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The dominant role of mergers in the size evolution of massive galaxies since $z \sim 1$

Carlos López-Sanjuan[1,2], Olivier Le Fèvre[2], Olivier Ilbert[2], Lidia Tasca[2], and the COSMOS and zCOSMOS Collaborations

[1] Centro de Estudios de Física del Cosmos de Aragón, Plaza San Juan 1, planta 2, E-44001 Teruel, Spain
[2] Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, F-13388, Marseille, France

Abstract

We estimate the merger rate, both major (stellar mass ratio $\mu \equiv M_{\star,2}/M_{\star,1} \geq 1/4$) and minor ($1/10 \leq \mu < 1/4$), of massive ($M_{\star} \geq 10^{11}$ $M_{\odot}$) early-type galaxies (ETGs) in the COSMOS field by close pairs statistics. We identify as close pairs those systems with a projected separation $10h^{-1}$ kpc $\leq r_{\rm p} \leq 30h^{-1}$ kpc in the sky plane and a relative velocity $\Delta v \leq 500$ km s^{-1}. The merger rate of massive ETGs evolves as a power-law $(1+z)^n$, with the minor merger rate showing little evolution with redshift, $n_{\rm mm} \sim 0$, in contrast with the increase of major mergers, $n_{\rm MM} = 1.8$. Our results shows that massive ETGs have undergone 0.89 mergers (0.43 major and 0.46 minor) since $z \sim 1$, leading to a mass growth of $\sim 30\%$. We find that $\mu \geq 1/10$ mergers can explain $\sim 55\%$ of the observed size evolution of these galaxies since $z \sim 1$. Another $\sim 20\%$ is due to the progenitor bias (younger galaxies are more extended) and we estimate that very minor mergers ($\mu < 1/10$) could contribute with an extra $\sim 20\%$. The remaining $\sim 5\%$ should come from other processes (e.g., adiabatic expansion or observational effects). These results suggest that mergers are the main contributor to the size evolution of massive ETGs, accounting for $\sim 50\%-75\%$ of that evolution in the last 8 Gyr. Nearly half of this merging evolution is related with minor ($\mu < 1/4$) events.

1 Introduction

It is now well established that massive early-type galaxies (ETGs) have, on average, lower effective radius ($r_{\rm e}$) at high redshift than locally, being ~ 2 and ~ 4 times smaller at $z \sim 1$ and $z \sim 2$, respectively [26, 3, 4]. These high-redshift compact galaxies are sparse in the local universe [25], suggesting that they evolve since $z \sim 2$ to the present. It has been proposed that high redshift compact galaxies are the cores of present day ellipticals, and that they increased their size by adding stellar mass in the outskirts of the galaxy [29]. Several studies suggest that repeated minor mergers, those merger events between galaxies with a mass ratio lower than 1/4, could explain the observed size evolution [1, 20], while other processes, as adiabatic expansion due to AGNs or to the passive evolution of the stellar population, should have a mild role at $z \leq 1$ [21].

We present the merger history, both minor and major, of massive ($M_\star \geq 10^{11}$ $M_\odot$) ETGs since $z \sim 1$ by close pair statistics in the Cosmological Evolution Survey (COSMOS, [23]) field, and use it to infer the role of mergers in the mass assembly and in the size evolution of these systems in the last ~ 8 Gyr.

2 Data and methodology

We define two samples selected in stellar mass from the COSMOS catalogue with photometric redshifts derived from 30 broad and medium bands described in [7], version 1.8. We restrict ourselves to objects with $i^+ \leq 25$ and $K_s \leq 24$. We supplement the previous photometric catalogue with the spectroscopic information from the zCOSMOS survey [12]. This is a pure magnitude selected sample with $I_{AB} \leq 22.5$. The first sample comprises 2047 principal massive galaxies with $M_\star \geq 10^{11}$ $M_\odot$ in the zCOSMOS area, where spectroscopic information is available, at $0.1 \leq z < 1.1$. The second sample comprises the 23992 companion galaxies with $M_\star \geq 10^{10}$ $M_\odot$ in the full COSMOS area and in the same redshift range. The mass limit of the companion sample ensures completeness for red galaxies up to $z \sim 0.9$. We segregate morphologically our principal sample thanks to the morphological classification defined in [24]. Their method use as morphological indicator the distance of the galaxies in the multi-space $C-A-G$ (Concentration, Asymmetry and Gini coefficient) to the position in this space of a training sample of ∼500 eye-ball classified galaxies. These morphological indices were measured in the HST/ACS images of the COSMOS field, taken through the wide F814W filter [10]. The galaxies in the training sample were classified into ellipticals, lenticulars, spirals of all types (Sa, Sb, Sc, Sd), irregulars, point-like and undefined sources, and then these classes were grouped into early-type (E,S0), spirals (Sa, Sb, Sc, Sd) and irregular galaxies. It is this coarser classification that was considered in building the training set. According to the classification presented in [24] our principal sample comprises 1285 (63%) ETGs (E/S0) and 632 (31%) spiral galaxies. The remaining 6% sources are half irregulars (65 sources) and half massive galaxies without morphological classification (65 sources). We stress that the classification of the principal sample is exclusively morphological, without taking into account any additional colour information, i.e., some of our ETGs could be star-forming. We checked that ∼95% of our massive ETGs are also quiescent (they have a rest-frame, dust reddening corrected colour $NUV - r^+ \geq 3.5$, [8]). Regarding the companion sample, we do not attempt to segregate it morphologically because the morphological classification is not reliable for all companion galaxies

To compute the merger fraction we looked for those galaxies in the companion sample that fulfil the close pair criterion for each galaxy of the principal sample. We define close pairs as those galaxies with a projected separation $10h^{-1}$ kpc $\leq r_{\rm p} \leq 30h^{-1}$ kpc in the sky plane and a relative velocity $\Delta v \leq 500$ km s^{-1}. In addition, we impose a mass difference between the pair members. We denote the ratio between the mass of the principal galaxy, $M_{\star,1}$, and the companion galaxy, $M_{\star,2}$, as

$$\mu \equiv \frac{M_{\star,2}}{M_{\star,1}} \tag{1}$$

and looked for those systems with $M_{\star,2} \geq \mu M_{\star,1}$. We define as major companions those close pairs with $\mu \geq 1/4$, while minor companions those with $1/10 \leq \mu < 1/4$. We use both spectroscopic and photometric redshifts in the samples to measure the merger fraction thanks to the methodology developed in [13].

To translate the measured merger fractions into merger rates (i.e., the number of mergers per galaxy and Gyr) we use the prescriptions in [15]. The most important uncertainty is the merger time scale, that we estimate from [9] cosmological simulations (see also [6]).

3 The merger rate of massive ETGs since $z \sim 1$

The evolution of the merger rate with redshift up to $z \sim 1.5$ is well parametrised by a power-law function [11, 14, 6],

$$R_{\rm m}\,(z) = R_{\rm m,0}\,(1+z)^n. \tag{2}$$

We find $n_{\rm mm} \sim 0$ for minor mergers, with a median merger rate of $R_{\rm mm}^{\rm ETG} = 0.060 \pm 0.008$ Gyr^{-1} at $z \leq 1$. This confirms the tendency found by [15, 17, 18, 19]. The evolution of the major merger rate of massive ETGs is

$$R_{\rm MM}^{\rm ETG} = (0.030 \pm 0.006)\,(1+z)^{1.8\pm0.3}\ {\rm Gyr}^{-1}. \tag{3}$$

Our results imply that the minor merger rate is higher than the major merger one at $z \leq 0.5$.

Regarding late-type galaxies (LTGs, spirals + irregulars), we find that the merger fraction of massive LTGs, both major and minor, is lower by a factor of 2-3 than that of massive ETGs (see also [18] for a similar result).

4 The role of mergers in size evolution since $z \sim 1$

Integrating the merger rates in previous section over cosmic time, we obtain the number of mergers per massive ETG, $N_{\rm m}^{\rm ETG}$. We estimate $N_{\rm m}^{\rm ETG} = 0.89 \pm 0.14$, with $N_{\rm MM}^{\rm ETG} = 0.43 \pm 0.13$ and $N_{\rm mm}^{\rm ETG} = 0.46 \pm 0.06$ between $z = 1$ and $z = 0$. This is, the number of minor mergers per massive ETGs since $z = 1$ is similar to the number of major ones. We estimate the assembled mass due to mergers by weighting the number of mergers with the average major ($\overline{\mu}_{\rm MM} = 0.48$) and minor merger ($\overline{\mu}_{\rm mm} = 0.15$). We obtain that *mergers with $\mu \geq 1/10$ increase the stellar mass of massive ETGs by $\delta M_\star = 28 \pm 8\%$ since $z = 1$*. In addition, an extra mass growth of $\delta M_\star \sim 10\%$ due to very minor mergers ($\mu < 1/10$) since $z = 1$ is compatible with the observed mass assembly of red massive galaxies [29, 2].

The size evolution is usually parametrized as

$$\delta r_\mathrm{e}\,(z) \equiv \frac{r_\mathrm{e}\,(z)}{r_\mathrm{e}(0)} = (1+z)^{-\alpha}, \tag{4}$$

where r_e is the effective radius of the galaxy. In the following we assume as fiducial α value that one reported by [28] from the combination of several works, $\alpha = 1.2$ ($\delta r_\mathrm{e} = 0.43$ at $z = 1$).

Following the prescriptions in this section, we trace the mass growth of massive ETGs with redshift both for minor, $\delta M_{\star,\mathrm{mm}}(z)$, and major mergers, $\delta M_{\star,\mathrm{MM}}(z)$. Then, we translate these mass growths to a size growth,

$$\delta r_\mathrm{e}\,(z) = [1 + \delta M_{\star,\mathrm{MM}}(z)]^{-1.30} \times [1 + \delta M_{\star,\mathrm{mm}}(z)]^{-1.65}. \tag{5}$$

This model yields a size evolution due to mergers of $\delta r_\mathrm{e}(1) = 0.70$ ($\alpha = 0.52 \pm 0.12$). This implies that *observed major and minor mergers can explain* $\sim 55\%$ *of the size evolution in massive early-types since* $z \sim 1$. We take into account the progenitor bias (i.e., those ETGs that have reached the red sequence at later times are systematically more extended than those appeared at high redshift [27, 22]) by applying a linear function $1 - 0.2z$ to the previous size growth due to mergers. We obtain $\delta r_\mathrm{e}(1) = 0.56$ ($\alpha = 0.84 \pm 0.12$), thus explaining $\sim 75\%$ of the size evolution with our current observations. The remaining $\sim 25\%$ of the evolution should be explained by other physical process (e.g., very minor mergers with $\mu < 1/10$ or adiabatic expansion) or by systematic errors in the measurements (e.g., lower merger time scales or an overestimation of the size evolution).

As we shown previously, a mass growth of $\delta M_\star \sim 10\%$ due to very minor mergers ($\mu < 1/10$) since $z = 1$ is compatible with the observed mass assembly of massive galaxies. Applying the same prescription than for major and minor mergers, we obtain an extra size growth of $\sim 20\%$. That is, $\delta r_\mathrm{e}(1) = 0.58$ and $\alpha = 0.78 \pm 0.12$ when all μ values are taking into account. Hence, mergers since $z \sim 1$ may explain $\sim 75\%$ of the observed size evolution, while $\sim 95\%$, $\delta r_\mathrm{e}(1) = 0.47$ and $\alpha = 1.1$, when the progenitor bias is taking into account. In addition, this model is also compatible with the observed evolution in the velocity dispersion of massive ETGs, $\delta\sigma_\star = (1+z)^{0.4}$ [5], as well as with their structural evolution. Finally, we explore all the possible uncertainties in our assumptions and in all cases merging is still the principal process in the size evolution of massive ETGs since $z \sim 1$.

In summary, our best model, capable of explain mass, size and velocity dispersion evolution of massive ETGs since $z = 1$, suggests *that* $\sim 75\%$ *of the evolution in size is due to mergers,* $\sim 20\%$ *to the progenitor bias and* $\sim 5\%$ *to other processes (e.g, adiabatic expansion).* Nearly half of the evolution due to mergers is related with minor ($\mu < 1/4$) events. These results and an extended discussion can be found in [16].

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References

[1] Bezanson, R., van Dokkum, P. G., Tal, T., et al. 2009, ApJ, 697, 1290
[2] Brammer, G. B., Whitaker, K. E., van Dokkum, P. G., et al. 2011, ApJ, 739, 24
[3] Buitrago, F., Trujillo, I., Conselice, C. J., et al. 2008, ApJl, 687, L61
[4] Cassata, P., Giavalisco, M., Guo, Y., et al. 2011, ApJ, 743, 96
[5] Cenarro, A. J. & Trujillo, I. 2009, ApJl, 696, L43
[6] de Ravel, L., Le Fèvre, O., Tresse, L., et al. 2009, A&A, 498, 379
[7] Ilbert, O., Capak, P., Salvato, M., et al. 2009, ApJ, 690, 1236
[8] Ilbert, O., Salvato, M., Le Floc'h, E., et al. 2010, ApJ, 709, 644
[9] Kitzbichler, M. G. & White, S. D. M. 2008, MNRAS, 1300
[10] Koekemoer, A. M., Aussel, H., Calzetti, D., et al. 2007, ApJS, 172, 196
[11] Le Fèvre, O., Abraham, R., Lilly, S. J., et al. 2000, MNRAS, 311, 565
[12] Lilly, S. J., Le Fèvre, O., Renzini, A., et al. 2007, ApJs, 172, 70
[13] López-Sanjuan, C., Balcells, M., Pérez-González, P. G., et al. 2010, A&A, 518, A20
[14] López-Sanjuan, C., Balcells, M., Pérez-González, P. G., et al. 2009, A&A, 501, 505
[15] López-Sanjuan, C., Le Fèvre, O., de Ravel, L., et al. 2011, A&A, 530, A20
[16] López-Sanjuan, C., Le Fèvre, O., Ilbert, O., et al. 2012, A&A, 548, A7
[17] Lotz, J. M., Jonsson, P., Cox, T. J., et al. 2011, ApJ, 742, 103
[18] Mármol-Queraltó, E., Trujillo, I., Pérez-González, P. G., et al. 2012, MNRAS, 422, 2187
[19] Newman, A. B., Ellis, R. S., Bundy, K., & Treu, T. 2012, ApJ, 746, 162
[20] Oser, L., Naab, T., Ostriker, J. P., & Johansson, P. H. 2012, ApJ, 744, 63
[21] Ragone-Figueroa, C. & Granato, G. L. 2011, MNRAS, 414, 3690
[22] Saglia, R. P., Sánchez-Blázquez, P., Bender, R., et al. 2010, A&A, 524, A6
[23] Scoville, N., Aussel, H., Brusa, M., et al. 2007, ApJs, 172, 1
[24] Tasca, L. A. M., Kneib, J.-P., Iovino, A., et al. 2009, A&A, 503, 379
[25] Trujillo, I., Cenarro, A. J., de Lorenzo-Cáceres, A., et al. 2009, ApJ, 692, L118
[26] Trujillo, I., Conselice, C. J., Bundy, K., et al. 2007, MNRAS, 382, 109
[27] van der Wel, A., Bell, E. F., van den Bosch, et al. H.-W. 2009, ApJ, 698, 1232
[28] van der Wel, A., Holden, B. P., Zirm, A. W., et al. 2008, ApJ, 688, 48
[29] van Dokkum, P. G., Whitaker, K. E., Brammer, G., et al. 2010, ApJ, 709, 1018