On the formation of massive galaxies: a simultaneous study of number density, size and intrinsic colour evolution in GOODS

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ABSTRACT
The evolution of number density, size and intrinsic colour is determined for a volume-limited sample of visually classified early-type galaxies selected from the Hubble Space Telescope/Advanced Camera for Surveys images of the Great Observatories Origins Deep Survey (GOODS) North and South fields (version 2). The sample comprises 457 galaxies over 320 arcmin² with stellar masses above $3 \times 10^{10} M_\odot$ in the redshift range $0.4 < z < 1.2$. Our data allow a simultaneous study of number density, intrinsic colour distribution and size. We find that the most massive systems ($> 3 \times 10^{11} M_\odot$) do not show any appreciable change in comoving number density or size in our data. Furthermore, when including the results from 2dF galaxy redshift survey, we find that the number density of massive early-type galaxies is consistent with no evolution between $z = 1.2$ and 0, i.e. over an epoch spanning more than half of the current age of the Universe. We find large discrepancies between the predictions of semi-analytic models. Massive galaxies show very homogeneous intrinsic colour distributions, with nearly flat radial colour gradients, but with a significant negative correlation between stellar mass and colour gradient, such that red cores appear predominantly in massive galaxies. The distribution of half-light radii – when compared to $z \sim 0$ and $z > 1$ samples – is compatible with the predictions of semi-analytic models relating size evolution to the amount of dissipation during major mergers.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: luminosity function, mass function.

1 INTRODUCTION
During the past decades the field of extragalactic astrophysics has undergone an impressive development, from simple models that were compared with small, relatively nearby samples to current surveys extending over millions of Mpc³ at redshifts beyond $z \sim 1$ along with numerical models that can probe cosmological volumes with the aid of large supercomputers. However, in the same period of time, our knowledge of the ‘baryon physics’ relating the dark and luminous matter components has progressed much slower, mainly due to the highly non-linear processes that complicate any ab initio approach to this complex problem.

The evolution of the most massive galaxies constitutes one of the best constraints one can impose on the modelling of galaxy formation. Within the current paradigm of galaxy growth in a Λ cold dark matter (ΛCDM) cosmology, massive galaxies evolve from subsequent mergers of smaller structures. The most massive galaxies are early-type in morphology and are dominated by old stellar populations, with a tight mass–metallicity relation and abundance ratios suggesting a quick buildup of the stellar component (see e.g. Renzini 2006). On the other hand, semi-analytic models (SAMs) of galaxy formation predict a more extended assembly history (if not star formation) from major mergers. By carefully adjusting these models, it has been possible to generate realizations that are compatible with the observed stellar populations in these galaxies (e.g. Bower et al. 2006; De Lucia et al. 2006; Kaviraj et al. 2006).

In this paper, we study the redshift evolution of a sample of the most massive early-type galaxies from the catalogue of Ferreras et al. (2009a), which were visually selected from the Hubble Space Telescope (HST)/Advanced Camera for Surveys (ACS) images of the GOODS North [Hubble Deep Field-North (HDF-N)].
and South [Chandra Deep Field South (CDFS)] fields (Giavalisco et al. 2004). Our data set complements recent work exploring the issue of size and stellar mass evolution (e.g. Bundy, Ellis & Conselice 2005; McIntosh et al. 2005; Borch et al. 2006; Fontana et al. 2006; Franceschini et al. 2006; Brown et al. 2007; Trujillo et al. 2007; van Dokkum et al. 2008). The coverage (320 arcmin$^2$), depth (1σ surface brightness limit per pixel of 24.7 AB mag arcsec$^{-2}$ in the $i$ band) and high resolution [full width at half-maximum (FWHM) ∼ 0.12 arcsec] of these images allow us to perform a consistent analysis of the redshift evolution of the comoving number density, size and intrinsic colour of these galaxies.

2 THE SAMPLE

The HST/ACS images of the GOODS North and South fields (v2.0) were used to perform a visual classification of spheroidal galaxies. This is a continuation of Ferreras et al. (2005) – that was restricted to the CDFS field. However, note that our sample does not apply the selection based on the Kormendy relation, i.e. the only constraint in this sample is visual classification. The analysis of the complete sample is presented in Ferreras et al. (2009a). Over the 320 arcmin$^2$ field of view of the North and South GOODS/ACS fields, the total sample comprises 910 galaxies down to $i_{AB} = 24$ mag (of which 533/377 are in HDF-N/CDFS). The available photometric data – both space- and ground-based – were combined with spectroscopic or photometric redshifts in order to determine the stellar mass content. Spectrophotometric redshifts are available for 66 per cent of the galaxies used in this paper. The photometric redshifts have an estimated accuracy of $\Delta(z)/(1 + z) ∼ 0.002 ± 0.09$ (Ferreras et al. 2009a). Stellar masses are obtained by convolving the synthetic populations of Bruzual & Charlot (2003) with a grid of exponentially decaying star formation histories (see appendix B of Ferreras et al. 2009a for details). A Chabrier (2003) initial mass function (IMF) is assumed. Even though the intrinsic properties of a stellar population (i.e. its age and metallicity distribution) cannot be accurately constrained with broad-band photometry, the stellar mass content can be reliably determined to within 0.2–0.3 dex provided the adopted IMF gives an accurate representation of the true IMF (see e.g. Ferreras, Saha & Burles 2008).

The half-light radius is determined using a non-parametric approach that measures the total flux within an ellipse with eccentricity computed from the second-order moments of the surface brightness distribution. The galaxy is considered to extend over a semimajor axis $a = 1.5 × a_{\text{Petro}}$, where $a_{\text{Petro}}$ is the Petrosian semimajor axis (Petrosian 1976). The projected half-light radius is defined as $R_{50} = \sqrt{a_{50} × b_{50}}$, where $a_{50}$ and $b_{50}$ are, respectively, the semimajor and semiminor axes of the ellipse that engulfs 50 per cent of the total flux. Those values need to be corrected for the loss of flux caused by the use of an aperture (see e.g. Graham et al. 2005). We used a synthetic catalogue of galaxies with Sérsic profiles and the same noise and sampling properties as the original GOODS/ACS images to build fitting functions for the corrections in flux and size. The corrections depend mostly on $R_{50}$ and, to second order, on the Sérsic index. Most of this correction is related to the ratio between the size of the object and that of the point spread function of the observations. The dependence with Sérsic index (or in general surface brightness slope) is milder, and for this correction the concentration (as defined in Bershady, Jangren & Conselice 2000) was used as a proxy.

We compared our photometry with the GOODS-MUSIC data (Grazian et al. 2006) in the CDFS. Our sample has 351 galaxies in common with that catalogue, and the difference between our total+corrected $i$-band magnitudes and the total magnitudes from GOODS-MUSIC is $\Delta i = i_{\text{AB}} − i_{\text{MUSIC}} = −0.17 ± 0.16$ mag. This discrepancy is mostly due to our corrections of the total flux. A bootstrap method using synthetic images shows that our corrections are accurate with respect to the true total flux to within 0.05 mag, and to within 9 per cent in half-light radius (see appendix A of Ferreras et al. 2009a). Our estimates of size were also compared with the $\text{galfit}$-based parametric approach of Häussler et al. (2007) on the GEMS survey. Out of 133 galaxies in common, the median of the difference defined as $(R_{50}^\text{HST} − R_{50}^\text{GEMS})/R_{50}^\text{GEMS} = −0.01 ± 0.16$ (the scatter is defined as the semi-interquartile range).

We focus here on a volume-limited sample comprising early-type galaxies with stellar mass $M_\star \gtrsim 3 × 10^{10} M_\odot$. This sample is binned according to fixed steps in comoving volume (a standard $\Lambda$CDM cosmology with $\Omega_m = 0.3$ and $h = 0.7$ is used throughout). The complete sample of 910 galaxies from Ferreras et al. (2009a) is shown in Fig. 1. Solid (open) circles represent early-type galaxies whose colours are compatible with an older (younger) stellar population. This simple age criterion is based on a comparison of the observed optical and near-infrared colours with the predictions from a set of templates with exponentially decaying star formation histories, all beginning at redshift $z_f = 3$, with solar metallicity. The ‘old’ population corresponds to galaxies with formation time-scales $\tau \lesssim 1$ Gyr (see Ferreras et al. 2009a for details). The ‘young’ component is compatible with stellar populations formed over longer time-scales. The black dots in the figure correspond to the sample of 457 galaxies used in this paper.

Figure 1. Sample of massive spheroidal galaxies extracted from the v2.0 ACS/HST images of the GOODS North and South fields (Ferreras et al. 2009a). We show in black the volume-limited subsample used in this paper. The sample is further subdivided into three mass bins, between $3 × 10^{10}$ and $10^{12} M_\odot$ (stellar mass), and in four redshift bins (top axis) centred around $z = 0.5, 0.7, 0.9$ and 1.0 (corresponding to look-back times of 5, 6.3, 7.3, and 7.7 Gyr before present, respectively). The dashed line tracks the characteristic stellar mass ($M_\star$) from GOODS-MUSIC (Fontana et al. 2006), scaled from the original estimate (using a Salpeter IMF) to our Chabrier IMF. The curved solid lines are the limiting ($i_{AB} = 24$) masses for two exponentially decaying star formation histories with solar metallicity, started at redshift $z_f = 3$ and with formation time-scales $\tau = 1$ (top) and 8 Gyr (models of Bruzual & Charlot 2003). Our sample is classified according to a best-fitting template which roughly separates into ‘red’ and ‘blue’ galaxies, represented in this figure as filled and hollow circles, respectively.
We further subdivide this sample into three mass bins, starting at \( \log (M_*/M_\odot) = 10.5 \) with a width \( \Delta \log (M_*/M_\odot) = 0.5 \) dex. For comparison, the characteristic stellar mass from the mass function of the GOODS-MUSIC sample is shown as a dashed line (Fontana et al. 2006) after being corrected to our choice of IMF. The GOODS-MUSIC masses are calculated using a Salpeter (1955) IMF, which will give a systematic 0.25 dex overestimate in \( \log M_* \) with respect to our choice of IMF, because of its (unphysical) extrapolation of the same power law down to the low-stellar-mass cut-off (see e.g. Bruzual & Charlot 2003). A single-law Salpeter IMF is an unlikely choice for the stellar populations in early-type galaxies as shown by comparisons of photometry with kinematics (Cappellari et al. 2006) or with gravitational lensing (Ferreras et al. 2008). Our sample stays safely away from the limit imposed by the cut in apparent magnitude (\( i_{\text{AB}} \leq 24 \)). The curved solid lines give that limit for two extreme star formation histories, corresponding to the ‘old’ and ‘young’ populations as defined above, i.e. formation epoch \( z_f = 3 \), solar metallicity and star formation time-scale \( \tau = 1 \) Gyr (top) and 8 Gyr (bottom). Note that within our sample of massive early-type galaxies there is none whose colours are compatible with young stellar populations (i.e. open circles). We emphasize here that this separation into ‘old’ and ‘young’ populations is just a simple way to classify our galaxies into red and blue objects. One could have considered other values for metallicity, time-scale or formation epoch, but the final separation will remain unchanged. We leave to another paper the detailed analysis of the stellar populations of this sample, which is done by combining the observed photometry with low-resolution slitless grism data from ACS/G800L within the PEARs programme (Ferreras et al. 2009b).

### 3 THE EVOLUTION OF MASSIVE GALAXIES

The redshift evolution of the comoving number density is shown in Fig. 2 (black dots). The \((1\sigma)\) error bars include both Poisson noise as well as the effect of a 0.3 dex uncertainty in the stellar mass estimates. These uncertainties are computed using a Monte Carlo run of 10,000 realizations. The figure includes data from GOODS-MUSIC (Fontana et al. 2006), COMBO17 (Bell et al. 2004) and Pal/DEEP2 (Conselice et al. 2007) (when only mass functions were available, we translated them into number densities by integrating over the masses considered in each bin). At \( z = 0 \), we show an estimate from the segregated 2dF galaxy redshift survey (GRS) luminosity function (Croton et al. 2005). We take their Schechter fits for early-type galaxies within an environment with a mean density defined by a contrast – measured inside radius \( 8 h^{-1} \text{Mpc} \) – in the range \( \delta_k = -0.43 \pm 0.32 \) (black open circles). In order to illustrate possible systematic effects in 2dFGRS, we also include the result for their full volume sample as grey open circles. The 2dFGRS data are originally given as luminosity functions in the rest-frame \( b_J \). We took a range of stellar populations typical of early-type galaxies in order to translate those luminosities into stellar masses. The error bars shown for the 2dFGRS data represent the uncertainty caused by this translation from light into mass over a wide range of stellar populations [with typical \( M/L(b_J) \) in the range 7, \ldots, 12 \( M_\odot/L_\odot \)]. The black solid lines show SAM predictions from Khochfar & Silk (2006a). Their SAM follows the merging history of dark matter haloes generated by the Extended Press–Schechter formalism down to a mass resolution of \( M_{\text{min}} = 5 \times 10^8 M_\odot \), and follows the baryonic physics within these haloes using recipes laid out in Khochfar & Burkert (2005, and references therein). The grey dashed lines are the predictions from the Millennium simulation (e.g. De Lucia et al. 2006). This model is extracted from their web-based data base,\(^1\) and is not segregated with respect to galaxy morphology. This explains the excess number density in the low-mass bin (bottom panel). Most of the galaxies belonging to the two higher mass bins have an early-type morphology. The predictions of the Millennium simulation are in agreement for the middle bin – i.e. masses between \( 10^{11} \) and \( 3 \times 10^{11} M_\odot \). However, for the most massive bin, the sharp decrease in density with redshift of the models is in remarkable disagreement with the observations. In contrast, Khochfar & Silk (2006a) predict a nearly constant density evolution at the highest mass bin out to \( z \sim 1 \). Our data confirm the results from the Palomar/DEEP2 survey (see fig. 16 in Conselice et al. 2007).

The main reason for this discrepancy is that active galactic nuclei feedback in the Millennium simulation prohibits the growth of massive galaxies by gas cooling and subsequent star formation in order to reproduce the right colour-bimodality and the luminosity function at \( z = 0 \). As shown in Khochfar & Silk (2008), the existence of a characteristic mass scale for the shut-off of star formation will lead to dry merging being the main mechanism for the growth of massive galaxies. In that respect, the evolution of the number mass function down to a mass resolution of \( M_{\text{min}} = 5 \times 10^8 M_\odot \), and follows the baryonic physics within these haloes using recipes laid out in Khochfar & Burkert (2005, and references therein). The grey dashed lines are the predictions from the Millennium simulation (e.g. De Lucia et al. 2006). This model is extracted from their web-based data base,\(^1\) and is not segregated with respect to galaxy morphology. This explains the excess number density in the low-mass bin (bottom panel). Most of the galaxies belonging to the two higher mass bins have an early-type morphology. The predictions of the Millennium simulation are in agreement for the middle bin – i.e. masses between \( 10^{11} \) and \( 3 \times 10^{11} M_\odot \). However, for the most massive bin, the sharp decrease in density with redshift of the models is in remarkable disagreement with the observations. In contrast, Khochfar & Silk (2006a) predict a nearly constant density evolution at the highest mass bin out to \( z \sim 1 \). Our data confirm the results from the Palomar/DEEP2 survey (see fig. 16 in Conselice et al. 2007).

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\(^1\) http://www.mpa-garching.mpg.de/millennium
density of massive galaxies in the Millennium simulation is mainly driven by mergers. The difference between the models from De Lucia et al. (2006) and Khochfar & Silk (2006b) is probably due to the different merger rates in their models. The Millennium simulation predicts a lower major merger rate compared to Khochfar & Silk (2006a) almost by a factor of 10 (Hopkins et al., in preparation).

Fig. 3 shows the redshift evolution of the half-light radius. Our methodology follows a non-parametric approach avoiding the degeneracies intrinsic to profile fitting. Our data (black dots) are compared with Trujillo et al. (2007, grey triangles) and with a \( z \sim 0 \) measurement from the Sloan Digital Sky Survey (SDSS) (Shen et al. 2003, taking their early-type sample). The error bars give the rms scatter of the size distribution within each mass and redshift bin. The lines correspond to the models of Khochfar & Silk (2006b). These models associate size evolution with the amount of dissipation encountered during major mergers along the merging history of an early-type galaxy. The points at high redshift (\( z > 1.2 \)) correspond to individual measurements from the literature (see caption for details). In all the comparisons shown in this paper with work from the literature, we have checked that the IMFs used are similar, so that stellar masses are compared consistently. All results quoted use either a Chabrier (2003) IMF or functions very close to it in terms of the total mass expected per luminosity unit, which – for early-type systems – mainly depends on the IMF at the loss mass end. Other functions used in the quoted data were Kroupa, Tout & Gilmore (1993), Kroupa (2001) or Baldry & Glazebrook (2003). Only for the GOODS-MUSIC data (Fontana et al. 2006), the Salpeter (1955) IMF was used.

Taking into account all data points between \( z = 0 \) and \( z \sim 2.5 \), one sees a clear trend of decreasing size with redshift for all three mass bins. However, our data (black dots) suggest milder size evolution for the most massive early-type galaxies between \( z = 1.2 \) and 0.4, corresponding to a 4 Gyr interval of cosmic time.

The depth and high spatial resolution of the ACS images also allow us to probe in detail the intrinsic colour distribution of the galaxies (i.e. the colour distribution within each galaxy). We follow the approach described in Ferreras et al. (2005) which, in a nutshell, registers the images in the two bands considered for a given colour, degrades them by the point spread function of the other passband, and performs an optimal Voronoi tessellation in order to achieve a signal-to-noise ratio per bin around 10 while preserving spatial resolution. The final binned data are used to fit a linear relation between colour and log (R/R\(_e\)) from which we determine the slope and the scatter about the best fit (using a biweight estimator). Fig. 4 shows the observer-frame \( V - i \) colour gradient (bottom panels) and scatter (top panels) as a function of stellar mass (left-hand panels) and half-light radius (right-hand panels). The solid circles correspond to binned data in stellar mass, showing the average value within each bin. Note the significant trend with increasing stellar mass towards redder cores (i.e. more negative colour gradients) and smaller scatter. The colour gradient is in most cases nearly flat. For comparison, we also show as small grey dots a continuation of the original sample from Ferreras et al. (2009a) towards lower stellar masses. Only for these low-mass bins do we find significantly large (and positive) gradients. Blue cores (i.e. positive colour gradients) dominate in spheroidal galaxies below 10\(^{10}\) M\(_{\odot}\). At higher masses, the homogeneous intrinsic colour distribution suggests no significant star formation and a fast rearranging process of the stellar populations if mergers take place during the observed redshift range. Note that this sample only targets objects visually classified as early-type galaxies. The early phases of major merging are therefore excluded from our sample. Nevertheless, the number density at the massive...
end (upper panel of Fig. 2) does not change significantly between \( z = 0 \) and \( z \sim 1 \), already suggesting that major merger events must be rare over those redshifts.

4 DISCUSSION AND CONCLUSIONS

Using a volume-limited sample of massive spheroidal galaxies from the v2.0 ACS/HST images of the GOODS North and South fields, we have consistently estimated the number density, size and intrinsic colour distribution over the redshift range 0.4 \( < z < 1.2 \). In combination with other samples, we find a significant difference in the redshift evolution according to stellar mass, in agreement with recent work based on other samples or different selection criteria (see e.g. Bundy et al. 2005; McIntosh et al. 2005; Borch et al. 2006; Fontana et al. 2006; Franceschini et al. 2006; Brown et al. 2007; Trujillo et al. 2007; van Dokkum et al. 2008). The most massive galaxies – which impose the most stringent constraints on models of galaxy formation – keep a constant comoving number density between \( z \sim 1 \) and 0 (i.e. over half of the current age of the Universe) but present a significant size evolution, roughly a factor of 2 increase between \( z = 1 \) and 0. When velocity dispersion is added to the analysis, a significant difference is found in the \( \sigma - R \) distribution between \( z = 0 \) and 1, suggesting an important change in the dynamics of these galaxies (van der Wel et al. 2008).

It is important to note that the lack of evolution in the number density relates to the bright end of the luminosity function, Faber et al. (2007) found a significant change in the number density of red galaxies with redshift. However, they also emphasize that this change does not refer to the most luminous galaxies. If we include all mass bins in our sample, we do find a significant decrease in the number density with redshift, as the lower mass bins – which contribute the most in numbers – do have a rather steep decrease in density (see Fig. 2). This difference suggests that the (various) mechanisms playing a role in the transition from blue cloud to red sequence must be strongly dependent on the stellar mass of the galaxies involved.

Some of the SAMs of massive galaxy evolution (Khochfar & Silk 2006a,b) are in good agreement with these observations. These models follow the standard paradigm of early-type galaxy growth through major mergers, with the ansatz that size evolution is related to the amount of dissipation during major mergers. The decreasing evolution in the comoving number density at high masses is explained within the models by a balance between the ‘sink’ (loss due to mergers of massive galaxies generating more massive galaxies) and ‘source’ terms (gain from mergers at lower mass) over the redshifts considered. One could argue that the sink terms would generate a population of extremely massive galaxies (above a few \( 10^{12} M_\odot \)), possibly the central galaxies within massive groups or clusters. However, this population – with predicted comoving number densities below \( 10^{-6} Mpc^{-3} \) – is very hard to study with current surveys. Furthermore, environment effects in these systems will complicate the analysis of size evolution (e.g. Khochfar & Ostriker 2008).

In a more speculative fashion, our data are also suggestive of weak or even no evolution in the number density of the most massive early-type galaxies over a redshift range 0.4 \( < z < 1.2 \). This would imply a negligible role of major mergers at the most massive end for \( z > 0.4 \), thereby pushing this stage of galaxy formation towards lower redshifts (Khochfar & Silk 2008). Another speculative scenario for the evolution of massive spheroidal galaxies would involve negligible major mergers at these redshifts and a significant amount of minor mergers which will ‘puff up’ the galaxy. Minor mergers are considered the cause of recent star formation observed in near-ultraviolet studies of early-type galaxies (Kaviraj et al. 2009). Larger surveys of luminous red galaxies are needed to confirm or disprove this important issue.

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REFERENCES


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