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Extremely compact massive galaxies at $z \sim 1.4$

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ABSTRACT

The optical rest-frame sizes of 10 of the most massive ($\sim 5 \times 10^{11}\, h_{70}^{-2}\,\mathrm{M}_{\odot}$) galaxies found in the near-infrared MUNICS survey at $1.2 < z < 1.7$ are analysed. Sizes are estimated in both the J and K' filters. These massive galaxies are at least a factor of $4^{+1.9}_{-1.0}$ ($\pm 1\sigma$) smaller in the rest-frame V-band than local counterparts of the same stellar mass. Consequently, the stellar mass density of these objects is (at least) 60 times larger than that of massive ellipticals today. Although the stellar populations of these objects are passively fading, their structural properties are rapidly changing since that redshift. This observational fact disagrees with a scenario where the more massive and passive galaxies are fully assembled at $z \sim 1.4$ (i.e. a monolithic scenario) and points towards a dry merger scenario as the responsible mechanism for the subsequent evolution of these galaxies.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: fundamental parameters – galaxies: high-redshift – galaxies: structure.

1 INTRODUCTION

In the local Universe, the population of galaxies with stellar masses larger than $10^{11}\,\mathrm{M}_{\odot}$ is dominated by passive early-type galaxies that are a factor of ∼3 more numerous than late-type galaxies above this mass threshold (Baldry et al. 2004). Their stellar populations are old and metal-rich and are characterized by a short formation time-scale (e.g. Heavens et al. 2004; Feulner et al. 2005; Thomas et al. 2005). In addition, these massive galaxies are large, with sizes (as parametrized by the effective radius) larger than 4 kpc (Shen et al. 2003).

Historically, two different formation scenarios have been proposed in order to explain the properties of these objects: the so-called monolithic collapse model (Eggen, Lynden-Bell & Sandage 1962; Larson 1975; Arimoto & Yoshii 1987; Bressan, Chiosi & Fagotto 1994) and the hierarchical merging model (White & Frenk 1991). In the former scenario, spheroidal galaxies form at a very early epoch as a result of a global starburst, and then passively evolve to the present. In the merger model, spheroids are formed by violent relaxation during major merger events.

Favouring the monolithic model is the fact that the bulk of stars in massive ellipticals are old (Mannucci et al. 2001) and have high [α/Fe] ratios (i.e. short star formation time-scales; Worthey et al. 1992). On the other hand, supporting a hierarchical merger scenario, current observations seem to find a decline in the number of massive galaxies at high z. The space density of red passively evolving early-type galaxies has moderately increased since $z \sim 1$ (Daddi, Cimatti & Renzini 2000; Pozzetti et al. 2003; Bell et al. 2004; Drory et al. 2004; Faber et al. 2005). At even higher redshift, $z \sim 1.7$, their space density appears to be a factor of 2–3 smaller than that of their local counterparts (Daddi et al. 2005; Drory et al. 2005; Saracco et al. 2005). In addition, new generations of semi-analytical models (e.g. De Lucia et al. 2006) are now able to produce results in better agreement with the stellar population properties of ellipticals.

An additional test to check the validity of the above two scenarios is to explore the size evolution of the spheroids through cosmic time. In this sense, the prediction from the monolithic model is that the stellar mass–size relation of these objects should remain unchanged after their formation, with the luminosity–size relation evolving in agreement with the fading of their stellar populations. In the hierarchical model, however, the stellar mass–size relation of these objects should change as a result of the increase in size of the remnants after each merger.

From the observational point of view, the evolution of the luminosity–size and stellar mass–size relations of the early-type galaxies since $z \sim 1$ is consistent with the passive aging of ancient stellar populations (Trujillo & Aguerri 2004; McIntosh et al. 2005).

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Consequently, the structural properties of the more massive galaxies seem not to change from $z \sim 1$ to the present. At $z > 1$ the situation is less clear. Large and deep near-infrared surveys are needed to collect a significant sample of massive passively evolving galaxies at $z > 1$ and to explore the sizes of the galaxies in their optical rest frame. Using the Faint Infrared Extragalactic Survey (FIRES: Franx et al. 2000), Trujillo et al. (2004, 2006) have shown that there is a hint that most massive galaxies ($M_\star \gtrsim 7 \times 10^{10}\, h_{70}^{-2}\, \mathrm{M}_\odot$) at $z \sim 2.5$ are a factor of 2 smaller than present-day counterparts with similar masses. However, the number of galaxies in that sample is not large enough to establish this result firmly. In addition, there has been a recent claim of four very compact (effective radii $r_\mathrm{e} \lesssim 1$ kpc in their local ultraviolet rest frame) and massive ($M_\star > 10^{11}\, h_{70}^{-2}\, \mathrm{M}_\odot$) passively evolving galaxies at $z \sim 1.7$ in the Ultra-Deep Field (Daddi et al. 2005). The low number of objects, together with the fact that some of these galaxies could be hosting an active galactic nucleus (AGN), makes the above claims uncertain.

To shed some light on the above issue, we estimate the sizes (in their local optical rest frame) of a sample of 10 very massive ($10^{11} < M_\star < 10^{12}\, \mathrm{M}_\odot$) galaxies spectroscopically classified as early-type galaxies at $1.2 < z < 1.7$, with no sign of AGN activity in their spectra (except for one object). These objects are consequently good candidates to test whether their sizes are equal to or smaller than those of their local counterparts. Throughout, we will assume a flat Λ-dominated cosmology ($\Omega_\mathrm{M} = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). All magnitudes are provided in the Vega system unless otherwise stated.

2 DESCRIPTION OF THE DATA

The near-infrared images used in this study were taken from the Munich Near-IR Cluster Survey (MUNICS: Drory et al. 2001), and its deeper follow-up project called MUNICS-Deep. MUNICS is a wide-field medium-deep photometric survey taken in the near-infrared and optical filters. Dedicated follow-up spectroscopy is available for a selected sub-sample (Feulner et al. 2003). The main part of the survey consists of 10 fields with a total area of ∼0.3 deg^2. For all these fields photometry in K', J, I, R, V and B is available, with limiting magnitudes ranging from $K' \simeq 19.5$ and $J \simeq 21$ to $B \simeq 24.0$ mag (50 per cent completeness for point sources; Snigula et al. 2002). This is sufficiently deep to detect passively evolving systems up to a redshift of $z \lesssim 1.4$, and at a luminosity of $0.5L^*$. The final K'-selected catalogue contains roughly 5000 objects and is described in Drory et al. (2001).

The sample of massive extremely red objects (EROs) studied here was selected in three survey fields (S2F1, S2F5 and S7F5). The primary selection criteria were $K' < 18.5$ and $R - K' > 5$, resulting in a list of 36 objects. Low-resolution near-infrared spectroscopy was carried out for ∼60 per cent of them, and 10 objects are identified as early-type galaxies at $1.2 < z < 1.7$, with stellar masses well exceeding $10^{11}\, \mathrm{M}_\odot$ (Saracco et al. 2003, 2005; Longhetti et al. 2005).

Seven out of the 10 EROs explored here are located in the field S2F1, for which deeper near-infrared images are available from the MUNICS-Deep survey (Goranova et al., in preparation). MUNICS-Deep aims to obtain a contiguous 1 deg^2 field (overlapping the MUNICS patches S2F1 and S2F5) in optical and near-infrared filters to a detection limit 2 mag deeper than MUNICS. To improve the size measurements of these seven EROs in the field S2F1, the deep K'- and J-band images from MUNICS-Deep were used. These were obtained with Omega2000 at the Calar Alto 3.5-m telescope at a pixel scale of 0.45 arcsec pixel^{-1}, a typical seeing of $\lesssim$1.0 arcsec, and limiting magnitudes of $K' \sim 21.5$ and $J \sim 23.5$ mag (again 50 per cent completeness limits for point sources). Basic data reduction (Goranova et al., in preparation) was performed using a modified version of the IRAF external package XDIMSUM.

For the remaining three objects, the sizes were estimated on the K'- and J-band images of the (shallower) MUNICS project. These images, taken with OmegaPrime at the Calar Alto 3.5-m telescope, have a pixel scale of 0.396 arcsec pixel^{-1}, a typical seeing of ∼1.2 arcsec, and a limiting magnitude of $K' \sim 19.5$.

Stellar masses have been derived from the K'-band absolute magnitudes by means of the mass-to-light ratio $M/L_{K'}$ derived from the best-fitting models (see details in Longhetti et al. 2005). The largest uncertainty in the stellar mass computation comes from the variation of M/L according to the age of the stellar population and the adopted initial mass function (IMF). However, it is worth noting that, given the extremely bright K'-band magnitudes ($K' < 18.4$) and the redshifts ($z > 1.2$) of our galaxies, their resulting stellar masses are well in excess of $10^{11}\, \mathrm{M}_\odot$ leaving aside any model assumption. In this Letter we use stellar masses derived using a Kroupa (2001) IMF. However, to estimate the uncertainty in the stellar masses we used a large set of different IMFs (Longhetti et al. 2005).

3 SIZE ESTIMATION

To estimate the sizes of the galaxies we have used the GALFIT code (Peng et al. 2002). GALFIT convolves Sérsic (1968) $r^{1/n}$ profile galaxy models with the point-spread function (PSF) of the images and then determines the best fit by comparing the convolved models with the science data using a Levenberg–Marquardt algorithm to minimize the χ^2 of the fit.

The spatial resolution of our images does not allow us to estimate accurately the shape (index n) of the surface brightness profiles. For that reason, and to decrease the number of free parameters in our fits, we have calculated the size of the galaxies by fixing the Sérsic index to $n = 1$ (i.e. an exponential profile) and $n = 4$ (i.e. a de Vaucouleurs profile). Both models are convolved with the image PSF. The effective radii provided by every fit ($r_{\mathrm{e},1}$ and $r_{\mathrm{e},4}$) are used to estimate a mean effective radius and indicate the range of variation of the sizes of our galaxies. The PSF that was used for every galaxy corresponds to the nearest (bright enough but non-saturated) star to the galaxy.

Neighbouring galaxies were excluded from each model fit using a mask, but in the case of closely neighbouring galaxies with overlapping isophotes, the galaxies were fitted simultaneously.

3.1 Testing the size estimates: simulations

The results presented in this Letter rely on our ability to measure accurate structural parameters. To gauge the accuracy of our size determination we have created 250 artificial galaxies uniformly generated at random in the following ranges: $18 \leqslant J \leqslant 21$, $0.1 \leqslant r_\mathrm{e} \leqslant 1.6$ arcsec (i.e. $0.8 \lesssim r_\mathrm{e} \lesssim 13.5\, h_{70}^{-1}$ kpc in the local rest frame at $z \sim 1.4$) and $0.5 \leqslant n \leqslant 8$. Simulations were done in the J band only, but our results can be extrapolated to the K band data because of their similar signal-to-noise ratio quality. The mock galaxies span a large range of surface brightness shapes (i.e. they are not restricted to $n = 1$ or $n = 4$) to model the different galaxy profiles found in the observations (Trujillo et al. 2006). To simulate the real conditions of our observations, we added a background sky image (free of sources) taken from a piece of the MUNICS-Deep field image in the J band. Finally, the galaxy models used ($n = 1$ and $n = 4$) were convolved with the observed PSF. The same procedure was used to retrieve the structural parameters in both the simulated and actual images.

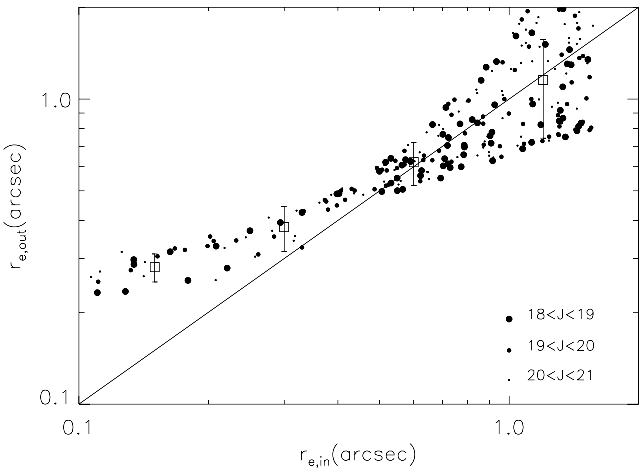

Figure 1. A comparison between the input intrinsic half-light radius (before seeing convolution) and recovered size values in our simulations for the MUNICS-Deep observations. The filled points are used to indicate the positions of individual mock galaxies. The open squares indicate the mean value and the bars correspond to the 1σ dispersion. According to the simulations, the retrieved sizes for the smallest objects should be considered only as an upper limit.

Fig. 1 shows the comparison between the input and recovered size values in our simulations. The recovered size value, $r_{\rm e,out}$, is evaluated as the mean value between the sizes recovered using n fixed to 1 and n fixed to 4: $r_{\rm e,out} = (r_{{\rm e,out},n=1} + r_{{\rm e,out},n=4})/2$. For that reason, the intrinsic scatter shown in Fig. 1 is independent of the magnitudes and mainly caused by the fact that the index n of the model galaxies is fixed whereas the mock galaxies span a large range of n. According to the simulations, our sizes for the smallest objects should be considered only as an upper limit. This systematic deviation of the size of the galaxies at small radii is probably an artefact due to the relative large size of the pixel ($\sim$ 0.45 arcsec) compared with the size of the galaxies. Simulations also provide us with a typical uncertainty in the estimation of the sizes of small galaxies of $\sim$0.1 arcsec. We will use this value to estimate the error bars in our measurements.

3.2 Testing the size estimates: crude upper limits and the effect of different image depths

A direct method of establishing a crude upper limit to the size of the objects is by fitting a Gaussian profile to the observed galaxies. Under the assumption that the intrinsic surface brightness profiles of the galaxies are also described by a Gaussian profile, the effective radius of the galaxy is given by

$$r_{\rm e} = 1/2 \times \sqrt{{\rm FWHM}^2_{\rm obj} + {\rm FWHM}^2_{\rm PSF}}. \qquad (1)$$

In general, galaxies have a surface brightness profile which is much more concentrated than a Gaussian profile, and consequently this method provides us with an upper (very conservative) limit on the size of the object. A direct Gaussian fit to our objects provide a typical value of ${\rm FWHM}_{\rm obj} \sim 1.2$ arcsec. Using the typical value of seeing that we have in our images, ${\rm FWHM}_{\rm PSF} \sim 1$ arcsec, this translates into an upper limit to the sizes of the galaxies of $r_{\rm e} \lesssim 0.8$ arcsec (or $r_{\rm e} \lesssim 6.5\,h_{70}^{-1}$ kpc at $z \sim 1.4$ in the cosmology used). Local galaxies with $M_\star \sim 5 \times 10^{11}\,h_{70}^{-2}\,{\rm M}_\odot$ are expected to have sizes of $\sim 10\,h_{70}^{-1}$ kpc (Shen et al. 2003). This crude upper limit estimation (according to our simulations this technique will produce estimates a factor of $\sim$1.5 larger than the input values) shows that our high-z massive galaxies are more compact than their local counterparts.

The sizes of three galaxies in our sample were estimated using shallower images than the rest of the sample. We have checked whether these shallow observations could introduce any bias in the size estimates of these three objects. For the seven galaxies where we have both shallow and deep observations we estimated the sizes in both cases, and the sizes agree within the error bars. We do not observe, in addition, any systematic difference. This result implies that using deeper observations does not unveil the contribution of light from missing wings in the surface brightness distributions. In other words, our images are catching almost all the light of these galaxies.

4 THE OBSERVED STELLAR MASS VERSUS SIZE RELATION

We have estimated the sizes of our galaxies in both the J and the K' bands. At $z \sim 1.4$, this implies estimation of the sizes in the local rest-frame V band and (approximately) I band. The results of our fitting are shown in Table 1. The seeing and the depth are slightly different amongst the near-infrared images which allows us to test the reliability of the size estimates. Interestingly, the sizes of individual objects both in J and in K' are very similar. This reinforces the idea that the sizes presented here are robust.

The stellar mass–size relation for the massive galaxies analysed here is presented in Fig. 2. Overplotted in this figure are the mean and dispersion of the distribution of the Sérsic half-light radii of early-type galaxies from the Sloan Digital Sky Survey (SDSS: York et al. 2000). We use the SDSS sample as the local reference. Local sizes are determined from a Sérsic model fit (Blanton et al. 2003) and the characteristics of the sample described in Shen et al. (2003). SDSS stellar masses are also derived using a Kroupa IMF. The mean of the redshift distribution of the SDSS galaxies used in this comparison is 0.1. We use the sizes estimated in the observed r' band and the z' band (S. Shen, private communication). This closely matches the V-band and I-band rest-frame filters at $z \sim 0.1$.

Fig. 2 shows that, at a given stellar mass, the most massive galaxies at $z \sim 1.4$ are much smaller than local ones. According to our simulations our sizes are upper limits, implying that our high-z galaxies are at least a factor of $4.0^{+1.9}_{-1.0}$ ($\pm 1\sigma$) smaller in the V band, and at least $3.2^{+1.8}_{-0.8}$ ($\pm 1\sigma$) smaller in the I band than local counterparts. This implies that the internal stellar mass density in the most massive galaxies at that redshift is a factor of $\gtrsim$60 (or at least a factor of 33 if the measurements obtained in the K' band are considered) larger than today. To test the robustness of our results we have checked two potential biases. First, following Maraston et al. (2006), we repeat the analysis under the assumption that our masses could be overestimated by a factor of $\sim$2. In this case, our galaxies will still be more compact than present-day galaxies of the same masses by a factor of 2.5–3. Secondly, following from the fact that present-day very massive ellipticals have large index n values, we repeat our analysis using the $r_{\rm e}$ values obtained by forcing the index n to be fixed to 8 during the fitting. In this case, our galaxies are still more compact than the local galaxies (of equal mass) by a factor of 2.7–3.3.

Most of our galaxies are more than 2σ away from the local relation. In fact, we have probed whether there is any galaxy in the SDSS sample as massive and compact as the ones that we have found. Using the catalogue used by Shen et al. (2003) to build the local SDSS relations (S. Shen, private communication), we have not found any local galaxy with $r_{\rm e} < 4$ kpc and $M_\star > 3 \times 10^{11}\,{\rm M}_\odot$, and only one with $r_{\rm e} < 5$ kpc (see also Bernardi et al. 2006). That means a comoving density of 10^{-7} Mpc^{-3}. The selection of our

Table 1. Main physical parameters of the 10 early-type galaxies. Note: the sizes of galaxies marked with an asterisk were obtained in the shallow MUNICS images.

Field	ID	z_{spec}	J (mag)	K' (mag)	$M_\star$ (10^{11} M$_\odot$)	$r_{e,J,n=1}$ (arcsec)	$r_{e,J,n=4}$ (arcsec)	$r_{e,K,n=1}$ (arcsec)	$r_{e,K,n=4}$ (arcsec)	FWHM J-band (arcsec)	FWHM K'-band (arcsec)
S2F5*	109	1.22	18.2	16.6	7.0	0.46	0.49	0.52	0.62	1.17	1.09
S7F5*	254	1.22	19.8	17.8	7.2	0.66	0.53	0.79	0.75	1.30	1.12
S2F1	357	1.34	19.5	17.8	9.0	0.32	0.34	0.30	0.35	0.98	0.97
S2F1	527	1.35	20.4	18.3	3.6	0.14	0.09	0.17	0.15	1.00	0.99
S2F1	389	1.40	20.3	18.2	4.6	0.21	0.18	0.21	0.34	1.00	1.00
S2F1	511	1.40	19.8	18.1	1.7	0.26	0.23	0.26	0.41	0.95	0.95
S2F1	142	1.43	19.6	17.8	5.9	0.31	0.38	0.28	0.24	0.97	1.00
S7F5*	45	1.45	19.6	17.6	4.7	0.45	0.53	0.56	0.74	1.14	1.18
S2F1	633	1.45	20.0	18.2	5.5	0.28	0.32	0.35	0.52	0.95	0.95
S2F1	443	1.70	20.5	18.4	6.2	0.33	0.39	0.37	0.40	0.99	0.95

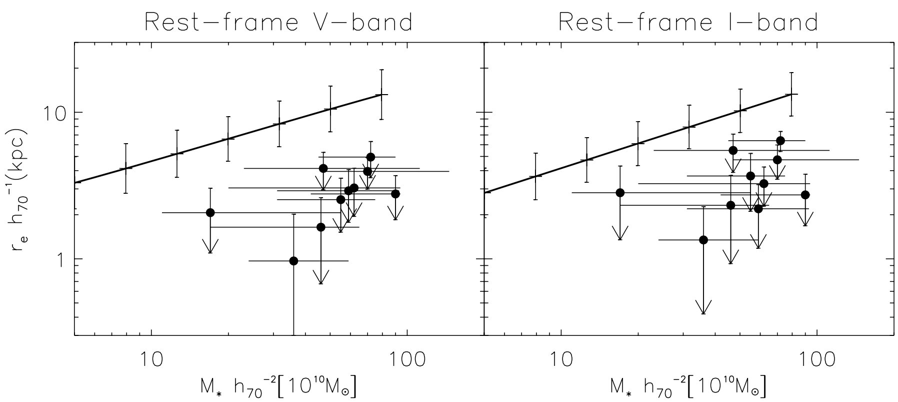

Figure 2. Distribution of rest-frame optical sizes versus stellar mass for massive MUNICS galaxies. The left-hand panel shows the distribution of galaxies with sizes estimated in the V-band local rest frame. The right-hand panel shows the distribution of galaxies with sizes estimated in the I-band local rest frame. Overplotted on the observed distribution of points are the mean and dispersion of the distribution of the Sérsic half-light radius of the SDSS galaxies as a function of the stellar mass. SDSS sizes were obtained in the r' and z' band (i.e. approximately V band and I band in the galaxies restframe at $z \sim 0.1$).

objects (including the spectroscopic follow-up) is not biased towards smaller objects. In fact, equally bright objects with sizes four times larger could be observed, and their sizes measured accurately if they were in our sample (see Fig. 1). When considering all the galaxies together, the possibility that they are all small by chance is rejected at the 4σ level.

5 DISCUSSION

As stated in the Introduction, it is possible to find in previous works some examples of significantly small massive galaxies at $z \gtrsim 1$. Daddi et al. (2005) have been the first to discuss in detail the nature of these objects. In addition to the four Daddi et al. objects, there is a group of compact ($r_e \lesssim 1$ kpc) and massive galaxies at $z \sim 1$ seen in fig. 9 of McIntosh et al. (2005). There is also evidence of compact massive galaxies in the studies of Trujillo et al. (2006) and di Serego Alighieri et al. (2005). Finally, Waddington et al. (2002) studied two $z \sim 1.5$ radio-selected early-type galaxies and found, using the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) imaging, sizes of ∼0.3 arcsec (∼ 2.5 kpc). Therefore the observational existence of these small galaxies appears currently to be well established.

A strong morphological K-correction has been suggested by Daddi et al. (2005) as one of the potential explanations of the compactness of their objects observed in the ultraviolet rest frame. However, our observations in the optical rest frame reject this possibility. Another potential explanation suggested by Daddi et al. (2005) is the presence of an unresolved nuclear component (i.e. an AGN). In fact, two of their four objects were detected in X-rays. However, the AGN hypothesis is unlikely to explain our observations. Only one of our galaxies (S2F1 443) is detected in a deep *XMM–Newton* pointing of the S2 fields (Severgnini et al. 2005), having $L_{2-10\,\mathrm{keV}} \gtrsim 10^{43}$ erg s^{-1}, and the spectral energy distributions of our objects lack AGN features. Consequently, if AGNs are present in the rest of our galaxies, their luminosities should be much fainter than 10^{43} erg s^{-1} or, alternatively, they must be heavily obscured (contributing very weakly to the stellar continuum). The quality of our data prevents us from providing a reliable point-like + Sérsic fit analysis of the surface brightness distributions (as done by Daddi et al. 2005). However, an argument against the biasing of our size estimates resulting from the AGN contribution (if at all present) is the fact that at both J and K the sizes of our objects are very similar. The AGN should contribute much more strongly in the J band (where the emission lines Hβ and O III should be at $z \sim 1.4$) than in the K band where there is not any significant line. The difference in sizes at J and K in our objects are in agreement (within the error bars). For that reason, we think that the AGN (if present) is not affecting (significantly) the size estimates. Consequently, we think a dry merger scenario can be considered as a reasonable mechanism for the subsequent evolution of our galaxies (Khochfar & Burkert 2003; Dominguez-Tenreiro et al. 2006; Naab, Khochfar & Burkert 2006).

The galaxies analysed in this paper are already very massive at $z \sim 1.4$ and their stellar population properties are consistent with passive fading. However, there is no observational evidence for galaxies as massive and compact as these in the local Universe. Consequently, the high-z galaxies have to increase their sizes since that redshift. This observational fact disagrees with a scenario where the most massive and passive galaxies are fully assembled at $z \sim 1.4$ (i.e. a monolithic scenario). It is worth noting that, whatever channel is used for our galaxies to evolve in size, this process should take place quickly (i.e. $\lesssim$2 Gyr), since galaxies with $M_\star > 10^{11}\, h_{70}^{-2}\, \mathrm{M}_\odot$ at $z \sim 0.8$ seem to be all already in place (Cimatti, Daddi & Renzini 2006), and to have sizes very similar to their current values (McIntosh et al. 2005).

A very efficient size evolutionary mechanism ($r_\mathrm{e} \propto M_\star^{1.3}$) is found in dissipationless mergers with radial orbits (Boylan-Kolchin, Ma & Quataert 2006). In this process, galaxies do not evolve parallel to the local relation ($r_\mathrm{e} \propto M_\star^{0.56}$). Interestingly, it turns out that these radial dissipationless mergers (along the filaments) of massive galaxies are thought to be the main channel of formation of the brightest cluster galaxies (BCGs). Consequently, our very massive and extremely compact galaxies at $z \sim 1.4$ are very likely candidates to evolve into current BCGs. We have explored whether the comoving number densities of the present-day BCGs are in agreement with the dry merger hypothesis. The Cole et al. (2001) local stellar mass function provides the following number densities for a Kroupa IMF: $\sim 2.5 \times 10^{-5}$ Mpc^{-3} for objects with $M_\star > 3 \times 10^{11}\, \mathrm{M}_\odot$ and $\sim 4 \times 10^{-7}$ Mpc^{-3} for objects with $M_\star \sim 10^{12}\, \mathrm{M}_\odot$. If we assume that the number densities of $M_\star > 3 \times 10^{11}\, \mathrm{M}_\odot$ objects at $z \sim 1.4$ are 30 per cent of the present-day values, and consider that to reach the mass of a BCG we need $\sim$4 of our galaxies, we would expect a comoving density of $\sim 20 \times 10^{-7}$ Mpc^{-3} for objects with $M_\star \sim 10^{12}\, \mathrm{M}_\odot$ today. This is slightly higher than the value measured for Cole et al. (2001) but works reasonable well because of the large uncertainties. Consequently, we think a dry merger scenario can be considered as a reasonable mechanism for the subsequent evolution of our galaxies (Khochfar & Burkert 2003; Domínguez-Tenreiro et al. 2006). Alternative mechanisms of galaxy evolution, like dissipative merging, will increase the mass of the galaxies very effectively but will basically maintain the sizes unchanged (Dekel & Cox 2006). This will make the discrepancy in sizes between the high-z and the local galaxies even larger. So we think that wet merging is not favoured as an evolutionary path for our objects.

An interesting open question is understanding how galaxies as massive as those we are considering can be so compact in the past. Recently Khochfar & Silk (2006a) have investigated the effect of dissipation in major mergers within the cold dark matter paradigm. They find that early-type galaxies at high redshifts merge from progenitors that have more cold gas available than their counterparts at lower redshifts. As a consequence, they claim that the remnant should be smaller in size at high redshift. Khochfar & Silk (2006b) have predicted that the size of objects at $z \sim 1.5$ with $M_\star \gtrsim 5 \times 10^{11}\, h_{70}^{-2}\, \mathrm{M}_\odot$ is a factor of $\sim$3 smaller than that of local counterparts. These estimates agree very well with our observations. If this scenario is correct, the progenitor galaxies that merge to form massive spheroidal galaxies are progressively less and less devoid of gas at lower redshift.

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