magnitude difference of $\sim 0.79$, which is comparable to that ($\sim 0.7$) of local merger pairs/triples in Liu et al. (2009) and corresponds to an $\sim 1:2$ luminosity ratio. We assume a fraction of $f_{\text{mass}}$ of the companion galaxy is accreted to the primary galaxy. Therefore, in each merger the central galaxy increases its luminosity (mass) by 25 per cent ($f_{\text{mass}}/0.5$) on average. If the major merger rate evolves in our estimated form above since $z = 0.6$ and the merger time-scale follows the formula of Kitzbichler & White (2008), it follows that a present-day BCG has on an average increased its mass (luminosity) by $\sim 35 \pm 15$ per cent ($f_{\text{mass}}/0.5$) from $z = 0.6$ at a mean rate of $6 \pm 2.6$ per cent ($f_{\text{mass}}/0.5$) per Gyr. Thus, a large fraction of the stellar mass of a present-day BCG is assembled via major dry mergers in the last $\sim 6$ Gyr.

6 SUMMARY AND DISCUSSION

In this work, we have identified four BCGs in major dry merging in 29 X-ray clusters at $0.3 \leq z \leq 0.6$, which are selected in a homogeneous cluster sample in COSMOS published by F07. These major mergers have two predominant members (nuclei) with the magnitude difference of $\sim 1.5$ and projected separation of $r_p < 10$ kpc, and showing signatures of interaction in the form of broad stellar plumes and/or significant asymmetries in residual images. They are composed of an old, passively evolving stellar population, and with negligible amount of young stars. Photometric analysis show that broad stellar plumes in their outskirts have roughly formed.
extended stellar envelopes (cD haloes), which provides evidence for the connection of mergers with the formation of stellar haloes.

We have obtained a major dry merger rate of $0.55 \pm 0.27$ merger per Gyr at $z \sim 0.43$ if the time-scale of our mergers follows the calibration of Kitzbichler & White (2008). This major merger rate at moderate redshift is higher than that rate of $0.12 \pm 0.03$ at $z \sim 0.07$ presented in Liu et al. (2009). We estimate that the major merger rate may increase in the form of $(1 + z)^{2.2 \pm 0.4}$ to $z = 0.6$. We conclude that a present-day BCG has on average increased its luminosity (mass) by $\sim 35 \pm 15$ per cent (by a factor of $\sim 1.5$) via major dry mergers from $z = 0.6$ at a mean merger rate of $6 \pm 2.6$ per cent per Gyr, under the assumption that half of the mass of the companion is accreted to the primary galaxy ($\alpha_{\text{mass}} = 0.5$). While the statistical uncertainty, which stems from the small size of our intermediate-redshift sample, is relatively large, the estimated amount of mass growth is roughly consistent with the most recent predictions of Laporte et al. (2013) from numerical simulations. Lidman et al. (2013) found that 3 of the 14 BCGs at $z \sim 1.1$ are likely to experience a major merger within 600 Myr and derived a mass growth rate of 7 per cent under the same assumption. Our rate is comparable to their mass growth rate at high redshift. Edwards & Patton (2012) showed that BCGs at $z \sim 0.3$ are adding as much as 10 per cent of their stellar mass via both major and minor mergers over 0.5 Gyr. It is not unreasonable that our rate is considerably lower than theirs since we include only major mergers in our analysis. Our study supports the notion that major dry mergers play the dominant role in the late mass assembly of BCGs. In conjunction with our previous findings in Liu et al. (2009), the discovery of these intermediate-redshift merging BCGs is clear evidence of ongoing assembly of BCGs via major dry mergers over the last $\sim 6$ Gyr.

ACKNOWLEDGEMENTS

We thank Shude Mao, David C. Koo, Hassen M. Yesuf for useful comments, and especially thank M. Bolzonella for his code and helpful suggestions. We also acknowledge the anonymous referee for a constructive report that improved the paper. This project was supported by the NSF grants of China (11103013, 11203033) and the Program for Liaoning Excellent Talents in University (LNET). The HST-COSMOS Treasury program was supported through NASA grant HST-GO-09822. We gratefully acknowledge the Program for Liaoning Excellent Talents in University and the Program for Liaoning Excellent Talents in University.

REFERENCES

Ascaso B., Lemaux B. C., Lubin L. M., Gal R. R., Kocevski D. D., Rumbaugh N., Squiers G., 2014, MNRAS, 442, 589
Bell E. F. et al., 2006, ApJ, 640, 241
Bernardi M., Hyde J. B., Sheth R. K., Miller C. J., Nichol R. C., 2007, AJ, 133, 1741
Bolzonella M., Miralles J.-M., Pelló R., 2000, A&A, 363, 476
Bolzonella M. et al., 2010, A&A, 524, A76
Brough S., Collins C. A., Burke D. J., Lynam P. D., Mann R. G., 2005, MNRAS, 364, 1354
Brough S., Tran K.-V., Sharp R. G., von der Linden A., Couch W. J., 2011, MNRAS, 414, L80
Bruzual G., Charlot S., 2003, MNRAS, 344, 1000 (BC03)
Burke C., Collins C. A., 2013, MNRAS, 434, 2856
Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, ApJ, 533, 682
Chabrier G., 2003, PASP, 115, 763
Collins C. A. et al., 2009, Nature, 458, 603
Combes F., Rampazzo R., Bonfanti P. P., Prugniel P., Sultenic J. W., 1995, A&A, 297, 37
De Lucia G., Blaizot J., 2007, MNRAS, 375, 2
de Vaucouleurs G., 1948, Ann. Astrophys., 11, 247
Edwards L. O. V., Patton D. R., 2012, MNRAS, 425, 287
Fabian A. C., 1994, ARA&A, 32, 277
Finoguenov A. et al., 2007, ApJS, 172, 182 (F07)
Gallagher J. S., III, Ostriker J. P., 1972, AJ, 77, 288
Graham A., Lauer T. R., Colless M., Postman M., 1996, ApJ, 465, 534
Ilbert O. et al., 2009, ApJ, 690, 1236
Jeltema T. E., Mulchaey J. S., Lubin L. M., Fassnacht C. D., 2007, ApJ, 658, 865
Jones C., Forman W., 1984, ApJ, 276, 38
Kitzbichler M. G., White S. D. M., 2008, MNRAS, 391, 1489
Laporte C. F. P., White S. D. M., Naab T., Ruszkowski M., Springel V., 2012, MNRAS, 424, 747
Laporte C. F. P., White S. D. M., Naab T., Gao L., 2013, MNRAS, 435, 901
Lauer T. R., 1988, ApJ, 325, 49
Lauer T. R. et al., 2007, ApJ, 662, 808
Lidman C. et al., 2012, MNRAS, 427, 550
Lidman C. et al., 2013, MNRAS, 433, 825
Lilly S. J. et al., 2009, ApJS, 184, 218
Liu F. S., Xie X. Y., Mao S., Wu H., Deng Z. G., 2008, MNRAS, 385, 23
Liu F. S., Mao S., Deng Z. G., Xia X. Y., Wen Z. L., 2009, MNRAS, 396, 2003
Liu F. S., Wen Z. L., Han J. L., Meng X. M., 2012a, Sci. China Phys., Mech., Astron., 55, 354
Liu F. S., Mao S., Meng X. M., 2012b, MNRAS, 423, 422
Liu F. S. et al., 2013, ApJ, 769, 147
McIntosh D. H., Guo Y., van den Bosch F. C., Yang X., 2008, MNRAS, 388, 1537
Matthews T. A., Morgan W. W., Schmidt M., 1964, ApJ, 140, 35
Merritt D., 1985, ApJ, 289, 18
Mobasher B. et al., 2007, ApJS, 172, 117
Mulchaey J. S., Lubin L. M., Fassnacht C., Rosati P., Jeltema T. E., 2006, ApJ, 646, 133
Naab T., Johansson P. H., Ostriker J. P., 2009, ApJ, 699, L178
Ostriker J. P., Hausman M. A., 1977, ApJ, 217, L125
Patel P., Maddox S., Pearce F. R., Aragón-Salamanca A., Conway E., 2006, MNRAS, 370, 851
Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2002, AJ, 124, 266
Peterson V., 1976, ApJ, 209, L1
Rasmussen J., Mulchaey J. S., Bai L., Ponman T. J., Raychaudhury S., Dariush A., 2010, ApJ, 717, 958
Richstone D. O., 1976, ApJ, 204, 642
Rines K., Finn R., Vikhlinin A., 2007, ApJ, 665, L9
Rix H.-W. R., White S. D. M., 1989, MNRAS, 240, 941
Ruszkowski M., Springel V., 2009, ApJ, 696, 1094
Salvato M. et al., 2009, ApJ, 690, 1250
Schombert J. M., 1988, ApJ, 328, 475
Sérsic J. L., 1968, Atlas de Galaxias Australes. Observatorio Astronomico, Cordoba
Smith G. P., Kneib J.-P., Smail I., Mazzotta P., Ebeling H., Czoske O., 2005, MNRAS, 359, 417
Stott J. P. et al., 2010, ApJ, 718, 23
Stott J. P., Collins C. A., Burke C., Hamilton-Morris V., Smith G. P., 2011, MNRAS, 414, 445
Tovmassian H. M., Andernach H., 2012, MNRAS, 427, 2047
Tran K.-V. H., Moustakas J., Gonzalez A. H., Bai L., Zaritsky D., Kautsch S. J., 2008, ApJ, 683, L17
von der Linden A., Best P. N., Kauffmann G., White S. D. M., 2007, MNRAS, 379, 867
Wen Z. L., Liu F. S., Han J. L., 2009, ApJ, 692, 511
White S. D. M., 1976, MNRAS, 174, 19

This paper has been typeset from a TeX/LATEX file prepared by the author.