The number density of superdense early-type galaxies at $1 < z < 2$ and the local cluster galaxies

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ABSTRACT

Many of the early-type galaxies observed so far at $z > 1$ turned out to have smaller radii with respect to that of a typical present-day early-type galaxy with comparable mass. This has generated the conviction that in the past early-type galaxies were more compact, hence denser, and that as a consequence, they should have increased their radius across the time to reconcile with the present-day ones. However, observations have not yet established whether the population of early-types in the early universe was fully represented by compact galaxies nor if they were so much more numerous than in the present-day Universe to require an evolution of their sizes. Here we report the results of a study based on a complete sample of 34 early-type galaxies at $0.9 < z_{\text{spec}} < 1.92$. We find a majority (62 per cent) of normal early-type galaxies similar to typical local ones, co-existing with compact early-types from $\sim 2$ to $\sim 6$ times smaller in spite of the same mass and redshift. The co-existence of normal and compact early-type galaxies at $< z > 1.5$ suggests that their build-up taken place in the first 3-4 Gyr, followed distinct paths. Also, we find that the number density of compact early-types at $< z > 1.5$ is consistent with the lower limits of the local number density of compact early-types derived from local clusters of galaxies. The similar number of compact early-types found in the early and in the present day Universe frustrates the hypothesized effective radius evolution while provides evidence that also compact ETGs were as we see them today 9-10 Gyr ago. Finally, the fact that (at least) most of the compact ETGs at high-$z$ are accounted for by compact early-types in local cluster of galaxies implies that the former are the direct progenitors of the compact early-type cluster galaxies establishing a direct link between environment and early phases of assembly of ETGs.

Key words: galaxies: evolution; galaxies: elliptical and lenticular, cD; galaxies: formation; galaxies: high redshift.

1 INTRODUCTION

The first studies of scaling relations between effective radius, surface brightness and stellar mass performed on the few early-type galaxies (ETGs) detected at $z > 1$ showed that many of them were smaller than the mean local population of ETGs of the same mass (Daddi et al. 2005; di Serego Alighieri et al. 2005; Trujillo et al. 2006). However, some doubts on this finding were raised since these studies were based on Hubble Space Telescope (HST) optical observations sampling the blue and UV rest-frame emission dominated by young stars or on seeing limited ground-based observations sampling the blue and UV rest-frame emission dominated by young stars or on seeing limited ground-based observations. This hypothesis has triggered many theoretical studies defining the possible mechanisms able to increase the size of ETGs: dry (minor) major merger in which two spheroids of (non) equal mass merge without involving the supposed negligible gas component (e.g. Ciotti et al. 2007; Naab et al. 2009; Nipoti et al. 2009); adiabatic expansion due to a systematic loss of mass from the central region of the galaxy thanks to (e.g.) AGN activity (e.g. Fan et al. 2008); age/color (hence M/L) radial gradients which, as the galaxy ages, tend to vanish resulting in an apparent increase of the effective radius (La Barbera et al. 2009).

In principle, any of these models could be tuned to mimic the desired effective radius evolution (Hopkins et al. 2010) even if minor
dry mergers seems to be favoured due to its efficiency in enlarging the size of galaxies (e.g. Naab et al. 2009) while the other effects contributing only for ~20 per cent (Hopkins et al. 2010; Bezanson et al. 2009). However, Nipoti et al. (2009) have recently shown that dry mergers would introduce substantial scatter in the scaling relations, a scatter not observed locally. Consequently, they conclude that ETGs cannot assemble more than 40 per cent of their mass via dry mergers. Above all, observations have not yet established whether compact ETGs at high-z were so much more numerous than those in the present-day Universe to require the evolution of their effective radius. A recent study suggest that not all the high-z early-types were more compact than typical local counterparts and that those more compact were older than the others (Saracco et al. 2009) analogously to what is observed in the local Universe (Bernardi et al. 2008; Shankar & Bernardi 2009; Valentini et al. 2010). Thus, the question naturally arising is whether the population of high-z ETGs was actually so different from the population we see today, in particular whether the number density of compact ETGs at high-z was so high to require a size evolution to not exceed the number density of compact ETGs in the local Universe.

To look after this issue we constructed a complete sample of ETGs in the redshift range 0.9 < zspec < 2 with spectroscopic confirmation of their redshift and covered by HST observations. In this letter we report the analysis we performed and the results we obtained. Throughout this paper we use a standard cosmology with H0 = 70 Km s⁻¹ Mpc⁻¹, Ωm = 0.3 and ΩΛ = 0.7. All the magnitudes are in the Vega system, unless otherwise specified.

2 SAMPLE SELECTION AND PARAMETERS

The sample of ETGs we used in this analysis has been selected on the southern field of the Great Observatories Origins Deep Survey (GOODS-South v2; Giavalisco et al. 2004) and it is complete to K = 20.2. It has been imaged in four HST-ACS bandpasses (F435W, F606W, F775W and F850LP) and targeted by extensive observations with ESO telescopes both in the optical (3 U-band filters) and in the near-IR (J, H and KS filters). We used the GOODS-MUSIC multiwavelength catalog (v.2; Grazian et al. 2006) composed of the 10 photometric bands listed above and the four Spitzer-IRAC bands 3.6 μm, 4.5 μm, 5.8 μm and 8.0 μm. The spectroscopic data come from the public ESO-VLT spectroscopic survey of the GOODS-South field (Vanzella et al. 2008 and references therein). The sample has been constructed by first selecting all the galaxies brighter than K = 20.2 over the ~143 arcmin² of the GOODS-South field, then by removing all the galaxies with measured spectroscopic redshift zspec < 0.9 and those with irregular or disk-like morphology.

This first step of the morphological classification has been made through a visual inspection of the galaxies carried out independently by two of us on the ACS images in the F850LP band. Finally, on the basis of the best-fitting procedure to the observed profile described below, we removed those galaxies (8) having a Sérsic index n < 2 or clear irregular residuals resulting from the fit. Out of the 38 early-type galaxies thus selected 34 have measured spectroscopic redshift 0.9 < zspec < 1.92 leading to ~90 per cent spectroscopic completeness.

Stellar masses M* and ages of the stellar populations were derived by fitting the last release of the Charlot & Bruzual models (hereafter CB08) to the observed Spectral Energy Distribution (SED) of the galaxy at fixed known redshift. We considered the Chabrier initial mass function (IMF, Chabrier 2003), four exponentially declining star formation histories (SFHs) with e-folding time τ = [0.1, 0.3, 0.4, 0.6] Gyr and metallicity 0.4 Z☉, Z☉, and 2 Z☉. Extinction AV has been fitted in the range 0 < AV < 0.6 mag and we adopted the extinction curve of Calzetti et al. (2000). For ~90 per cent of the sample the best fitting template is defined by SFHs with τ < 0.3 Gyr, AV < 0.4 mag and Z = Z☉.

This is a critical point in the estimation of the size of ETGs at high-z. Thus, the average size and scatter we measured for our sample of ETGs (1 10−11 M☉) characterized by < R_e > = 7.5 ± 2 kpc. Mancini et al. studied a sample (1.4 < z < 1.6) in the range 1 - 3 × 10¹¹ M☉ whose average effective radius is < R_e > = 7.5 ± 1 kpc. There are no ETGs that massive as 3 × 10¹² M☉ in our sample. However, we estimate < R_e > = 7.5 ± 3 kpc for ETGs in the range 2 - 3 × 10¹¹ M☉ and < R_e > = 5.3 ± 3 kpc in the range 1 - 3 × 10¹¹ M☉. The ETGs studied by Damjanov et al. (2009) (1.5 < z < 1.85) on deep HST-NIC3 images with masses in the range 0.3 - 2 × 10¹¹ M☉ have < R_e > = 2.5 ± 1.3 kpc as those (in the same mass range) at z ≈ 1 studied by Ferreras et al. (2009) on the deep HST-ACS images of the GOODS fields (North+South). Our ETGs in the range 0.3 - 2 × 10¹¹ M☉ have < R_e > = 2.6 ± 1.7 kpc. van der Wel et al. (2005) studied a sample of ETGs on the HST-ACS images of the GOODS-South field 12 out of which (0.9 < z < 1.15 and masses larger than 0.5 × 10¹¹ M☉) are in common with our sample. The mean radii of these 12 ETGs resulting from their and our estimate are < R_e > = 3.2 ± 2.0 kpc and < R_e > = 3.6 ± 2.2 kpc respectively, in agreement also with the 12 ETGs at 1 < z < 1.4 studied by Newman et al. (2010) in a comparable mass range (< R_e > = 3.1 ± 1.6). We have also 8 ETGs in common with the sample studied by Cimatti et al. (2008) 7 out of which in the mass range 2 - 8 × 10¹⁰ M☉. For these ETGs the resulting mean radius is < R_e > = 1.4 ± 0.7 kpc from both the studies. Thus, the average size and scatter we measured for our
ETGs agree very well with those found in previous studies based on high S/N HST imaging and spectroscopic redshift. More difficult is the comparison with other studies focused on the population of massive galaxies which usually classify them on the basis of their SED making use of photometric redshift. Recently, Williams et al. (2010) studied the size evolution of a large sample of galaxies selected on the UKIDSS Ultra-Deep Survey (UDS, Warren et al. 2008) on high S/N HST imaging and spectroscopic redshift. More difficult is the comparison with other studies focused on the population of massive galaxies which usually classify them on the basis of their SED making use of photometric redshift. Recently, Williams et al. (2010) studied the size evolution of a large sample of galaxies selected on the UKIDSS Ultra-Deep Survey (UDS, Warren et al. 2008). The mean radius resulting from the ground-based K-band images of their selected quiescent massive (> 6 × 10^10 M_⊙) galaxies is < R_e > ∼ 2 kpc. This estimate, in agreement with the one derived by Franx et al. (2008) on deep ground-based observations of quiescent galaxies in the GOODS-South field, is quite smaller than those reported above for similar mass ranges (< R_e > ∼ 3 − 4 kpc). Similarly, the mean radii (< R_e > ∼ 2 kpc) estimated by Buitrago et al. (2008) and Trujillo et al. (2007) on shallow (2−4 ks) HST images of passive galaxies at z > 1.5 with masses > 10^11 M_⊙. The comparison with these studies is made uncertain both by the different methods used to select and classify galaxies and by the quite different data sets: ground-based and/or shallow observations can affect systematically the size of galaxies (e.g. Stabenau et al. 2008 and Mancini et al. 2010) and mass estimate can be affected by the uncertainties related to SED fitting (e.g. Longhetti & Saracco 2009; Muzzin et al. 2009; Mancini et al. 2010) especially when the redshift is a free parameter (Stabenau et al. 2008).

3 SUPERDENSE EARLY-TYPES AT 1 < z < 2 AND THE LOCAL EARLY-TYPE CLUSTER GALAXIES

In Fig. 2 the size-mass (SM) relation, the relation between the effective radius R_e [kpc] and the stellar mass M_∗ [M_⊙] of our galaxies (filled symbols), is compared with the relation found by Shen et al. (2003) for the local population of ETGs (solid line). The original local relation is based on masses derived using Bruzual and Charlot (2003) models which provide masses ∼ 1.2 times larger than those derived with CB08 models (Longhetti and Saracco 2009). We thus corrected the relation by this scaling factor to make the comparison with our data consistent. It is evident that more than half of the sample, 21 out of 34 ETGs (filled triangles), lies within one sigma from the local SM relation, that is ~62 per cent of the sample is composed of ETGs, we say normal, having morphological and physical parameters which agree with the mean local values. The recent measure of the velocity dispersion obtained for three normal ETGs, one of which belonging to the ACS sample (filled triangle marked by open circle in Fig. 2) confirms that they are similar to the typical low ETGs also from the dynamic point of view (Cappellari et al. 2009; Onodera et al. 2010). The remaining ~ 38 per cent (13 galaxies) of the sample is composed of ETGs (filled circles), we say compact, which diverge more than one sigma from the local SM relation having effective radii from ~ 2 to ~ 6 times smaller than the radius derived from the local relation for the same mass. This is better shown in the lower panel of Fig. 2 where the degree of compactness, defined as the ratio between the effective radius R_e and the effective radius R_e,max of an equal mass galaxy at z = 0 as derived from the local SM relation, is plotted as a function of the mass. The recent attempt to measure the velocity dispersion of a compact galaxy (van Dokkum et al. 2009; red open circle in Fig. 2) seems to confirm an higher stellar mass density than in normal early-types. It is interesting to note that ETGs more compact than the mean local value exist for any value of the effective radius and of the stellar mass spanned by our sample. Moreover, the degree of compactness does not show any dependence on mass. Thus, it is clear that the population of high-z ETGs is not primarily composed of superdense ETGs but it is dominated by normal ETGs similar to local ones. We also report in Fig. 2 the 29 brightest cluster galaxies with z_c > 350 km/s selected by Bernardi et al. (2008) in local cluster of galaxies (open squares). They populate the SM relation at high masses (> 10^11 M_⊙) and a few of them (5−6) are compact. The critical question is whether the number density of compact ETGs in the early Universe was so high to require that they have increased their radii to not exceed the number density of compact ETGs in the present-day Universe, in practice whether compact ETGs were much more numerous at earlier epochs, or if their number has not changed across the time. A recent estimate by Valentijn et al. (2010) fixes the lower limit of the number density of compact ETGs in the local Universe considering compact ETGs only in local clusters of galaxies and assuming that no compact ETGs are present among the population of non-cluster galaxies. They find a lower limit of n = 1.8 × 10^-6 Mpc^-3 for stellar masses M_∗ > 3 × 10^10 M_⊙ and of n = 0.8 × 10^-5 Mpc^-3 for masses M_∗ > 8 × 10^10 M⊙. Their local densities have been computed considering compact those ETGs diverging more than one sigma from the local SM relation of Shen et al. (2003), according to our definition (Valentinuzzi, private communication). We find that the comoving number density of compact ETGs over the volume of about 4.4 × 10^3 Mpc^3 sampled by the GOODS area between 0.9 < z < 1.2 (average redshift < z > ∼ 1.5) is compatible even with the local lower limits. In particular, we find n = (2.2 ± 0.7) × 10^-5 Mpc^-3 for masses M_∗ > 3 × 10^10 M_⊙ and n = (0.8 ± 0.4) × 10^-3 Mpc^-3 for masses M_∗ > 8 × 10^10 M⊙. van Dokkum et al. (2010) and Guo et al. (2009) indicate that Shen et al. (2003) might have underestimated the sizes of massive galaxies by a factor of up to two. We point out that the method used to define and compare compact ETGs in our and in the Valentijn et al. (2010) sample (1σ from the SM relation) takes the results away from any possible systematics in the local relation since it would affect the
Figure 2. Upper panel - The effective radius $R_e$ of the 34 ETGs at $0.9 < z < 2$ is plotted as a function of their stellar mass $M_*$ (filled symbols). The solid line is the local Size-Mass relation $R_e = 2.88 \times 10^{-6} (M_*/M_\odot)^{0.56}$ (Shen et al. 2003) and the dotted lines represent the relevant scatter. Filled circles mark those early-types more than 1\sigma smaller than local ETGs with comparable stellar mass as derived by the local relation. Filled triangles mark the ETGs falling within 1\sigma from the local relation. Cyan open circles are normal ETGs with stellar velocity dispersion measurements, one of which included in the ACS sample (Cappellari et al. 2009; Onodera et al. 2010). Red open circle is the compact ETGs with stellar velocity dispersion measurement (van Dokkum et al. 2009). Open squares are the ETGs with $\sigma > 350$ km/s from Bernardi et al. (2008) on the basis of their $\sigma_e > 350$ km/s. Lower panel - The compactness, defined as the ratio between the effective radius $R_e$ of the galaxy and the effective radius $R_e(\sigma=0)$ of an equal mass galaxy at $z = 0$ as derived by the local S-M relation, is plotted as a function of the stellar mass Symbols are as in the upper panel.

4 DISCUSSION AND CONCLUSIONS

The high spectroscopic completeness and the deep HST imaging of the GOODS-South field have allowed us to select a complete sample of 34 ETGs with $K < 20.2$ at $0.9 < z_{spec} < 2$ on the basis of their redshift and morphology. Only 13 of them diverge more than one sigma from the local size-mass relation having effective radii from $\sim 2$ to $\sim 6$ times smaller than the radii derived from the SM relation for the same masses. Their number density does not exceed the one measured in the local Universe. Indeed, our analysis shows that the young Universe contained nearly the same number of compact early-type galaxies than present-day Universe and, consequently, that the hypothesis of their growth in radius in the last 9-10 Gyr is not justified. On the contrary, this provides evidence that they were as we see them today even 9-10 Gyr. Actually, Mancini et al. (2010) reached similar conclusion for very high-mass ($> 2.5 \times 10^{11} M_\odot$) ETGs at $1.4 < z < 1.7$ and more recently Newman et al. (2010) show that $< 10^{11} M_\odot$ ETGs do not show signs of size evolution at $z < 1.4$ while estimate a possible evolution for larger masses. It is important to note that these and our results obtained over the redshift range $0.9 < z_{spec} < 2$ imply that if the compact ETGs detected at $z > 2.3$ (e.g. van Dokkum et al. 2008) are actually all so small and represent most of the population of ETGs at that redshift, then the size evolution they should undergo must take place over a very short period of about 1 Gyr. This would be difficult to account for by mergers in current models (see also Newman et al. 2010). The previously claimed size evolution was proposed to explain the apparently large number of compact galaxies found in the many of the first samples of high-z ETGs. This enhanced number could be probably due to selection and observational biases that remain to be understood. Recent studies conducted on local samples of galaxies point out that the selection of old galaxies, the criterion usually used to select high-z early-type galaxies, is strongly biased toward smaller ETGs for fixed mass (Bernardi et al. 2008; Shankar et al. 2009).
Table 1. Number and stellar mass density of early-type galaxies in the early and in the present-day Universe. Measurements of the stellar mass density and of the number density of early-type galaxies at \( < z > = 1.5 \) are shown for the whole population of early-types \( M_{\star}^{\mathrm{etg},i} \) and \( N_{\mathrm{etg}}^{\mathrm{i}} \) (left panels) and for the compact early-types \( M_{\star}^{\mathrm{etg},c} \) and \( N_{\mathrm{etg}}^{\mathrm{c}} \) (right panels) for different ranges of stellar mass \( M_{\star} \), (upper panels) and of effective radius \( R_{\mathrm{e}} \) (lower panels). \( N_{\mathrm{gal}} \) is the number of galaxies falling in each interval. It is worth noting that a high-density sheet-like structure containing 7 ETGs and accounting for an overdensity factor of about 8 in redshift space is present at \( z \approx 1.6 \) in the GOODS-South field (Cimatti et al. 2008; Kurk et al. 2009). Out of the 7 ETGs five are compact. The bracketed values are the estimates obtained without considering the 5 compact galaxies belonging to this overdensity. The lower limits to the local number density of compact ETGs \( n_{\mathrm{etg},c} \) are from Valenzini et al. (2010).

| \( \Delta M_{\star} \) in \( 10^{11} M_{\odot} \) | \( N_{\mathrm{gal}}^{\mathrm{i}} \) in \( 10^{6} M_{\odot} \) Mpc\(^{-3} \) | \( n_{\mathrm{etg}}^{\mathrm{i}} \) in \( 10^{-3} \) Mpc\(^{-3} \) | \( N_{\mathrm{gal}}^{\mathrm{c}} \) in \( 10^{6} M_{\odot} \) Mpc\(^{-3} \) | \( n_{\mathrm{etg}}^{\mathrm{c}} \) in \( 10^{-3} \) Mpc\(^{-3} \) |
|---|---|---|---|---|
| \( > 1 \) | 7 | 1.5 \( \pm 0.6 \) | 0.95 \( \pm 0.4 \) | (3) | 0.6(0.4) \( \pm 0.4 \) | 0.4(0.2) \( \pm 0.2 \) | 0.5 |
| \( > 0.8 \) | 12 | 2.3 \( \pm 0.7 \) | 1.9 \( \pm 0.6 \) | 5(3) | 1.0(0.6) \( \pm 0.5 \) | 0.8(0.5) \( \pm 0.4 \) | 0.8 |
| \( > 0.3 \) | 25 | 3.8 \( \pm 0.8 \) | 5.1 \( \pm 1.0 \) | 11(7) | 1.6(1.0) \( \pm 0.5 \) | 2.2(1.4) \( \pm 0.7 \) | 1.8 |
| 0.1 \& 4 | 33 | 4.6 \( \pm 0.9 \) | 9.0 \( \pm 2.0 \) | 13(8) | 1.8(1.1) \( \pm 0.5 \) | 3.4(2.3) \( \pm 1.0 \) | 2.4 |

| \( \Delta R_{\mathrm{e}} \) in kpc | \( N_{\mathrm{gal}}^{\mathrm{i}} \) in \( 10^{6} M_{\odot} \) Mpc\(^{-3} \) | \( n_{\mathrm{etg}}^{\mathrm{i}} \) in \( 10^{-3} \) Mpc\(^{-3} \) | \( N_{\mathrm{gal}}^{\mathrm{c}} \) in \( 10^{6} M_{\odot} \) Mpc\(^{-3} \) | \( n_{\mathrm{etg}}^{\mathrm{c}} \) in \( 10^{-3} \) Mpc\(^{-3} \) |
|---|---|---|---|---|
| \( < 1 \) | 5 | 0.4 \( \pm 0.2 \) | 0.3 \( \pm 0.2 \) | (4) | 0.3(0.2) \( \pm 0.2 \) | 1.7(1.0) \( \pm 1.0 \) | 0.6 |
| 1 \& 4 | 24 | 3.4 \( \pm 0.7 \) | 6.4 \( \pm 1.0 \) | 9(6) | 1.5(1.0) \( \pm 0.5 \) | 7.1(1.2) \( \pm 0.6 \) | 1.7 |
| 2 \& 4 | 15 | 2.2 \( \pm 0.6 \) | 4.0 \( \pm 1.0 \) | 3(3) | 0.6(0.6) \( \pm 0.4 \) | 0.5(0.3) \( \pm 0.3 \) | 0.6 |

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