Evolution of massive galaxies in the second half

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The intriguing life of massive galaxies
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The evolving structure of massive quiescent galaxies

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Abstract. The evolution of size and shape of massive quiescent galaxies over cosmic history has been challenging to explain within standard models of galaxy assembly. Several mechanisms have been proposed to explain the size growth of these systems, including major mergers, expansion, and late accretion via a series of minor mergers. The central mass density is shown to be an excellent tool for discriminating between different evolutionary scenarios. We present here the analysis performed on a spectroscopic sample of ~ 500 quiescent systems with stellar masses $M_* > 10^{10}$ $M_\odot$ spanning the redshift range $0.2 < z < 2.7$ for which we calculate stellar mass densities within central 1 kpc and show that this quantity evolves linearly with redshift. Our results do not change when only systems at constant number density are considered in order to account for the mass growth during mergers and to relate progenitors to their descendants. Discrepancy between our findings and other recent studies performed on an order of magnitude smaller samples emphasizes the need for larger homogeneous spectroscopic samples to be used in such analysis.

Keywords. galaxies: evolution, galaxies: fundamental parameters, galaxies: high-redshift, galaxies: stellar content, galaxies: structure

1. Introduction

The recent discovery of a population of compact massive quiescent galaxies ('Red Nuggets') at redshift $1 < z < 3$ (e.g., Szomoru *et al.* 2012 and references therein) has posed profound challenges to standard models of galaxy formation and evolution. Compared to present-day galaxies of similar (stellar) mass ($M_* \sim 10^{11}$ $M_\odot$), these high-z compacts are (depending on z) a factor of $\sim 2-5$ smaller (e.g., Damjanov *et al.* 2009) with half-light or effective radii $R_e \lesssim 1$ kpc. Furthermore, while their ellipticities resemble those of massive spheroids at $z \sim 0$, their Sérsic indices are better matched to the local disk-dominated population of massive galaxies, suggesting that 'red nuggets' may constitute a new class of objects (Chevance *et al.* 2012). Several mechanisms have been proposed to explain observed structural evolution of these systems, including major mergers, expansion, and satellite accretion. Low fraction of close pairs among quiescent galaxies observed at $0 < z < 2$ (e. g., Man *et al.* 2012) and the small number of near equal mass mergers produced in N-body simulations (e. g., Shankar *et al.* 2010) suggests that major mergers can only be partly responsible for the observed size growth and that additional secular processes, such as adiabatic expansion (Fan *et al.* 2010, Damjanov *et al.* 2009) and/or a series of minor mergers (Naab *et al.* 2009, Hopkins *et al.* 2010), may be needed to expand these compact systems.

Recent studies that have been tracing massive galaxies at constant number density over the redshift range $0 < z < 3$ in order to link progenitors and their descendants (van Dokkum *et al.* 2010, Patel *et al.* 2013) seem to confirm the predictions of a two-phase model of massive galaxy assembly (Oser *et al.* 2012). The two phases of this model involve (1) in situ star formation phase at $z \gtrsim 2$ in which star-formation is the dominant mechanism driving the structural evolution of massive galaxies and (2) the accretion phase at $z \lesssim 2$ when a series of minor mergers becomes the controlling factor in shaping these systems. However, the low inferred rate of mergers at $1 < z < 2$ (Newman *et al.* 2012) and the fine tuning of these stochastic processes needed to explain the tightness of local scaling relations such as the size-luminosity relation (Nair *et al.* 2011) suggest that a series of minor mergers may not be the only mechanisms driving the size growth of massive galaxies after their star formation ceases. We focus here on the change with time (redshift) of the stellar mass confined within the central 1 kpc region of a massive quiescent galaxy as a powerful tool for testing the minor mergers scenario.

2. Central mass density evolution

One of the parameters that can be effectively used to discriminate between different evolutionary scenarios is the central stellar mass density of massive quiescent galaxies, which is conveniently described by the mass density within the central kiloparsec, $\rho(R_e < 1$ kpc). If a massive system grows by accumulating low density material in its outskirts (through accretion of low surface brightness satellites), its central stellar density will not change. On the other hand, if these systems increase their size by blowing out the baryonic material from central regions (via AGN feedback or stellar mass loss), their central mass density will decrease sharply (Hopkins *et al.* 2010).

To test these predictions, we used a compilation of ~ 500 quiescent massive galaxies with confirmed spectroscopic redshifts in the range $0.2 < z < 2.7$ (described in detail in Damjanov *et al.* 2011) and a combination of their stellar masses (based on the spectral energy distribution fitting) and the parameters of their Sérsic profiles. We calculated central mass densities by assuming that the total stellar mass is following the light profile and that systems in our sample have spherical symmetry. The resulting values are in excellent agreement with the results of a previous analysis where a slightly different method was used for deprojecting galaxy light profile (MYSIC subsample, Bezanson *et al.* 2009). Upper panels of Figure 1 show the steady evolution in the central mass density as a function of redshift for our sample of galaxies with high resolution HST imaging providing spatial sampling of ~ 1 kpc at $z \sim 2$. Within our uncertainties, this growth of central stellar mass density with redshift can be parameterized rather simply as almost linear growth with redshift: $\rho \propto (1+z)^{0.96\pm0.29}$ †. The decrease in the central stellar mass density by a factor of ~ 3.5 since $z \sim 2.5$ may prove challenging to explain in a scenario in which the structural evolution is driven by a succession of minor mergers. Taking dynamical friction into account, the expected change in ρ is a factor of 1.5 over our redshift range (Naab *et al.* 2009), which seems insufficient to explain the rather dramatic changes in size and, consequently, central density observed in our sample.

The resulting steady evolution of the central mass density is based on the assumption that the mass of passive galaxies does not change in the redshift range we are probing. However, it has been shown that the number density of massive quiescent galaxies evolves with redshift (e.g., Brammer *et al.* 2011). In order to take into account the change of mass during mergers, we selected a subsample of quiescent galaxies that follow the change in

† The best fit is obtained by fitting the median values in the six redshift bins, i.e. giving each redshift range equal weight. The range of 1 σ errors is obtained by using the bootstrap resampling method. This fit is shown in red in the upper panels of Figure 1, with the corresponding uncertainty shown as a gray band.

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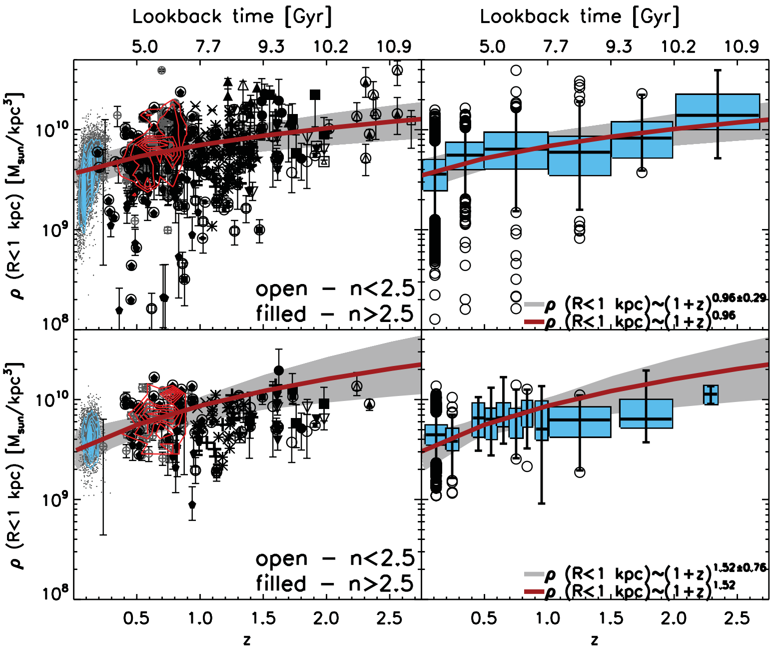

Figure 1. Central stellar mass density (within 1 kpc) of massive quiescent galaxies as a function of redshift. Upper panels show the complete sample from Damjanov *et al.* (2011), while the lower panels present the objects at constant number density (based on the analysis given in Patel *et al.* 2013). *Left panels:* Each symbol type corresponds to a different survey, while blue (red) contours denote the regions of constant density of $z \sim 0$ ($0.2 < z \lesssim 0.9$) galaxies in size-redshift parameter space. A legend mapping data points to individual surveys is provided in Damjanov *et al.* (2011). *Right panels:* The box-and-whisker diagram for $\rho(R_e < 1\,\mathrm{kpc})$ divided into redshifts bins. The top and bottom of the box show the 25th and 75th percentile of the distribution. The horizontal line bisecting the box is the median. The top and bottom of the error bars correspond to the 9th and 91st percentile. Circles are outliers.The red line and the grey shaded area in all four panels show the best fit to the median redshift points and the $\pm 1\sigma$ errors of the best relation, respectively. Note that in the lower panels fitted medians lie at $z < 1$. See text for details.

mass with redshift at constant number density by employing Eq. 2 from Patel *et al.* (2013) and selecting the bin width of $(\log M_*(n_c = 1.4 \times 10^{-4}\,\mathrm{Mpc}^{-3})/\mathrm{M}_\odot)^{+0.2}_{-0.2}$ to account for the uncertainties in mass estimates within our compilation. Furthermore, we select to fit the median values of central mass densities for galaxies in eight $\Delta z = 0.1$ redshift bins at $z < 1$ since at higher redshifts, unlike in our sample, the fraction of star-forming objects among massive galaxies at constant number density is not negligible (Patel *et al.* 2013, van Dokkum *et al.* 2010). The change in the central mass density of massive systems at $z < 1$ selected in this fashion can be presented by a power law that is even steeper than the one obtained using the complete sample ($\rho \propto (1+z)^{1.52 \pm 0.76}$, lower panels of Figure 1), confirming that at the constant number density central mass density of quiescent galaxies decreases ~ 2.8 times from $z = 1$ to $z = 0$, a factor that may be difficult to explain by invoking (only) the minor mergers scenario.

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3. Conclusions

Central mass density evolution is an excellent indicator for discriminating between different scenarios proposed to explain the structural evolution of massive quiescent galaxies. Using a compilation of ~ 500 passive systems from Damjanov *et al.* (2011) we find that the observed evolution of $\rho(R_e < 1\,\mathrm{kpc})$ is a linear function of redshift, showing an increase of at least a factor of 3.5 over the redshift range $0 < z < 2.5$. These results are not altered if, in order to trace the same galaxy population, we select only massive galaxies at the constant number density at redshifts $z < 1$, where a large fraction of systems selected in this way are passive. Our findings are in a good agreement with the central densities found at high redshift (e.g, Bezanson *et al.* 2009). However, recent results based on a small sample of 34 quiescent galaxies spanning the redshift range $0.9 < z_{\mathrm{spec}} < 2$ (Saracco *et al.* 2012) suggest that the central density of massive quiescent systems is independent of redshift. Similar conclusions are reached in a study of 23 massive ($M_* \sim 10^{11}\,\mathrm{M}_\odot$) galaxies drawn from the Sloan Digital Sky Survey, where the central mass densities based on De Vaucouler profiles are compared to the central densities at $z > 1$ (Tiret *et al.* 2011). This discrepancy highlights the need to perform a self-consistent analysis of the central mass density on a large homogeneous sample of massive galaxies covering a wide range of spectroscopically confirmed redshifts. Furthermore, current theoretical models do not explore in detail the effects of dynamical friction during minor mergers. For example, one of the factors that needs to be considered is the trajectory of accreted systems (Naab, priv. comm.). More detailed theoretical predictions on the possible decrease in ρ during minor mergers would allow us to fully explore the indicative potential of the observed evolution in the central stellar mass density of massive galaxies.

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