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# Correlations between the size and the stellar population properties of quiescent galaxies.

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## Abstract

We aim to state new constraints on the mechanisms that can drive the growth in size of massive galaxies through the stellar population properties of quiescent galaxies within the stellar mass–size plane. Our sample is composed of $\sim 830$ quiescent galaxies down to $I \leq 23$ from the ALHAMBRA survey with reliable size measurements up to redshift $z \sim 1$. The stellar content (age, metallicity, and extinction) of galaxies is retrieved via SED-fitting and composite stellar population models using the multi-band photometry of ALHAMBRA and the code MUFFIT. At fixed stellar mass, our results point out that more compact quiescent galaxies are older, more rich in metals, and slightly less reddened by dust than their more extended counterparts since $z \sim 1$. We state that the regions of constant stellar population parameters in the stellar mass–size plane are well reproduced by lines of the form $M_\star \propto r_{\rm c}^{0.5-0.6}$, which are also compatible with constant values of velocity dispersion using spectroscopic quiescent galaxies from SDSS. This result points out that the driver of stellar populations would be partly related to dynamical properties of galaxies, as well as to stellar mass. Scenarios including mergers or the "progenitor" bias also agree with these results to explain the growth in size of quiescent galaxies.

## 1 Introduction

As revelead in previous studies, there are tight correlations between the stellar mass of galaxies and their stellar population properties (see e. g. [15, 25, 8] and references in these works). In general, more massive galaxies exhibit older stellar populations (usually referred as the "downsizing" scenario, e. g. [7]), that are also more rich in metals (stellar mass metallicity correlation or MZR, e. g. [15]) than their less massive counterparts. Nevertheless, other parameters such as the stellar surface density or velocity dispersions also present remarkable correlations with the stellar content of galaxies (e. g. [26, 18, 14, 4]). Consequently, it is still matter of debate which is the driver of the stellar content of galaxies.

Recently, many studies have revealed that massive spheroids/quiescent galaxies has grown in size a factor of 4 since redshift $z \sim 2$, whereas since $z \sim 1$ has doubled in size (e. g. [27, 31, 29]). Although this fact has been widely studied, there is no consensus about which is the mechanism responsible for this strong growth in size. Among the mechanisms proposed in the literature, the more promising ones are: i) Mergers (e. g. [21]), the accretion of less massive galaxies at lower redshifts via mergers would produce an increase in size. ii) The "puffing-up" scenario (e. g. [12]) or a redistribution of the stellar content of galaxies via AGN or quasar feedbacks. iii) The "progenitor" bias (e. g. [30, 28]) or the arrival of new and larger members to the red population.

A detailed study of the distribution of stellar population parameters of quiescent within the stellar mass–size plane (MSP) at different redshifts may constrain the mechanism responsible for the growth in size, as well as to shed light on the mechanisms driving the evolution and assembly of galaxies. For this reason, we explore the stellar content of the quiescent galaxies from the ALHAMBRA survey[1] ([19]) as a function of their sizes. Throughtout the present study, we assume a ΛCDM cosmology with $H_0 = 71$ km s$^{-1}$ , $\Omega_{\rm M} = 0.27$, and $\Omega_\Lambda = 0.73$. Stellar masses are given in solar mass units [M$_\odot$] and magnitudes in AB-system [22].

## 2 Sample of quiescent galaxies from the ALHAMBRA survey

Our reference catalogue is the sample of quiescent galaxies published by [9], which was obtained by an optimized rest-frame colour-mass diagram corrected for extinction. This catalogue is complete in stellar mass and provides mass-weighted formation epochs, ages, metallicities, extinctions, stellar masses, and redshifts for $\sim 8\,500$ quiescent galaxies at $0.1 \leq z \leq 1.1$ from the ALHAMBRA survey. This survey was acquired at the 3.5 m telescope of the Calar Alto Observatory[2] (CAHA) and comprises 20 top-hat medium bands in the optical range ($\lambda\lambda$3500–9700 Å, $FWHM \sim 300$ Å) and 3 in the NIR ($J$, $H$, and $K_{\rm s}$). The effective area of this surveys is $\sim 2.8$ deg$^2$ along the northen hemisphere. The stellar population properties were obtained via SED-fitting techniques using the code MUFFIT ([10]) including the removal of strong emission lines and the photometry and photo-$z$ constraints of the ALHAMBRA Gold catalogue[3] ([20], $I \leq 23$). For the analysis, the sets of single stellar population (SSP) models of [2] and [32] (hereafter BC03 and EMILES, respectively) were used to build two independent sets of composite stellar population models (mixtures of two SSPs, more details in [10, 9]). Extinctions were added as a foreground screen to the composite stellar population models with values in the range $A_V = 0.0$–3.1 using the extinction law of [13].

As the ALHAMBRA survey partly overlaps with some *Hubble* fields, we build a subsample of shared quiescent galaxies with reliable size measurements, circularized radius $r_{\rm c}$, from the Advanced Camera for Surveys (ACS) general catalogue of structural parameters [16]. Finally, there are 830 quiescent galaxies in common at $0.1 \leq z \leq 0.9$ with reliable size measurements to study the distribution of stellar population parameters within the MSP.

[1] http://www.alhambrasurvey.com
[2] http://www.caha.es
[3] http://cosmo.iaa.es/content/alhambra-gold-catalog

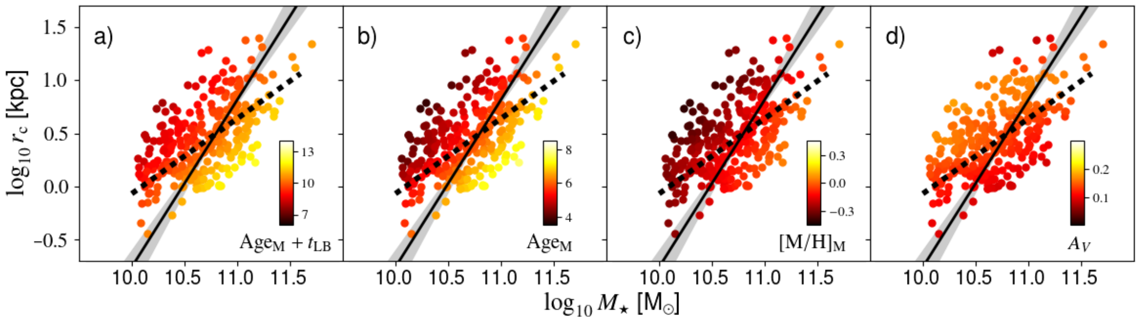


Figure 1: *From left to right* distribution of mass-weighted formation epochs, ages, metallicities, and extinctions of quiescent galaxies (*panels a, b, c*, and *d*, respectively) in the stellar mass–size plane at $0.3 \leq z < 0.5$ using EMILES models. Solid black line show the curve of constant formation epoch, whereas the grey area is the 1 $\sigma$ uncertainty. Dashed black line illustrates the stellar mass–size relation of quiescent galaxies at this redshift.

## 3 Stellar population parameters in the stellar mass–size plane

Before studying the mass-weighted formation epochs, ages, metallicities, and extinctions as a function of size, we carried out a bidimensional and locally weighted regression method or LOESS ([6, 5]) in the MSP. This allows us to average the values in the MSP without assuming any predefined function or model. As a result, we obtain clear correlations between the stellar populations of quiescent galaxies and their sizes at $0.1 \leq z \leq 0.9$ (see Fig. 1). At fixed stellar mass, more compact quiescent galaxies are older and more rich in metals. These differences can amount to $\Delta\mathrm{Age_M} = 2$–3 Gyr and $\Delta[\mathrm{M/H}]_\mathrm{M} \sim 0.2$ dex (see panels a, b, and c in Fig. 1). There are also hints pointing out that more compact quiescent galaxies show lower extinctions with differences of $\Delta A_V \lesssim 0.1$ (panel d in Fig. 1).

These correlations with the size strongly reflect that the stellar mass is not the only parameter driving the evolution of the stellar population of galaxies. To constrain the real driver, we empirically determine the regions of constant stellar population parameters within the MSP. At $0.1 \leq z \leq 0.9$ and for $\log_{10} M_\star \geq 9.6$, we find that the values of mass-weighted formation epoch, $\mathrm{Age_M}+t_\mathrm{LB}$, are properly fitted by a plane of the form: $\mathrm{Age_M}+t_\mathrm{LB}(z)/\mathrm{Gyr} = a \cdot \log_{10} M_\star/\mathrm{M}_\odot + b \cdot \log_{10} r_\mathrm{c}/\mathrm{kpc} + c(z)$. The regions of constant formation epoch are those that $M_\star \propto r_\mathrm{c}^\alpha$, where $\alpha = -b/a$. As a result, we retrieve that $\alpha = 0.5$–$0.6 \pm 0.1$ (see black line in Fig. 1). Note that $\alpha$ slightly depends on the models. We repeat this process for the rest of stellar population parameters (ages, metallicities, and extinctions) getting also a compatible result with $\alpha = 0.5$–$0.6$. In addition, we checked whether the slope of the stellar mass–size relation matches the empirical $\alpha$ obtained above for stellar population parameters. After fitting our distribution of quiescent galaxies to a function of the form $r_\mathrm{c}/\mathrm{kpc} = A(z) \cdot (M_\star/5 \cdot 10^{10}\mathrm{M}_\odot)^{1/\beta}$, we obtain a slope of $\beta = 1.39 \pm 0.04$, i. e. incompatible with the empirical value obtained for stellar population parameters (see dashed line in Fig. 1).

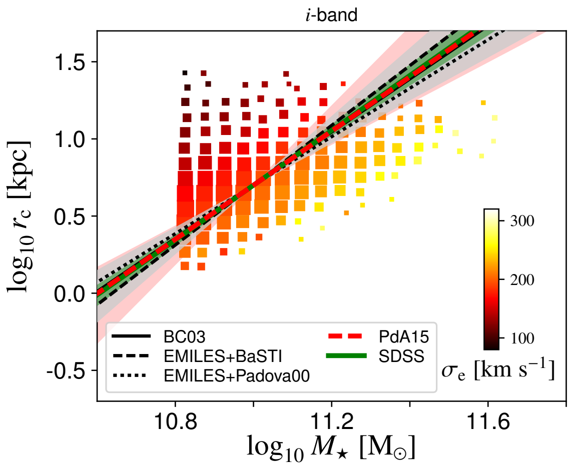


Figure 2: Velocity dispersions of SDSS quiescent galaxies in the stellar mass–size plane at $0.02 \le z \le 0.08$ for the $i$-band. Colours illustrate the average velocity dispersion in each bin, while the marker size illustrates the number of galaxies. Black lines exhibit the empirical curves of constant formation epoch for BC03 and EMILES. Green line shows the curve of constant velocity dispersion from SDSS data. Red dashed line shows the relation obtained by [23] at $z \sim 1$. Shaded areas delimit the 1 $\sigma$ uncertainties for each case.

Furthermore, the average growth in size of our sample of quiescent galaxies is around $2.3 \pm 0.1$ since $z \sim 1$ in good agreement with previous results such as [27, 29].

Motivated by previous studies as [26, 18, 14, 4], we explored the distribution of surface densities and velocity dispersions within the MSP. By definition, constant curves of mass surface density imply that $M_\star \propto r_{\rm c}^2$, which largely differs to the value of $\alpha$ obtained before. As ALHAMBRA is a photometric survey, we explore the distribution of velocity dispersions of quiescent galaxies making use of the he NYU Value Added Galaxy Catalogue DR7 of the Sloan Digital Sky Survey (SDSS, [1]). We selected all the quiescent galaxies using a $ugJ$ colour-colour diagram ([24]) at $0.02 \le z \le 0.08$ and $\log_{10} M_\star \ge 10.8$. A set of quality criteria is applied to remove unreliable velocity dispersions and sizes using the SDSS $i$-band as in [23] ($70 \le \sigma \le 320$ km s$^{-1}$ , $0.3 \le r_{\rm c} \le 30$ kpc, and $r_{\rm c} \ge 1''$). To avoid aperture effects, all the velocity dispersions were corrected to one effective radius, $\sigma_{\rm e}$, following [3]. Values of $\sigma_{\rm e}$ are averaged in equally-sized bins of stellar mass and circularized effective radius (see Fig. 2). Our results strongly agree with a correlation between average values of $\sigma_{\rm e}$ and $r_{\rm c}$ at fixed stellar mass. The more compact the quiescent galaxy, the larger the velocity dispersion at fixed stellar mass. As above, to determine the curves of constant $\sigma_{\rm e}$, the distribution of average $\sigma_{\rm e}$ values are fitted to a plane. As a result, the curves of constant $\sigma_{\rm e}$ for the quiescent galaxies from SDSS are properly expressed as $M_\star \propto r_{\rm c}^{0.56\pm0.05}$ (see green solid line in Fig. 2). In a similar way, [23] retrieved that $M_\star \propto r_{\rm c}^{0.57\pm0.18}$ for massive spheroid-like galaxies at $z \sim 1$ (see red solid line in Fig. 2). Both results being compatible with our empirical relation for stellar population parameters since $z \sim 1$ (see black lines in Fig. 2).

# 4 Implications on the evolution and formation of galaxies

As revealed in Section 3, there are tight correlations between the stellar population parameters and its position in the MSP, meaning, the stellar mass is not the only parameter driving the stellar content of galaxies. This allows to empirically constrain its driver as $M_\star \propto r_\mathrm{c}^\alpha$ with $\alpha \sim 0.5$–$0.6 \pm 0.1$. Moreover, constant values of $\sigma_\mathrm{e}$ are also compatible with this value ($\alpha \sim 0.56$). This suggests that the driver of stellar populations would be partly related to dynamical properties of galaxies, as well as to stellar mass.

The distributions of mass-weighted formation epochs, ages, metallicities, and extinctions within the MSP may constrain the mechanisms responsible of the growth in size of galaxies. Under the "puffing-up" scenario assumption, AGN and quasar feedbacks would produce a redistribution of the stellar content in the inner parts of galaxies yielding an increase in size of a galaxy. Therefore, the most extended galaxies would show older ages than their more compact counterparts at fixed stellar, that is, the opposite distribution than the one revealed here (see Section 3). In view of these results, the "puffing-up" scenario can be discarded as a responsible mechanism of the growth in size of galaxies.

Regarding the "progenitor" bias, an arrival of recently quenched galaxies to the population of quiescent galaxies with larger effective radius would show that more extended quiescent galaxies exhibit younger stellar populations. Previous works such as [27, 17, 29, 8] reveal that star-forming galaxies are typically larger than quiescent ones, as well as there is an increasing number of quiescent galaxies at lower redshifts. Both results support that part of the growth in size of galaxies may be due to the "progenitor" bias. On the other hand, mergers acting on the MSP can also yield a growth in size of the relation (e. g. [21]). When the merger history of galaxies is independent of the size, as showed by [11], this would not alter the distribution of stellar populations in the MSP, but increasing the average size. Consequently, mergers and the "progenitor" bias acting in parallel would explain in part the evolution in size of quiescent galaxies.

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## References

[1] Blanton, M. R., Schlegel, D. J., Strauss, M. A., et al. 2005, AJ, 129, 2562

[2] Bruzual, G. & Charlot, S. 2003, MNRAS, 344, 1000

[3] Cappellari, M., Bacon, R., Bureau, M., et al. 2006, MNRAS, 366, 1126

[4] Cappellari, M., McDermid, R. M., Alatalo, K., et al. 2013a, MNRAS, 432, 1862

[5] Cappellari, M., Scott, N., Alatalo, K., et al. 2013b, MNRAS, 432, 1709

[6] Cleveland, W. & Devlin, S. 1979, Journal of the American Statistical Association, 83, 596

[7] Cowie, L. L., Songaila, A., Hu, E. M., & Cohen, J. G. 1996, AJ, 112, 839

[8] Díaz-García, L. A., Cenarro, A. J., López-Sanjuan, C., et al. 2018, ArXiv e-prints[arXiv:1802.06813]

[9] Díaz-García, L. A., Cenarro, A. J., López-Sanjuan, C., et al. 2017, ArXiv e-prints[arXiv:1711.10590]

[10] Díaz-García, L. A., Cenarro, A. J., López-Sanjuan, C., et al. 2015, A&A, 582, A14

[11] Díaz-García, L. A., Mármol-Queraltó, E., Trujillo, I., et al. 2013, MNRAS, 433, 60

[12] Fan, L., Lapi, A., De Zotti, G., & Danese, L. 2008, ApJ, 689, L101

[13] Fitzpatrick, E. L. 1999, PASP, 111, 63

[14] Franx, M., van Dokkum, P. G., Förster Schreiber, N. M., et al. 2008, ApJ, 688, 770

[15] Gallazzi, A., Charlot, S., Brinchmann, J., White, S. D. M., & Tremonti, C. A. 2005, MNRAS, 362, 41

[16] Griffith, R. L., Cooper, M. C., Newman, J. A., et al. 2012, ApJS, 200, 9

[17] Ilbert, O., McCracken, H. J., Le Fèvre, O., et al. 2013, A&A, 556, A55

[18] Kauffmann, G., Heckman, T. M., White, S. D. M., et al. 2003, MNRAS, 341, 54

[19] Moles, M., Benítez, N., Aguerri, J. A. L., et al. 2008, AJ, 136, 1325

[20] Molino, A., Benítez, N., Moles, M., et al. 2014, MNRAS, 441, 2891

[21] Naab, T., Johansson, P. H., & Ostriker, J. P. 2009, ApJ, 699, L178

[22] Oke, J. B. & Gunn, J. E. 1983, ApJ, 266, 713

[23] Peralta de Arriba, L., Balcells, M., Trujillo, I., et al. 2015, MNRAS, 453, 704

[24] Schawinski, K., Urry, C. M., Simmons, B. D., et al. 2014, MNRAS, 440, 889

[25] Thomas, D., Maraston, C., Bender, R., & Mendes de Oliveira, C. 2005, ApJ, 621, 673

[26] Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, AJ, 120, 165

[27] Trujillo, I., Conselice, C. J., Bundy, K., et al. 2007, MNRAS, 382, 109

[28] Valentinuzzi, T., Poggianti, B. M., Saglia, R. P., et al. 2010, ApJ, 721, L19

[29] van der Wel, A., Franx, M., van Dokkum, P. G., et al. 2014, ApJ, 788, 28

[30] van Dokkum, P. G. & Franx, M. 2001, ApJ, 553, 90

[31] van Dokkum, P. G., Franx, M., Kriek, M., et al. 2008, ApJ, 677, L5

[32] Vazdekis, A., Koleva, M., Ricciardelli, E., Röck, B., & Falcón-Barroso, J. 2016, MNRAS, 463, 3409