Dissecting the size evolution of elliptical galaxies since $z \sim 1$: puffing-up versus minor-merging scenarios

Ignacio Trujillo,1,2* Ignacio Ferreras3 and Ignacio G. de la Rosa1,2,4

1Instituto de Astrofísica de Canarias, C/Vía Láctea s/n, La Laguna, E-38200 La Laguna, Tenerife, Spain
2Departamento de Astrofísica, Universidad de La Laguna, E-38205 La Laguna, Tenerife, Spain
3Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT
4Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT

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ABSTRACT

At a fixed stellar mass, the size of low-redshift early-type galaxies is found to be a factor of 2 larger than that of their counterparts at $z \sim 1$, a result with important implications for galaxy formation models. In this paper, we have explored the buildup of the local mass–size relation of elliptical galaxies using two visually classified samples. At low redshift, we compiled a subsample of 2656 elliptical galaxies from the Sloan Digital Sky Survey, whereas at higher redshift (up to $z \sim 1$), we extracted a sample of 228 objects from the Hubble Space Telescope/Advanced Camera for Surveys images of the Great Observatories Origins Deep Survey. All the galaxies in our study have spectroscopic data, allowing us to determine the age and mass of the stellar component. Contrary to previous claims in the literature, using the fossil record information contained in the stellar populations of our local sample, we do not find any evidence for an age segregation at a given stellar mass, depending on the size of the galaxies. At a fixed dynamical mass, there is only a $\lesssim 9$ per cent size difference in the two extreme age quartiles of our sample. Consequently, the local evidence does not support a scenario whereby the present-day mass–size relation has been progressively established via a bottom-up sequence, where older galaxies occupy the lower part of this relation, remaining in place since their formation. We do not find any age-segregation difference in our high-$z$ sample either. Therefore, we find a trend in size that is insensitive to the age of the stellar populations, at least since $z \sim 1$. This result supports the idea that the stellar mass–size relation is formed at $z \sim 1$, with all galaxies populating a region which roughly corresponds to 1/2 of the present size distribution. We have explored two possible scenarios for size growth: puffing up or minor merging. The fact that the evolution in size is independent of the stellar age, together with the absence of an increase in the scatter of the relationship with redshift does not support the puffing-up mechanism. The observational evidence, however, cannot reject at this stage the minor-merging hypothesis. We have made an estimation of the number of minor-merger events necessary to bring the high-$z$ galaxies into the local relation compatible with the observed size evolution. Since $z = 0.8$, if the mass ratio of the merger is 1:3, then we estimate $\sim 3 \pm 1$ minor mergers and if the ratio is 1:10, then we obtain $\sim 8 \pm 2$ events.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: fundamental parameters – galaxies: stellar content – galaxies: structure.

1 INTRODUCTION

Present-day galaxies show a clear correlation between mass and size, with the most massive galaxies having the larger sizes. This mass–size relationship has been known both for elliptical and for spiral galaxies for many years. With the advent of large surveys, like the Sloan Digital Sky Survey (SDSS, York et al. 2000), it has been possible to quantify this correlation with high accuracy (see e.g. Shen et al. 2003). However, the mechanisms by which this relationship is built remain uncertain. For instance, we do not have conclusive answers to questions like ‘were the galaxies born in situ at the positions where we find them in the local mass–size relation or were they born in another part in this diagram, drifting to their
present locations? If so, then ‘how much have they grown and what are the mechanisms responsible for this displacement?’ Answering these questions is directly connected to our understanding of how the assembly of the galaxies has proceeded through cosmic time. In this paper, we will particularly focus on spheroidal galaxies as it has been shown in the last few years that their stellar mass–size relation has dramatically changed with redshift.

Several papers have explored the evolution of the stellar mass–size relation of spheroid-like galaxies (e.g. Trujillo et al. 2004; McIntosh et al. 2005; Trujillo et al. 2006a, 2007; Buítrago et al. 2008; Ferreras et al. 2009b; Saracco, Longhetti & Gargiulo 2011). In general, they all agree with a significant evolution of this relation with redshift. Their results can be summarized as follows: at a fixed stellar mass, spheroid-like galaxies were significantly more compact at higher redshift (e.g. Daddi et al. 2005; Trujillo et al. 2006b; Longhetti et al. 2007; Zirm et al. 2007; van der Wel et al. 2008; van Dokkum et al. 2008; Cimatti et al. 2008; Damjanov et al. 2009; Carrasco, Conselice & Trujillo 2010), with an increase in the effective radii by a factor of $\sim 2(4)$ from $z \sim 1(2)$ (e.g. Trujillo et al. 2007). However, these observational results say little about the amount of the size evolution of individual galaxies in the mass–size plane. Nevertheless, at least a few basic statements can be established regarding the growth of individual galaxies based on the current observational evidence. First, at high-$z$, there are no big spheroidal objects, implying that the present-day large elliptical galaxies have either formed recently (in situ) with large sizes or they are the product of the evolution of previous compact galaxies that populated the high-$z$ stellar mass–size plane. Secondly, the near absence of compact massive galaxies in the nearby Universe (Trujillo et al. 2009; Taylor et al. 2010; Valentinuzzi et al. 2010), which were very common in the early Universe, indicates that individual objects (at least the very old and compact ones) have evolved significantly in size.

Some recent works have conducted a detailed analysis of the buildup of the local spheroid mass–size relationship (van der Wel et al. 2009; Valentinuzzi et al. 2010). These works propose that the formation of this relation is a result of two steps: (i) the continuous emergence of galaxies as early-type systems with larger sizes, as cosmic time increases, due to the decreasing availability of gas during their formation phase (Khochfar & Silk 2006); and (ii) their subsequent growth through either gas expulsion in the so-called puffing-up scenario (Fan et al. 2008, 2010; Damjanov et al. 2009) or by minor-merging activity (Hopkins et al. 2009a; Naab, Johansson & Ostriker 2009). If the above scenario is correct, that is, the new assembled galaxies are born with larger sizes as redshift decreases, we should observe that the number density of spheroid-like massive galaxies at a fixed stellar mass should decrease with increasing redshift. Furthermore, a gradual change in the age of the galaxies at a fixed stellar mass should be expected, in the sense that larger galaxies should be younger. However, there is no compelling evidence of a significant drop in the number density of elliptical galaxies up to $z \sim 1$ (see e.g. Ferreras et al. 2009b), weakening this formation scenario. On the other hand, in van der Wel et al. (2009) and Valentinuzzi et al. (2010), there is some hint that larger spheroid-like galaxies, at a fixed dynamical and stellar mass, are younger than their compact mass equivalents.

In this paper, we re-examine the buildup of the mass–size relationship of spheroidal galaxies with two significant improvements in relation to previous work. First, this paper addresses the issue of the evolution of early-type galaxies in the mass–size plane by comparing a nearby with a distant sample of galaxies, classified and analysed in the same way. We will show in this paper that previous studies of the local stellar mass–size relation of early-type galaxies are severely contaminated by galaxies of other morphological types. For this reason, this study is the first one exploring objects that have been classified only visually, and not by any other criteria, like structural parameters or colours. The second advantage of this work is that we have quality spectra for all our targets, allowing us – by exploring their spectral energy distributions (SEDs) – to obtain reliable star formation histories (SFHs). Spectroscopic data are essential to robustly determine the properties (stellar mass and age) of the underlying stellar populations in both local and high-redshift samples, allowing us to make a much more consistent assessment of the increase in galaxy size on an individual galaxy basis. The information about the ages allows us to explore whether the size evolution depends on the properties of the stellar populations of these galaxies. This information is a key to distinguish between the two most likely mechanisms of size growth proposed in the literature for elliptical galaxies: the puffing-up versus the minor-merging scenarios. In this paper, we will discuss in detail the implications of our findings for these two models.

This paper is structured as follows. In Section 2, we describe the local sample. The connection between the stellar age and the mass–size relationship is explored in Section 3. In Section 4, we present our moderate-redshift sample and in Section 5, we quantify the size evolution of our galaxies. Section 6 is devoted to explore which evolutionary scenario is more plausible according to these observations, finally concluding in Section 7 with an overview of our results. In this paper, we adopt a standard $\Lambda$CDM cosmology, with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.
Dynamical mass–size relation of the sample used in this paper (NA10 sample; black dots in the right-hand panel) compared to the early-type sample selection of Graves et al. (2009, grey data points). This figure illustrates the different positions in the mass–size diagram that spiral galaxies (i.e. contaminants) have in this diagram (see text for details). LTG contaminants are not distributed homogeneously over the early-type galaxy footprint: face-on LTGs mainly live in the top part of the diagram (large radii), whereas edge-on LTGs populate the bottom left-hand corner (low sizes and masses).

Figure 1. Dynamical mass–size relation of the sample used in this paper (NA10 sample; black dots in the right-hand panel) compared to the early-type sample selection of Graves et al. (2009, grey data points). This figure illustrates the different positions in the mass–size diagram that spiral galaxies (i.e. contaminants) have in this diagram (see text for details). LTG contaminants are not distributed homogeneously over the early-type galaxy footprint: face-on LTGs mainly live in the top part of the diagram (large radii), whereas edge-on LTGs populate the bottom left-hand corner (low sizes and masses).

below. We take advantage of the fact that virtually all the galaxies in the sample of Graves et al. (2009) have their morphology visually studied by the Galaxy Zoo project (Lintott et al. 2011). We use their fraction of votes for ellipticals ($p_{\text{el}}$), spirals (both clockwise and anticlockwise, $p_{\text{p}}$) and edge-on spirals ($p_{\text{edge}}$) to identify the late-type galaxy (LTG) contaminants. We have carried out a further visual check of these contaminants, finding a complete agreement with the results of Galaxy Zoo. Despite the small overall contamination rate ($\sim$1.8 per cent), the face-on LTGs concentrate in the region with large radii, while the edge-on LTGs ($\sim$8 per cent) concentrate towards low values of $R_e$ and $M_{\text{dyn}}$.

The spectroscopic data and photometric parameters of the NA10 sample are retrieved from the SDSS archive. We have used spectra from the DR7 (Abazajian et al. 2009) to benefit from the improved flux calibration introduced in the DR6 (see Adelman-McCarthy et al. 2008). The SDSS spectroscopic data cover a wavelength range from roughly 3800 to 9200 Å at an average spectral resolution of 3.25 Å [full width at half-maximum (FWHM)]. This instrumental resolution is not constant but varies in a complex way with wavelength, fibre and arrangement. All spectra are both de-redshifted and corrected for Galactic foreground extinction, using the dust maps of Schlegel, Finkbeiner & Davis (1998). Hereafter, all size estimates are quoted as the circularized effective radius $R_e \equiv (b/a)^{1/2} \times R_{\text{dev}}$, with parameters $R_{\text{dev}}$, $a$ and $b$ taken from the photometric SDSS pipeline. In principle, velocity dispersion data ($\sigma$) are also available from the DR7 SDSS pipeline, although with a moderately high ratio of missing values, amounting to over 15 per cent of our SDSS sample. Consequently, we have recalculated the values of velocity dispersion with the same spectral fitting method used in this study (STARLIGHT, see Section 3), taking as velocity dispersion the smoothing parameter of the stellar population mixture that produces the best fit to the observed spectrum. La Barbera et al. (2010) show that there is good agreement between the STARLIGHT and SDSS-DR7 velocity dispersion values, with only a small systematic trend at the low ($\sim$90 km s$^{-1}$) and high ($\sim$280 km s$^{-1}$) ends of the $\sigma$ range. Very few measurements (0.4 per cent) are excluded, with $\sigma < 40$ km s$^{-1}$, because they are considerably smaller than the resolution of the base single stellar population (SSP) models (58 km s$^{-1}$). We have used the Jørgensen, Franx & Kjærgaard (1995) prescriptions to correct the velocity dispersion to the same fraction of the effective radius, $R_e/8$, instead of the fixed fibre diameter (3 arcsec).

3 THE LOCAL MASS–SIZE PLANE: DISTRIBUTION OF GALAXIES ACCORDING TO THEIR STELLAR AGE

Both van der Wel et al. (2009) and Valentinuzzi et al. (2010) have argued that there is an age gradient within the mass–size plane of early-type galaxies: at fixed mass, galaxies with larger sizes are found to be younger. As it was argued in Section 1, this observation is expected if newly assembled spheroidal galaxies feature larger sizes than those systems assembled earlier. For this reason, we have revisited the age distribution of our galaxies in the NA10 sample.

The age of the stellar populations of our galaxies is estimated as follows. We use the spectral fitting code STARLIGHT (Cid Fernandes et al. 2005) to find combinations of SSP models that, broadened with a given velocity dispersion, achieve the best match with the observed galaxy spectrum. For this study, we have used the SEDs of the MILES SSP models (Vazdekis et al. 2010) with a Kroupa universal initial mass function (Kroupa 2001). These models are based on the MILES$^1$ stellar library (Sánchez-Blázquez et al. 2006), which combines both a rather complete coverage of the stellar atmospheric parameters and a relatively high and nearly constant spectral resolution, 2.3 Å (FWHM), optimally suited for the spectral resolution of the SDSS data. Our base for the fitting using STARLIGHT consists of 138 solar-scaled SSP models with six different metallicities, ranging from $Z = 1/50$ to 1.6 $Z_{\odot}$ and 23 different ages, from 0.08 to 11.22 Gyr. Extinction due to foreground dust is modelled with the CCM law (Cardelli, Clayton & Mathis 1989) and masks are used to avoid emission lines or bad pixels. The $M_{\text{gas}}$ parameter – the fraction of the initial stellar mass which still remains as stars at a later time – is extracted from the model predictions and used to calculate the stellar mass of our galaxies, $M_*$. In this work, we have

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1 http://www.mies.es/proyecto/miles
Correlation between the effective radius and stellar mass (panel a), central velocity dispersion (panel b) and dynamical mass estimated assuming homology (panel c) and non-homology (panel d) for our local sample. The grey triangles (black crosses) represent the youngest (oldest) quartiles of the age (mass-weighted) distribution according to our modelling with starlight. The dotted line in panel (a) is the scaling relation of early-type galaxies according to Shen et al. (2003).

Figure 2. Correlation between the effective radius and stellar mass (panel a), central velocity dispersion (panel b) and dynamical mass estimated assuming homology (panel c) and non-homology (panel d) for our local sample. The grey triangles (black crosses) represent the youngest (oldest) quartiles of the age (mass-weighted) distribution according to our modelling with starlight. The dotted line in panel (a) is the scaling relation of early-type galaxies according to Shen et al. (2003).

Figure 3. Zoom-in of the mass–size distribution of our local sample. The regions shown are those where the two extreme age quartiles of the sample (young as a dashed line and old as a solid line) have galaxies over a similar range of stellar masses (left-hand panel) and dynamical masses (middle and right-hand panels). An estimate of the size difference in the overlapping regions is given at the top of each panel.

two families, at a fixed stellar mass, is negligible (being compatible with zero change within the statistical uncertainty). The reasons for this discrepancy could be several. On the one hand, Valentinuzzi et al. (2010) segregates their galaxies using luminosity-weighted ages instead of mass-weighted ages as used here. Another possibility is that their early-type selection criteria based on the automatic code morphot could include a larger number of spiral galaxies as contaminants, in contrast with a visual classification. We have explored whether using luminosity-weighted ages changes our results and find that this is not the case. In fact, if we repeat the previous exercise using luminosity-weighted ages, we find that the difference between the two extreme quartiles is 1.7 ± 0.9 per cent (i.e. very similar to the mass-weighted ages). Finally, our stellar mass–size relation is compared with the early-type relation of Shen et al. (2003). The agreement is very good for objects with the stellar mass $M_\star < 3 \times 10^10 M_\odot$. However, at the high-mass end, we note that the sizes of our galaxies are slightly larger than those provided by Shen et al. (2003), a result in agreement with Guo et al. (2009), who find a similar underestimate of the Shen et al. sizes of a similar sample of visually inspected early-type galaxies.

Our previous results show that at a fixed stellar mass galaxies do not show any significant difference in age. However, an interesting change is found when dynamical masses are considered instead of stellar ones (panels c and d). In this case, the age segregation is apparent, with younger galaxies having slightly larger sizes. Under the assumption of dynamical homology (i.e. estimating the dynamical masses as $M_{dyn} = 5\sigma^2 R_e/G$, Cappellari et al. 2006), the size difference between the two extreme quartiles reaches a value of ~16 per cent (~13 per cent in the case of luminosity-weighted ages). However, elliptical galaxies are well known for not being a homologous family. If we repeat the same analysis using this time the dynamical mass accounting for the non-homology following the expression provided by Bertin, Ciotti & Del Principe (2002):

$$M_{dyn,n} = K(n)\sigma^2 R_{e,n}/G,$$

with

$$K(n) \simeq \frac{73.32}{10.465 + (n - 0.95)^2} + 0.954,$$

and $n$ being the Sérsic index of the elliptical galaxies in our sample (determined from Blanton et al. 2005), we find that the size difference, $\Delta R_e/R_e$, decreases significantly to ~9 per cent (~8 per cent in the case of luminosity-weighted ages). Our findings about the size

\[\Delta R_e/R_e = 2.8\pm2.1\% \quad \Delta R_e/R_e = 15.7\pm0.9\% \quad \Delta R_e/R_e = 9.4\pm0.3\%\]

\[\begin{array}{ccc}
\text{Stellar} & \text{Dyn–Hom} & \text{Dyn–NoHom} \\
\end{array}\]

\[\begin{array}{cccc}
10 & 11.5 & 11 & 11.5 \\
11.6 & 11.6 & 11.6 \\
\end{array}\]
difference between the old and young galaxies at a fixed dynamical mass are in qualitative agreement with the findings by van der Wel et al. (2009).

Given that dynamical mass estimates depend on the velocity dispersion quadratically, one would expect that the size difference of the galaxies in the two age quartiles could be linked to a change in the velocity dispersion between the young and the old populations. Panel (b) of Fig. 2 confirms this point: at fixed velocity dispersion, the older subsample is significantly larger ($35.3 \pm 0.5$ per cent; $25.3 \pm 1.7$ per cent in the case of luminosity-weighted ages) than the younger galaxies. Alternatively, one could interpret this result as follows: at fixed effective radius, older galaxies have lower velocity dispersion than their younger counterparts (although the region of overlap between old and young galaxies at fixed size is arguably rather small).

Although we agree qualitatively with van der Wel et al. (2009) on a size difference between the young and old galaxy families at a fixed dynamical mass, our results about the size difference at a fixed velocity dispersion are in contrast with them. These authors show (in their fig. 1) that at fixed velocity dispersion the age of the galaxies is independent of their size. The reason for this discrepancy could be two-fold: first, their ages are luminosity weighted, in contrast with our mass-weighted ages and, secondly, their sample suffers from some contamination of spiral galaxies in key places of the mass–size diagram.

Irrespective of the comparison with other works, our results indicate that the size variation due to changes in the stellar population ages of the elliptical galaxies in the local Universe is very small. Although the age trend goes in the direction (i.e. older galaxies being more compact than young ones at a fixed stellar mass) that one would expect from a progressive bottom-up scenario for the buildup of the local mass–size relation model, it is clear that the differences in size are very small to be able to reproduce the large size variation with cosmic time found at high redshift. We will return to this point more extensively in the following sections. We conclude that the stellar population ages do not resemble the age of the full assembly of the elliptical galaxies and, consequently, that after the formation of the bulk of their stellar content, elliptical galaxies have experienced a significant evolution in their size.

3.1 Dynamical structure change in the galaxies with age

The virial theorem predicts that, at fixed mass, the velocity dispersion will change as the inverse of the root square of the galaxy size. Consequently, one would expect, due to the strong size evolution with redshift observed in the elliptical population, that the velocity dispersion of the high-redshift objects is significantly larger than those found in local galaxies. However, observations are at odds with this scenario (Cenarro & Trujillo 2009): the velocity dispersion of the elliptical galaxies, at a fixed stellar mass, only changes moderately with redshift. Hopkins et al. (2009b) have explained this mild change in the velocity dispersion, suggesting that the contribution of the dark matter halo to the gravitational potential of the galaxy changes with cosmic time. According to that model, in the present Universe, the contribution of the dark matter halo on settling the velocity dispersion of the galaxies will be higher than in the past.

We can explore whether our local sample shows any hint of a dynamical structure change as a function of the age as suggested by the Hopkins et al. (2009b) idea. To do that we explore both the baryonic fraction (top panel) and the velocity dispersion (bottom panel) of our local galaxies against the age of their stellar populations in

![Figure 4](https://academic.oup.com/mnras/article-abstract/415/4/3903/1750192)  
**Figure 4.** The stellar mass-weighted age is shown with respect to the baryon fraction (top panel) or velocity dispersion (bottom panel) for a range of stellar masses as labelled. The points and error bars give the median value and error in age bins chosen at a fixed number of galaxies per bin. The thick lines indicate that the dynamical masses have been calculated assuming homology, whereas the mass estimates assuming non-homology are shown as the thin lines.

The strong trend habitually found between the stellar populations and velocity dispersion is evident, with the oldest galaxies being the most massive ones (see e.g. Bernardi et al. 2005; Graves et al. 2009; Napolitano, Romanowsky & Tortora 2010; Rogers et al. 2010), with a larger dark matter content within the optical radius (see e.g. Ferreras, Saha & Williams 2005b; Tortora et al. 2009; Leier et al. 2011). This trend of an increased dark matter content with galaxy mass is also consistent with the results pertaining to whole haloes, as shown when comparing observed stellar mass functions with cosmological halo abundances (see e.g. Moster et al. 2010).

We can now probe in more detail Fig. 4: at a fixed stellar mass, the oldest galaxies feature higher velocity dispersions and a lower baryon fraction. The higher velocity dispersion for the older galaxies is in agreement with the findings of Cenarro & Trujillo (2009) at high redshift and supports the idea of Hopkins et al. (2009b). However, the decrease in the baryonic fraction as a function of age seems at odds with the high-$z$ findings. It is interesting to note that our estimation of the dynamical mass is done with the sizes found in the local Universe, so a direct relation with the baryonic fraction estimated at high $z$ is not straightforward. From the analysis of the local relation, we find that the age of the most massive local ellipticals is quite homogeneous and also their dynamical structure change is limited to $M_*/M_{\text{dyn}} \sim 0.4 \pm 0.1$. This suggests that the most massive elliptical galaxies formed via an earlier, very homogeneous formation process. This scenario is consistent with the observed lack
of evolution in the number density of massive early-type galaxies (see e.g. Fontana et al. 2006; Ferreras et al. 2009b; Banerji et al. 2010).

For our intermediate and lower stellar mass bins, elliptical galaxies show a much more important trend between the age and dynamical structure. For instance, we see that for present $M_\ast \sim 10^{11} M_\odot$ ellipticals, the baryonic fraction can change between 0.3 and 0.7 and the velocity dispersion between 150 and 250 km s$^{-1}$. We note that our trend, at fixed stellar mass, towards a lower baryon fraction in older populations is at odds with Shankar & Bernardi (2009) and Napolitano et al. (2010). They obtain the opposite trend, namely more dark matter in the younger populations at a fixed stellar mass (Napolitano et al. 2010), or corrected luminosity (Shankar & Bernardi 2009). However, our range of stellar masses and ages is much shorter, concentrated towards the high-mass end. Furthermore, the age estimates of Napolitano et al. (2010) are based on broad-band photometry alone, a method considered robust on the determinations of the stellar M/L but not on age estimates (e.g. Ferreras et al. 2005b). Shankar & Bernardi (2009) use instead the spectroscopic ages from Gallazzi et al. (2005) who use a combination of spectroscopic line strengths. In an independent study carried out with 40 000 Early-Type Galaxies from the SDSS (de la Rosa et al., in preparation), several methods and SSP models are compared. The method of Gallazzi et al. (2005) with Bruzual & Charlot (2003) models provides systematically younger ages than the spectral-fitting technique with the MILES population synthesis models used for this study. Furthermore, by comparing the performance of the model–method combination with repeated observations of the same SDSS targets ($\sim 2300$ repeated spectra), the spectral-fitting approach is shown to be considerably more robust than other age-dating methods. The difference between older and younger galaxies may reflect different channels of galaxy formation within the same stellar mass bin. As the size of the galaxies is proportional to the dynamical mass and inversely proportional to the square of the velocity dispersion, we obtain, as expected, a slight trend to smaller galaxies as a function of the stellar population ages. This trend is unable to explain the strong size evolution found at high redshift.

The detailed analysis of the local mass–size relation reveals that the information contained is unable to fully explain which mechanisms have followed the elliptical galaxies to reach their present sizes. For this reason, it is necessary to conduct a direct comparison of the properties of the local galaxies with those of equivalent galaxies at high $z$ to extract such information. This is what we do in the following sections.

4 MODERATE-REDSHIFT SAMPLE

In order to understand in more detail the size evolution of massive galaxies and their relation to age, we include in our study a sample of visually classified early-type galaxies at moderate redshift ($z \lesssim 1$). The comparison with the local sample allows us to probe the evolution of the mass–size relationship over the past $\sim 8$ Gyr. The deep images of the Great Observatories Origins Deep Survey (GOODS) fields (Giavalisco et al. 2004) taken by the Advanced Camera for Surveys (ACS) onboard the Hubble Space Telescope (HST) provide the optimal data set for visual classification of galaxy morphologies out to redshifts $z \lesssim 1$. We use the catalogue of early-type galaxies from Ferreras et al. (2005a) and Ferreras et al. (2009a) in the North and South GOODS fields, comprising 910 visually classified early-type galaxies brighter than $F775W = 24$ mag (AB). For a proper comparison with the evolved local sample, we need a reliable estimate of the stellar age. The broad-band photometry of the GOODS sample is not good enough for our purposes, and we consider a subsample with available spectral data. The PEARLS sample of early-type galaxies (Ferreras et al. 2009c) comprises 228 galaxies from the GOODS catalogue, with available slitless spectroscopy using grism G800L (HST/ACS). The spectral resolution depends on the galaxy size, with an average value $R \equiv \lambda/\Delta \lambda \sim 50$ for our objects. This sample covers a redshift range $0.4 < z < 1.3$. The lower redshift was dictated mainly by the requirement of having the 4000-A break within the sensitivity range of the grism data. In Ferreras et al. (2009c), stellar ages are determined using a grid of composite models, including chemical enrichment, from which best-fitting ages and metallicities are obtained. However, in order to reduce the systematics, we use only this modelling to generate the best-fitting spectra at similar resolution to those from the local sample. We note this method should introduce a very small systematic, given that the values of the reduced $\chi^2$ obtained for the PEARLS sample are always of the order of 1, and that the method used in this paper to determine ages uses the full SED for fitting, not individual absorption lines.

Ages and stellar masses are recomputed from these spectra, using the same methodology as for the local sample (i.e. STARLIGHT; Cid Fernandes et al. 2005), with the only difference being the age range of the model populations. For these galaxies, we restrict the oldest SSPs to the age of the Universe at the redshift of the galaxy. This approach is well justified as STARLIGHT uses the full SED to constrain the stellar populations, an equivalent technique to the one used with the PEARLS data set. Comparisons between STARLIGHT ages and stellar masses and those determined with the chemical enrichment modelling in Ferreras et al. (2009c) are fully consistent within error bars.

4.1 Backtracking the evolution of local early-type galaxies

By extracting the SFHs of our local galaxies, one can backtrack their evolutionary paths and estimate the amount of new stellar mass created due to the formation of new stars as well as the age of the stellar populations at a given redshift. To minimize systematic effects, we apply the same methodology to both local and distant galaxies to determine their ages. In Fig. 5, we show the predicted amount of stellar mass for the galaxies in our local sample formed since $z \approx 1$ according to their SFHs.

Fig. 5 uses the best-fitting models from STARLIGHT to quantify the net increase in stellar mass from recent phases of star formation. We show the mass growth as the ratio between the stellar mass already in place at some redshift ($M_\ast$) and the current mass at redshift zero ($M_\ast$) for four redshift bins. The sample is split at the median in age measured at zero redshift. One can see that the stellar mass growth at $z \lesssim 0.6$ stays well below 10 per cent for most of the galaxies, especially for the most massive galaxies, which belong mostly to the oldest half (black solid lines).

We have applied to all our galaxies in the local relation the evolution in mass predicted from their SFHs and we have rebuilt the local stellar mass–size relation, taking into account that evolution. We consider both the change in the stellar age (mass weighted) and the change in the stellar mass of the galaxy. For simplicity, we assume that, within a galaxy, the SFH does not have a radial trend. Our sample does not allow us to probe in detail this point, but we note that studies of the colour gradient of early-type galaxies at moderate redshift find almost always the star formation concentrated in the centre, that is, in a blue core (Ferreras et al. 2005a, 2009a). The stellar mass–size relation of our PEARLS sample in comparison
with the local sample is shown in Fig. 6. The figure shows how the local stellar mass–size relation will look like at different redshifts if we correct for the stellar mass evolution. One can see that the redshifted local stellar mass–size relation changes very little in the high-mass regime. The evolution is more evident at lower masses, where the galaxies clearly deviate from the local relationship.

5 SIZE EVOLUTION

We are now in a position to explore the size evolution of the early-type galaxies after accounting for the stellar mass growth due to new star formation. In fact, the comparison with the observed PEARs sample for similar stellar ages will allow us to determine the evolution of size at a given stellar mass.

At the top left-hand corner of Fig. 6, the local sample is shown using the same criterion as in Fig. 2, with individual galaxies shown as the small dots. We include in that panel the local trend of SDSS early-type galaxies (long-dashed line, Shen et al. 2003), showing agreement with our local sample, except for the most massive end, as discussed in Section 3. In the following panels, PEARs individual galaxies appear as the solid (open) circles, with ages younger (older) than the median within each redshift bin. The standard downsizing trend is apparent in this figure, with the younger PEARs galaxies having the lowest stellar masses. If the proposed model in van der Wel et al. (2009) were correct, with the youngest galaxies being more extended, at a given stellar mass, than the older counterparts, then one would expect this segregation to be more evident at higher redshifts, where the effect of look-back times makes it easier to discriminate with respect to age (i.e. a reduced age–metallicity degeneracy). However, no clear trend with respect to galaxy size is found in our data.

Our best-fitting models for the local sample predict very small stellar mass changes (see Fig. 5), at levels that correspond to $\Delta \log M_s \lesssim 0.05$ dex along the horizontal direction in Fig. 6. The comparison with the PEARs sample shows that there is a notable ‘vertical’ evolution (i.e. change in size). This one can be illustrated by comparing the (redshift zero) size of the local galaxies with the observed size of the PEARs galaxies, within subsamples of the same stellar age. Fig. 7 shows the size evolution for galaxies with stellar mass in the range $5 \times 10^{10} < M_s/M_\odot < 3 \times 10^{11}$. We have fitted our evolution using the following parametrization: $R(z) = R(0)(1 + \gamma z)$ with $R(0)$ being the size obtained from the local stellar mass–size relation (Shen et al. 2003). Our data are compatible with $\gamma = -0.657 \pm 0.122$ for the full galaxy sample, with $\gamma = -0.631 \pm 0.176$ for the young subsample, and $\gamma = -0.674 \pm 0.160$ for the older subsample (uncertainties quoted at the 68 per cent confidence level).

Fig. 7 shows that the size evolution is significant, in agreement with, for example, Trujillo et al. (2007), with galaxies at $z \sim 1$ being $\sim 50$ per cent smaller in size than their local counterparts. Note the little difference between the trends of the samples segregated with respect to age (large open/solid grey circles). This is one of the most important results of this work and implies that the amount of size evolution that elliptical galaxies suffer since $z \sim 1$ is independent of the age of the galaxies at each redshift interval. This means that the full population of elliptical galaxies, independently of its level of star formation, experiences a similar evolutionary mechanism for assembly. This is once more a result in contradiction to the idea that younger galaxies at all redshifts are born with significantly larger sizes than their older massive counterparts. In other words, our results point out to a similar displacement in the stellar mass–size relation of all the galaxies in the sample (independently of their age).

6 CONSTRaining THE DIFFERENT EVOLUTIONARY PATHS OF THE ELLIPTICAL GALAXIES SINCE $z \sim 1$

In this section, we explore the current most likely scenarios proposed to explain the evolution of elliptical galaxies in the mass–size plane. We use the results obtained here and in previous papers to constrain those scenarios.

In what follows, we consider that both the size and the stellar mass growth of the elliptical galaxies can be described as the contribution of three different processes: (i) formation of new stars in the galaxies as a result of gas consumption; (ii) accretion of already formed stars from merging of different subunits; and (iii) gas ejection from the activity of either an active galactic nucleus (AGN) and/or supernova galactic winds. We parametrize the effect of these three processes in the mass and size of the galaxies as follows:

$$\Delta M_s = \Delta M_{s, SF} + \Delta M_{s, acc},$$

$$\Delta R_e = \Delta R_{e, SF} + \Delta R_{e, acc} + \Delta R_{e, agn},$$

with $\Delta M_{s, SF}$ and $\Delta M_{s, acc}$ representing the increase in the stellar mass due to star formation and by accretion of new stars on to the galaxies, respectively. $\Delta R_{e, SF}$, $\Delta R_{e, acc}$ and $\Delta R_{e, agn}$ correspond, respectively, to the increase in size by star formation, accreted stars and by expansion due to galactic winds either created by the effect of a central AGN or created by supernova explosions.

6.1 Observational facts

The results of this paper show that $\Delta M_{s, SF}$ is very small (i.e. $\Delta M_{s, SF} \ll M_s$) and also that the evolution of the size of the
galaxies is quite independent of the age of their stellar population, so $\Delta r_{e}(\text{old}) \sim \Delta r_{e}(\text{young})$. Due to the little increase in the stellar mass due to in situ star formation, we assume from now on, to simplify the discussion, that, if any, $\Delta M_{s} \approx \Delta M_{s,\text{acc}}$ for the elliptical galaxies since $z \sim 1$.

6.2 Puffing-up model: AGN and/or supernova galactic wind effects

Fan et al. (2008, 2010) have proposed a mechanism based on the removal of gas as a result of AGN activity to explain the size growth of early-type galaxies. According to these authors, the rapid expulsion of large amounts of gas by quasar winds destabilizes the galaxy structure in the inner, baryon-dominated regions and leads to a more expanded stellar distribution. A similar idea – but based on the gas expulsion associated to stellar evolution – has been proposed by Damjanov et al. (2009). The prediction from the puffing-up model can be parametrized as follows:

$$\Delta M_{s,\text{SF}} = 0,$$

$$\Delta M_{s,\text{acc}} = 0,$$

$$\Delta M_{s} = 0,$$

$$\Delta r_{e,\text{SF}} = 0,$$

$$\Delta r_{e,\text{acc}} = 0,$$

$$\Delta r_{e} = \Delta r_{e,\text{agn}}.$$  \hspace{1cm} (8, 9, 10)

In other words, all the galaxies in the stellar mass–size relation should just evolve vertically in this relation without any increase in stellar mass. Consequently, the size evolution we observe at a fixed stellar mass should be directly interpreted as the total size evolution of the galaxies.

This model agrees with observations at predicting a small formation of new stars due to the removal of gas from the galaxies. In addition, this model fits well with the lack of evidence of significant evolution in the number density of massive ellipticals since $z \sim 1$. However, we find that our data are in conflict with the model in several aspects. First, according to the Fan et al. (2008) model, after the formation of the compact structure, the AGN activity will remove the gas, triggering a fast growth process ($\sim 20–30$ Myr based on recent simulations$^{2}$; Ragone-Figueroa & Granato 2011). This

$^{2}$ In the case of supernova winds, an important mass-loss event could last even $\sim 0.5–1$ Gyr.
woulid imply that galaxies with stellar populations older than \( \sim 1 \) Gyr should be already located in the local stellar mass–size relation. This is not what our data show. We have galaxies (old and young) at the same distance from the local relation at all redshifts. For instance, at \( z = 1 \), the mass-weighted age of our sample is 3.9 Gyr for the old subsample and 3.5 Gyr for the young subsample. We can consequently assure that the mechanism that is operating in the size evolution of our galaxies does not know about the age of the stellar populations. This is in contradiction to the puffing-up model. In addition, a natural prediction from the puffing-up model is that the scatter of the stellar mass–size relation will increase with redshift (Fan et al., 2010), with some galaxies already in place in the local relation and others still in a very compact phase. We do not observe any increase in the scatter of the stellar mass–size relation with redshift in our data.

### 6.4 Minor dry merging

Another possible scenario for elliptical galaxy growth involves minor mergers on parabolic orbits (e.g. Khochfar & Burkert 2006; Maller et al. 2006; Hopkins et al. 2009b; Naab et al. 2009). Through this channel, the new accreted stars as well as the redistribution of stars in the main galaxy preferentially populate the outer region of the objects. For this reason, this mechanism has been considered a very efficient way of size growth. Fan et al. (2010), following Naab et al. (2009), show that the fractional variation in the gravitational radius and the velocity dispersion of the main galaxy before (i) and after (f) a minor merger is

\[
\frac{R_f}{R_i} = \frac{(1 + \eta)^2}{1 + \eta^{2-\alpha}}
\]

and

\[
\frac{\sigma_f^2}{\sigma_i^2} = \frac{1 + \eta^{2-\alpha}}{1 + \eta},
\]

respectively, with \( \eta \) defined as \( M_i = M_\star (1 + \eta) \) and \( \alpha \) representing the exponent of the local stellar mass–size relation (\( R = b M_\star^a \)). Shen et al. (2003) propose \( a \approx 0.56 \) with \( b = 2.88 \times 10^{-6+1.1a} \) (in units of \( 10^{11} M_\odot \)). In what follows, we implicitly assume that the gravitational radius is proportional to the effective radius of our galaxies. This is only strictly correct as long as the galaxies do not change the shape of their surface brightness profiles during the minor-merger process.

It can be shown that after \( N \) mergers of equal mass ratio \( \eta \), the final radius, mass and velocity dispersion can be written as

\[
\frac{R_f}{R_i} = \left[ \frac{(1 + \eta)^2}{1 + \eta^{2-\alpha}} \right]^N,
\]

\[
\frac{M_f}{M_i} = (1 + \eta)^N
\]

and

\[
\frac{\sigma_f^2}{\sigma_i^2} = \left( \frac{1 + \eta^{2-\alpha}}{1 + \eta} \right)^N,
\]

respectively. We can now make an estimation of the number, \( N \), of minor mergers a galaxy requires in order to reach the present stellar mass–size relation. The final size of the galaxy can be written in terms of the initial size, the size evolution at a fixed stellar mass (provided by the observations) and the difference in stellar mass as follows:

\[
\log R_f \approx \log R_i + \Delta \log R \bigg|_{M_{\text{fixed}}} + \alpha \log(M_f/M_i).
\]

The evolution at a fixed stellar mass for different redshifts is determined by the size evolution found in our data: \( \Delta \log R \big|_{M_{\text{fixed}}} = -\log(1 + yz) \), with \( y = -0.657 \pm 0.122 \). Using equations (13), (14) and (16), we find the number of minor mergers

\[
N = \frac{- \log(1 + yz)}{\log \left( \frac{(1 + \eta)^{2-\alpha}}{1 + \eta^{2-\alpha}} \right)}.
\]

We show in Fig. 8 this number as a function of redshift for two different values of \( \eta \): 1/3 and 1/10. As expected, the number of minor mergers is a function both the redshift and the mass increase per merger, \( \eta \). We can use these estimations in the number of minor mergers as a function of redshift to determine the increase in size, stellar mass and velocity dispersion that individual galaxies suffer if their evolution is dictated by the minor-dry-merging scenario. This
We find that elliptical galaxies and we observe ~3 ± 1 mergers with the ratio 1:3 or ~8 ± 2 mergers with the ratio 1:10. The data analysed in this work together with the evidence collected in recent papers (e.g. Kaviraj et al. 2009; Shankar et al. 2010; Nierenberg et al. 2011) only leave the minor-merging scenario as a viable mechanism for the increase in the size of elliptical galaxies at least since z ~ 1. Proving ultimately, however, that elliptical galaxies grow by minor merging will require a direct quantification on the minor-merger events found in high-redshift galaxies and an exploration of the age and metallicity gradients of the stellar population in local elliptical galaxies.

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