SUPERDENSE MASSIVE GALAXIES IN THE ESO DISTANT CLUSTER SURVEY (EDisCS)

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ABSTRACT

We find a significant number of massive and compact galaxies in clusters from the ESO Distant Clusters Survey (EDisCS) at 0.4 < z < 1. They have similar stellar masses, ages, sizes, and axial ratios to local z ∼ 0.04 compact galaxies in Wlde field Nearby Galaxy clusters Survey (WINGS) clusters, and to z = 1.4–2 massive and passive galaxies found in the general field. If non-brightest cluster galaxies of all densities, morphologies, and spectral types are considered, the median size of EDisCS galaxies is only a factor 1.18 smaller than in WINGS. We show that for morphologically selected samples, the morphological evolution taking place in a significant fraction of galaxies during the last Gyr may introduce an apparent, spurious evolution of size with redshift, which is actually due to intrinsic differences in the selected samples. We conclude that the median mass–size relation of cluster galaxies does not evolve significantly from z ∼ 0.7 to z ∼ 0.04. In contrast, the masses and sizes of BCGs and galaxies with M∗ > 4 × 10¹¹ M⊙ have significantly increased by a factor of 2 and 4, respectively, confirming the results of a number of recent works on the subject. Our findings show that progenitor bias effects play an important role in the size-growth paradigm of massive and passive galaxies.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: formation – galaxies: structure

Online-only material: color figures

1. INTRODUCTION

High-z studies (as far as z ∼ 2.4) have found a significant number of massive, passively evolving galaxies (stellar mass M∗ > 10¹⁰ M⊙) with relatively small effective radii Re < 2 kpc (see, among others, Trujillo et al. 2006; Cimatti et al. 2008; van Dokkum et al. 2008; van der Wel et al. 2009; Saracco et al. 2009), sometimes named superdense9 galaxies (SDGs). The general claim by various authors is that local galaxies are three to six times larger in size when compared to high-z ones, at the same stellar mass. In addition, Trujillo et al. (2009) found a complete absence of massive, old, and extremely compact galaxies in the local universe.

However, Valentiniuzzi et al. (2010, hereafter V10) have shown that 22% of local cluster members in the Wlde field Nearby Galaxy clusters Survey (WINGS) sample with M∗ > 3 × 10¹⁰ M⊙ and Σ₉₀ > 3 × 10¹⁰ M⊙ kpc⁻² have the same characteristics of the high-z SDGs reported in the literature by various authors. In the same Letter, the authors found that selecting galaxies with old stellar populations is equivalent to selecting the smaller ones, for a given stellar mass. Since a large number of galaxies have stopped forming stars at relatively low redshift (z < 1.4), and these tend to be the largest, it is not valid to compare high-z passive galaxies with all low-z passive ones. To avoid selection effects when making comparisons with passive galaxies at high redshift, one needs to select locally those galaxies which were already passive at the cosmic time the high-z data correspond to.

More recently, Taylor et al. (2009) revisited the search of SDGs in SDSS-DR7 and found a relatively small but significant number of SDGs. Following the same criterion used in V10, they find a 1.3% fraction of SDGs.

The issue is much debated. Mancini et al. (2010) have analyzed a sample of 12 galaxies at 0.5 < z < 1.9 in the Cosmos field, finding masses and sizes compatible with the local Sloan Digital Sky Survey (SDSS) ones. Furthermore, by using a set of simulated early-type galaxies, they have shown that the low signal-to-noise ratio of high-z images can cause measured effective radii to be lower than the intrinsic values. In a recent paper, van Dokkum et al. (2010) select galaxies with a constant number density at different cosmic times. They use all galaxies instead of only passive ones and find that galaxies have grown in size by a factor of 4 from z ~ 2 to z ~ 0.

Even more recently, while Szomoru et al. (2010) confirm the extreme compactness of a z = 1.9 galaxy with the HST-WFC3, Saracco et al. (2010) show that the comoving number density of compact early-type galaxies over the volume of about 4.4 × 10⁵ Mpc³ sampled by the GOODS area between 0.9 < z < 1.92 is compatible even with the local lower limits given in V10.

In this Letter, we present the results of a search for SDGs in the ESO Distant Clusters Survey (EDisCS) at z ~ 0.7, and we report the comparison of the mass–size relation (MSR) with the same relation in WINGS clusters at z ~ 0. We further discuss selection effects which may introduce a spurious size evolution with redshift if not properly taken into account.

2. THE DATA

The high-z cluster sample is extracted from EDisCS, a multiwavelength photometric and spectroscopic survey of galaxies.
in 20 fields containing galaxy clusters at 0.4 < z < 1 (White et al. 2005). We will use a sub-sample of eight clusters, which have HST-ACS images for high-precision size measurements (Desai et al. 2007) and cluster central velocity dispersions (σclus ≥ 400 km s⁻¹, σclus ~700 km s⁻¹) similar to local WINGS clusters (Halliday et al. 2004; Milvang-Jensen et al. 2008; Desai et al. 2007). Three of these clusters have z ~ 0.5, the rest of them have z = 0.7–0.8.

Galaxy stellar masses were estimated using the kcorrect tool (Blanton & Roweis 2007) that models the available observed broadband photometry (VRIJK or BVIJK), fitting templates obtained with spectrophotometric models. The stellar masses are defined as the mass locked into stars, including stellar remnants, at any time, using a Kroupa (2001) initial mass function (type 2 mass in V10). Taking into account the statistical errors on the mass estimates, the error of the stellar mass on individual galaxies is of the order ~0.1 dex, even though it has to be taken into account that the scatter (rms) in the relation between masses computed with different models is typically ~0.2 dex (for further details, see Fritz et al. 2007; Longhetti & Saracco 2009; Vulcani et al. 2010).

We use visual morphological classifications from Desai et al. (2007).

We measure galaxy effective radii Re with the GIM2D tool (Simard et al. 2002) on the HST images in F814W band, by using a single-component Sersic fit. The circularized Re is determined by numerically integrating the curve of growth of the fitted Sersic model and solving the equation Flux(≤ R_e) = 0.5 · Flux(∞) (for further details, see Saglia et al. 2010). The typical random error on the EDisCS’s sizes is of the order of 20% (Simard et al. 2009).

We use a mass limited sample of EDisCS spectroscopically confirmed cluster members, with stellar masses ≥4 × 10¹⁰ M⊙. This mass limit corresponds to the mass of an object whose observed magnitude is equal to the faint magnitude limit of the spectroscopic survey, with the reddest possible color. We correct for spectroscopic incompleteness using Milvang-Jensen et al. (2008) completeness functions.

The local sample examined in this Letter comes from the WINGS (Fasano et al. 2006). WINGS is a multiwavelength photometric and spectroscopic survey designed to provide a robust characterization of the properties of galaxies in nearby clusters.

We use only cluster members of the subset of WINGS clusters that have an average spectroscopic completeness larger than 50% (21 out of 78 clusters) and correct for spectroscopic incompleteness using the prescriptions given in Cava et al. (2009). These WINGS clusters have redshifts 0.04 < z < 0.07 and central velocity dispersions 558 < σclus / km s⁻¹ < 1368.

WINGS effective radii, axial ratios, and Sersic indices are measured on the V-band images with GASPHOT (Pignatelli et al. 2006), an automated tool which performs a simultaneous fit of the major and minor axis light growth curves with a two-dimensional flattened Sersic law, convolved by the appropriate, space-varying point-spread function (PSF). As a measure of galaxy size, we use the circularized effective radii, calculated in the same way it was done for EDisCS sizes (see above). We note here that SDG fractions and number densities are updated accordingly in this Letter compared to V10 (see next sections).

The maximum error on WINGS sizes, based on extensive simulation runs, is of the order of 10% (see Pignatelli et al. 2006).

As a consistency check on sizes, we run GIM2D on one representative V-band WINGS cluster image, to compare the resulting circularized Re and Sersic index n of ~800 galaxies with GASPHOT values. We found a systematic difference in sizes of 0.033 ± 0.002 dex, in the sense that GASPHOT sizes are larger than GIM2D ones. This difference becomes larger (as far as ~0.3 dex) for larger galaxies, somehow confirming that GIM2D has the tendency to systematically underestimate the sizes of the largest galaxies at all luminosities (see Simard et al. 2002). On the other hand, we do not find any systematic difference regarding the Sersic index estimate.

Stellar masses of WINGS galaxies have been determined by fitting the optical spectrum (in the range ~3600 to ~7000 Å), with the spectrophotometric model fully described in Fritz et al. (2007), and correcting for color gradients outside of the fiber (see V10). The model derives the integrated spectrum as the combination of stellar populations of 13 different ages, allowing dust extinction to vary with the stellar population age and using the single metallicity (either z = 0.05, 0.02, or 0.004) that gives the lowest χ² fit of the observed spectrum. Although the masses were calculated in two different ways, we have shown in V10 (and soon in Fritz et al. 2010) that there is no significant systematic offset between different methods that could be capable of biasing our results.

WINGS morphologies are derived from V images using the purposely devised tool MORPHOT. We have verified that the differences in classification between MORPHOT and an experienced human classifier are comparable to the differences between two experienced human classifiers (G. Fasano et al. 2010, in preparation).

For the sake of comparing the median sizes of the two surveys, we divide the total sample into four mass intervals, selected to have a statistically significant number of objects in each one of them:

1. BIN1: 4 × 10¹⁰ ≤ M*/M⊙ < 6 × 10¹⁰
2. BIN2: 6 × 10¹⁰ ≤ M*/M⊙ < 1 × 10¹¹
3. BIN3: 1 × 10¹¹ ≤ M*/M⊙ < 2 × 10¹¹
4. BIN4: 2 × 10¹¹ ≤ M*/M⊙ ≤ 4 × 10¹¹
and will refer to them with the label BIN[1–4].

3. EDisCS SUPERDENSE GALAXIES

In Figure 1, we present the MSR (bottom panel) and the mass–density relation (top panel) of EDisCS cluster members with M* > 4 × 10¹⁰ M⊙. Colors differentiate the morphological types (see the caption and legend); large open squares are the brightest cluster galaxies (BCGs) listed in White et al. (2005).

In the top panel, the dashed line isolates the EDisCS SDGs (larger dots in both panels) with the same density selection criteria (Σ200 ≳ 3 × 10⁹ M⊙ kpc⁻²) used in V10, above the mass completeness limit of this Letter. These criteria were chosen to select galaxies with mass and density ranges similar to those of high-z (z > 1.4) passively evolving galaxies.

As apparent in Figure 1, we do find a significant number of SDGs in the EDisCS sample. Indeed, EDisCS SDGs represent 41% of the total cluster population of galaxies more massive than M* > 4 × 10¹⁰ M⊙. This is an even larger fraction than V10 found in WINGS local clusters, where 17% are SDGs for the mass limits and radii adopted in this Letter. A decline with

References:

10. Their short names found in other EDisCS’s papers are CL1138, CL1138a, CL1040, CL1216, CL1054-11, CL1054-12, CL1232, and CL1354.
11. http://cosmo.nyu.edu/mlb144/kcorrect/
12. http://web.oapd.inaf.it/wings
time of the SDG fraction in clusters might be expected given that (1) the “oldest” galaxies in the universe (those who stopped forming stars very early on) inhabit clusters since very high redshifts and clusters accrete throughout their history galaxies with more extended star formation histories and (2) as shown in V10, at any given mass the oldest galaxies tend to be the most compact. Therefore, the original population of old and compact galaxies in clusters get progressively diluted by larger galaxies infalling into clusters at later times.

Of the EDisCS SDGs, 41% are ellipticals, 36% are S0s, 20% are late-type galaxies, and for 4% of them it was not possible to assign a reliable visual morphological classification. In Table 1, we present the main mean properties of EDisCS SDGs.

4. SELECTION EFFECTS

We have seen that the morphological fractions among the EDisCS SDGs are considerably different from WINGS SDGs. The latter show a larger fraction of S0s and a corresponding lower fraction of later types. This is expected, as many studies have come to the conclusion that a large fraction of today’s passive early-type galaxies have evolved from star-forming late-type galaxy progenitors in clusters (Dressler et al. 1997; Fasano et al. 2009) and thus become important at different cosmic times, in contrast with Whiley et al. (2008), we note that the size and mass evolution of our sample of high-z BCGs with redshift is compatible with the observational study of Bernardi (2009) and with the theoretical expectations of De Lucia & Blaizot (2007) that predict a factor of 3–4 growth in mass between $z \sim 1$ and $z = 0$.

Table 1

| Quantity | EDisCS | WINGS |
|----------|--------|-------|
| SDG fraction | 41% | 17% |
| Ellipticals | 41% | 28% |
| S0s | 36% | 64% |
| Late type | 20% | 8% |
| Unknown morphology | 3% | |
| Effective radius ($R_e$) | $1.70 \pm 0.08$ | $1.79 \pm 0.04$ |
| Sersic index ($n$) | $3.71 \pm 0.14$ | $3.21 \pm 0.09$ |
| Axial ratio ($b/a$) | $0.59 \pm 0.11$ | $0.62 \pm 0.03$ |
| Stellar mass ($M_*\) | $(1.08 \pm 0.08) \times 10^{11} M_\odot$ | $(1.02 \pm 0.04) \times 10^{11} M_\odot$ |

Note. Errors on the medians are reported too.

So far, we have seen that a considerable fraction of EDisCS cluster members are SDGs and that galaxy sizes in EDisCS and WINGS, at all mass ranges considered, are rather similar and do not suggest a strong increase in size with redshift.

The BCGs and the most massive cluster galaxies with $M_* > 4 \times 10^{11} M_\odot$ have to be discussed separately, due to their peculiar nature and evolution (see, among others, Fasano et al. 2010). Indeed, the EDisCS BCGs have mean mass and size of $M_* \sim 4 \times 10^{11} M_\odot$ and $R_e \sim 8.5$ kpc, respectively. In contrast, WINGS BCGs have mean values of $M_* \sim 10^{12} M_\odot$ and $R_e \sim 33.6$ kpc, suggesting that the mean size and mass of BCGs have respectively increased by factors of $\sim 4$ and $\sim 2$ between $z \sim 0.7$ and $z \sim 0.04$. Although this result seems in contrast with Whiley et al. (2008), we note that the mass of local BCGs in that paper was calculated inside an aperture of 37 kpc, which is approximately the median half-luminosity circularized radius in the V-band of our local sample of BCGs. This is consistent with a picture where the BCG progenitors increase their mass via minor mergers in the outer regions, leaving practically unchanged the dense core (see Hopkins et al. 2010). We also note that the size and mass evolution of our sample of high-z BCGs with redshift is compatible with the observational study of Bernardi (2009) and with the theoretical expectations of De Lucia & Blaizot (2007) that predict a factor of 3–4 growth in mass between $z \sim 1$ and $z = 0$.

Figure 1. Circularized effective radius $R_e$ and mass–density inside $R_e$ as a function of stellar mass for all EDisCS spectroscopic member galaxies with $M_* \geq 4 \times 10^{11} M_\odot$. The different colors mark the morphological type: blue for late types (later than S0s), green for S0s, red for ellipticals, and black for galaxies without a classification. Bigger dots highlight the SDGs. Big open magenta squares are the BCGs. The solid and dashed lines in the bottom panel are the median completeness weighted MSRs of EDisCS and WINGS, respectively, obtained excluding the BCGs. Error bars are lower and upper quartiles of the median completeness weighted MSRs of EDisCS and WINGS, respectively.
Because stellar ages cannot be used as a proxy for morphology, given that the timescale for morphological transformation is longer than the timescale for star formation quenching.

Table 2

| WINGS/EDisCS   | BIN1  | BIN2  | BIN3  | BIN4  |
|----------------|-------|-------|-------|-------|
| All galaxies   | 1.16±0.23 | 1.24±0.48 | 1.48±0.56 | 1.62±0.93 |
| Early-type galaxies | 1.76±0.19 | 1.79±0.44 | 1.62±0.67 | 1.25±0.95 |
| WINGS early/EDisCS all | 1.13±0.22 | 1.18±0.48 | 1.40±0.28 | 1.01±0.98 |

Note. Errors come from the standard error propagation technique.

Figure 2. Comparison of the MSR of EDisCS (top panel) and WINGS (bottom panel). Color coding is the same as for Figure 1. The black straight line delimits the area above which there are no early-type galaxies in EDisCS. The histogram at the bottom right represents the luminosity-weighted age distribution of EDisCS early-type galaxies above (blue dashed line) and below (solid red line) this line. The black solid and dotted (shifted by −0.01 dex in mass) lines are the median MSR for early-type and all types of galaxies in EDisCS, respectively. The dashed black line is the median MSR for WINGS early-type galaxies (shifted by +0.01 dex). Error bars are lower and upper errors on the medians.

(A color version of this figure is available in the online journal.)

5. DISCUSSION AND CONCLUSION

We have found that 41% of EDisCS galaxies with $M_\star \sim 4 \times 10^{10} \, M_\odot$ are SDGs. Their properties are similar to WINGS SDGs, apart for a significantly different morphological mix: the prevalence of S0s in WINGS is not found in EDisCS.

Such a result is not unexpected, given our previous findings: in V10 we have found that 17% (for the mass limits and radii adopted here) of WINGS clusters members at $z \sim 0$ are SDGs. More than 50% of them have stellar ages older than 9 Gyr, a clear indication that they were already old and compact at the EDisCS’s epoch. The evolution of the SDG fraction in clusters with redshift is expected if SDGs are massive and old galaxies, formed in cluster seeds and preferentially found in today’s massive clusters, while they are rarer in the field (see Taylor et al. 2009) and therefore in the population of galaxies infalling into clusters at later and later times.

We find that when galaxies of all morphological types are considered, the median size of cluster galaxies at $z \sim 0.7$ is only a factor 1.18 smaller than the local median. We conclude that from $z \sim 0.7$ to $z \sim 0.04$, there is at most a very modest evolution in galaxy sizes in clusters.

Similarly to our V10 analysis of age selection effects, we have shown that comparing high-$z$ morphologically selected samples with local ones can be misleading. In agreement with previous results regarding the morphological evolution in clusters, we have found that the largest EDisCS late-type galaxies are found to be large early types in WINGS clusters, as it is apparent studying the morphologies above the tilted line in Figure 2. The BCGs, instead, have been found to evolve both in mass (a factor
of \( \sim 2 \) and size (a factor of \( \sim 4 \)), in agreement with other recent theoretical and observational results.

Our findings show that the progenitor bias (in age or morphology) plays an important role in the size-growth paradigm and must be carefully taken into account when comparing local galaxy sizes with those of massive high-z galaxies.

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