

The entertaining life of massive galaxies

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Abstract

Massive galaxies experienced an enormous structural evolution in the last ten billion years. The most viable explanation is that massive galaxies have undergone a significant number of minor mergers which have deposited most of their material in the outer regions of the massive galaxies. This scenario is still far from being observationally proved since the number of satellite galaxies surrounding the massive objects appears insufficient at all redshifts. The presence also of a population of nearby massive compact galaxies with mixture stellar properties is another piece of the puzzle that still does not nicely fit within a comprehensive scheme. I will review these and other intriguing properties of the massive galaxies in this contribution.

1 Introduction

The discovery that massive galaxies were much more compact in the past [4] revolutionized our traditional picture of how these objects have developed with cosmic time. A monolithic-like scenario, where the bulk of the stellar population as well as the structure of these galaxies are formed in a single dissipative event followed by a passive evolution, is no longer supported by the observations. There has been an enormous debate about the reality of this huge structural evolution. Most of the critics against this discovery focused on the reliability of the size estimations and the accuracy of the stellar mass determinations of these $z > 1$ objects. Today, ultra-deep observations of these galaxies as well as the first dynamical estimations of their masses have inclined the vast majority of the community to accept as real the size evolution of the massive galaxies.

The stellar mass-size relation of massive galaxies seems to be at place (although with a different “zeropoint” position than in the present-day universe) since at least $z \sim 3$ [2] and the scatter along this relation has not significantly changed since then. However, the number of galaxies that populate these relations have grown with time as the number density of

massive galaxies have continuously increasing since that epoch (e.g. [13]). That means that the new massive galaxies that are incorporated in the stellar mass-size relation are located in such sense that do not alter dramatically this relation. In order to maintain the scatter of this relation relatively constant with time, the newcomers should evolve later in size similarly as the older galaxies that already populated the stellar mass-size relation. On what follows I will summarize the different scenarios that have been proposed to explain the significant structural change of the massive galaxies as well as the observational evidence favoring the different mechanisms. We adopt a cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 What is the physical mechanism behind the size evolution?

If we accept the reality of the structural evolution of the massive galaxies, the next question to solve is how these objects have reached their present configuration. We can summarize the different proposed scenarios in three categories. It is worth stressing that the following mechanisms can take all place simultaneously and certainly they should all have a role in the evolution of the massive galaxies. Consequently, when we use the word rejected or supported by the observations we will be referring to the role of such mechanism as the main driver of the size evolution.

- Major mergers. This was the earliest theoretical suggestion (e.g. [12]) and it was also the first hypothesis rejected by the observations (e.g. [10]). Simply, there is not enough number of major mergers that can account by the huge size evolution observed (a factor of 4 since $z \sim 2$) plus the relatively modest evolution in stellar mass (a factor of 2 since $z \sim 2$). The predicted size evolution as a function of the increase in mass goes as $\Delta r_e \propto \Delta M$ in major mergers which is insufficient to produce the observed size evolution.
- Puffing up. [5] proposed a scenario where the size evolution is connected to the massive expulsion of gas by the effect of an AGN. According to this mechanism, the removal of gas changes the gravitational potential of the galaxy making the object to puff up to its new (larger) configuration. This evolution is fast ($< 1 \text{ Gyr}$) and the model predicts a dichotomy of massive objects at all redshifts: young ones ($< 1 \text{ Gyr}$) with small sizes and high velocity dispersions ($\sim 400 \text{ km s}^{-1}$) and old ones ($> 1 \text{ Gyr}$) with present-day sizes and moderate velocity dispersion ($\sim 200 \text{ km s}^{-1}$). This is not observed in nature: massive compact galaxies at high- z are “old” at those epochs and there is not an age segregation in the stellar mass-size relation since, at least, $z = 1$ for objects with spheroid-like morphologies [16].
- Minor mergers. This model [8] proposes that most of the size evolution of the massive galaxies has taken place due to the continuous accretion of minor bodies. The stars of these merged satellites are mainly located in the periphery of the main body, making this mechanism an excellent vehicle for the size evolution. The predicted increase in size as a function of the increase in mass goes as $\Delta r_e \propto \Delta M^2$. This evolutionary path

predicts the following observables: a continuous increase in size of the global population of massive galaxies, a size growth not related with the age of the main galaxy, a mild velocity dispersion evolution of the massive galaxy with time [7].

3 Observational evidence favoring the minor merging scenario

There are many observational evidences favoring the minor merging hypothesis as the main channel of massive galaxies growth:

- The size evolution of the spheroid-like massive galaxies is not related with the age of their stellar population. Since $z \sim 1$, spheroid-like massive galaxies, at a given fixed stellar mass, still need to grow by a factor ~ 2 to reach their present configuration. This significant size evolution is observed, at all redshifts, to be independent of the stellar age of the massive galaxies [16]. An external accretion of stars (where the infalling satellites do not have previous knowledge about the age of the central galaxy) fits well within this scheme.
- There is a progressive and steady formation of the outer galaxy envelopes. The central stellar mass density of the massive galaxies at high- z do not dramatically differ from the central stellar mass density of the nearby massive galaxies [1]. The majority of the evolution of the stellar mass density profile of the massive galaxies has taken place at their extended wings. Massive galaxies have steadily increased their number of stars at farther distances [18]. This progressive build is very suggestive of a continuous accretion of new stars with cosmic time in the periphery of these galaxies.
- At a fixed stellar mass, the velocity dispersion of the massive galaxies has mildly declined since $z \sim 2$. [3] compiled from the literature the velocity dispersions of many massive ($M_\star \sim 10^{11} M_\odot$) galaxies since $z \sim 2$. This data was complemented with the measurement of the velocity dispersions of massive galaxies in the SDSS (for having a local reference) and with the first estimation of the velocity dispersion of massive galaxies at $z > 1.5$. All this data together (Fig. 1) clearly indicated that the evolution of the velocity dispersion of the massive galaxies, at a fixed stellar mass, has only moderately declined with cosmic time. This mild evolution of the velocity dispersion is in good agreement with the idea that most of the structural evolution of the massive galaxies has taken place in their outer regions. This again fits well with a scenario of accretion of new stars that is smooth and mostly locate stars in the periphery of these objects.

4 Some puzzling observations

4.1 Nearby massive compact galaxies: relics of the early universe?

After the discovery that massive galaxies at high- z were compact, there was an observational effort to try finding massive ($M_\star \sim 10^{11} M_\odot$) and compact ($r_e \sim 1$ kpc) objects in the nearby

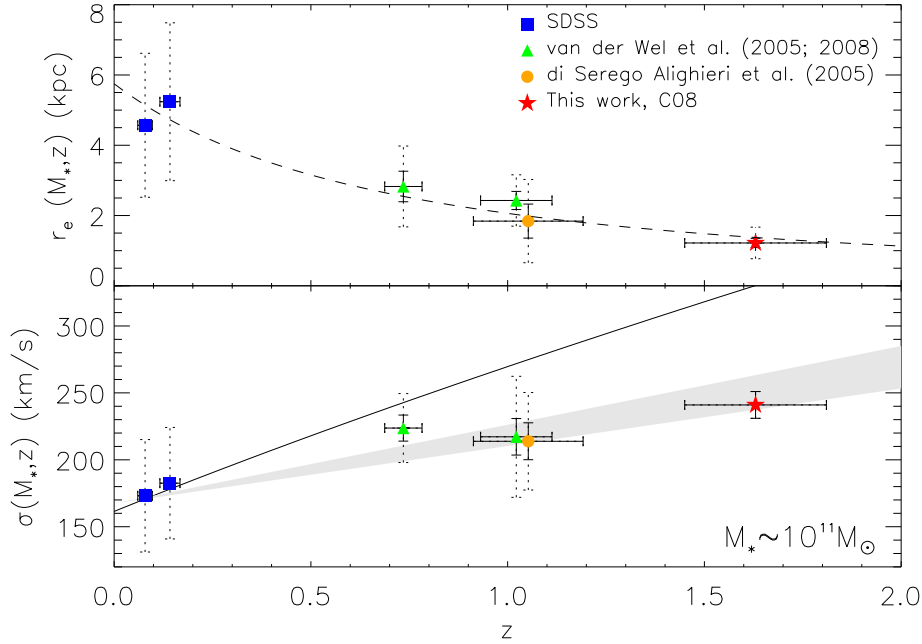


Figure 1: *Top panel:* size evolution of $M_* \sim 10^{11} M_\odot$ spheroid-like galaxies as a function of redshift. Dashed error bars, if available, show the dispersion of the sample, whereas the solid error bars indicate the uncertainty of the median value. The dashed line represents the observed evolution of sizes $r_e(z) \propto (1+z)^{-1.48}$ found in [2] for galaxies of similar stellar mass. *Bottom panel:* velocity dispersion evolution of the spheroid-like galaxies as a function of redshift, with symbols as given above. The solid line represents the prediction from the ‘puffing-up’ scenario [5], whereas the gray area illustrates the velocity dispersion evolution within the merger scenario of [7]. Figure from [3].

Universe (see Fig. 2). According to the theoretical predictions [7] around 10% of the massive compact galaxies since $z \sim 2$ should have survived intact due to the stochastic nature of the merging channel. Taking into account that the number density of massive galaxies at $z \sim 2$ was a factor of 10 smaller than today, around 1% of the present-day massive galaxy population should be composed by relics (i.e. they should appear today as old compact massive galaxies) from that early epoch of the Universe. Observationally, it is found that less than 0.03% of the current massive galaxies are as compact as the ones found at $z \sim 2$ [15]. Moreover, these galaxies are not only very scarce but young (~ 2 Gyr [6]). Consequently, it seems that massive compact relics of the early universe are non-existent today.

4.2 Satellites surrounding massive galaxies: are they enough?

If the minor merging scenario is the main channel of massive galaxy evolution one would expect that a direct test of this hypothesis could be done by counting the number of satellites surrounding these galaxies and exploring their evolution with redshift. Estimating the number

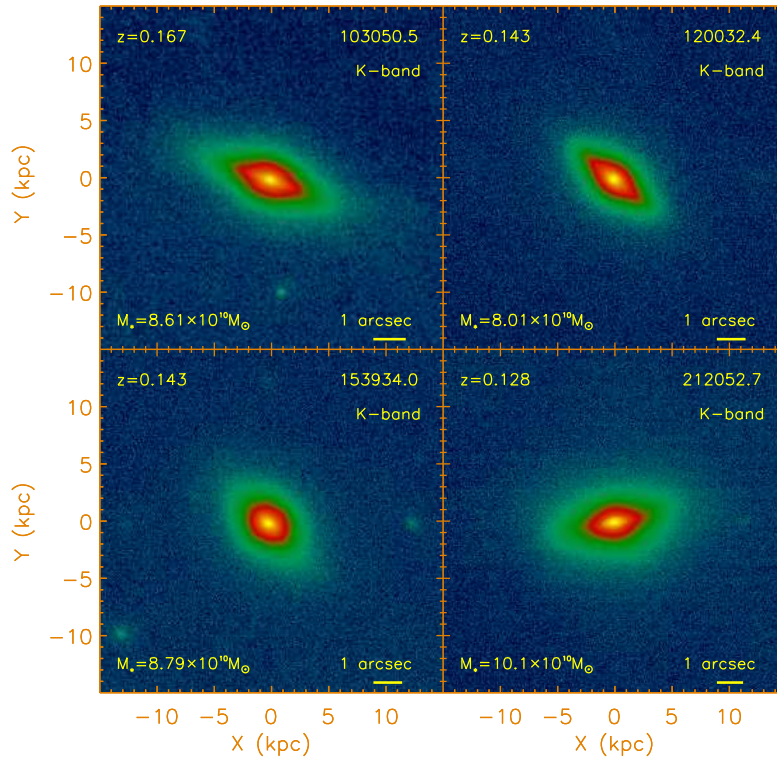


Figure 2: *K*-band Gemini high-resolution imaging of four nearby massive compact galaxies. Figure taken from [17].

of satellites around massive galaxies have been done by many authors (e.g. [11]). As expected, the fraction of massive galaxies with nearby satellites depends on two parameters: the search radius to find the satellite and the mass ratio between the massive galaxy and the satellite. To give a number, [9] found that around 13% of the local galaxies with $M_* > 10^{11} M_\odot$ have a satellite with a mass ratio 1:10 or smaller within a projected radius of 100 kpc to the host galaxy. This fraction is constant with redshift [11] (at least up to $z \sim 2$). If the explored mass ratio is decreased down to 1:100, the fraction of massive galaxies with a nearby satellite increases up to $\sim 30\%$.

The above fractions can be directly compared with the predictions from Λ CDM cosmological simulations. In particular, these numbers can be confronted with the semianalytical predictions based on those simulations. This simple exercise was conducted by [14] using three different semianalytical models run over the Millenium simulations. Interestingly, the theoretical models predicted correctly the constancy on the fraction of massive galaxies with nearby satellites across the cosmic time. However, all models overpredicted by a factor of ~ 2 the value of this fraction (see Fig. 3). In other words, in the simulations there is an excess of satellites that could later merge with the massive host galaxy. Whether this excess of satellites in the simulations is also overpredicting the size evolution that is obtained in the simulations is a matter of analysis at the moment of writing this review.

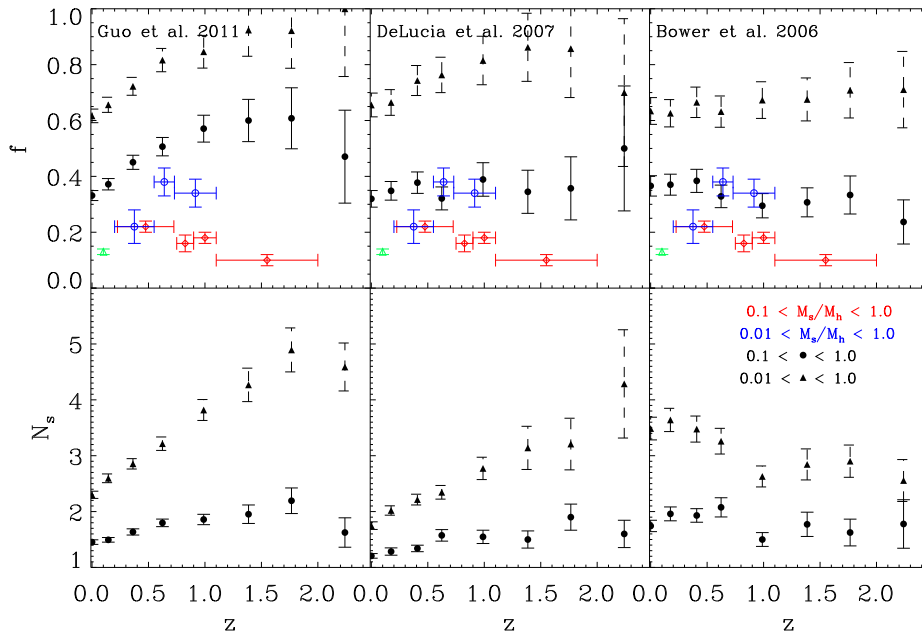


Figure 3: For each model, and from top to bottom, are shown the fraction of massive galaxies that have at least one satellite within a sphere of 100 kpc radius and a projected distance smaller than 100 kpc, and the average number of satellites per massive galaxy when they have one of such objects around. The full circles (triangle) stand for the satellites with stellar mass ratios of $0.1 < M_s/M_h < 1$ ($0.01 < M_s/M_h < 1$). The error bars represent one standard deviation. The observational data from [11] are overplotted as red (blue) open circles (diamonds) for mass ratios of $0.1 < M_s/M_h < 1$ ($0.01 < M_s/M_h < 1$). The local observational reference ($z = 0.1$) from [9] for the fraction of massive galaxies with satellites with mass ratios of $0.1 < M_s/M_h < 1$ is plotted as a green open triangle, no data are available for smaller satellites. Figure taken from [14].

5 Summary

The discovery that massive galaxies were much more compact in the past has opened a fruitful era of research trying to put this finding within a galaxy formation context. Both theory and observations seem to converge to a scenario where the main channel of size and mass evolution of the massive galaxies is through a continuous accretion of minor bodies as cosmic time progresses. This active life of the massive galaxies follows after a rapid (dissipative) collapse which would have formed the bulk of the present-day body of the most massive objects.

Although the general picture of massive galaxy evolution seems to be at place, still a few observational results challenge this scenario: the nearly absence of old compact massive relics in the present-day universe and the apparent few satellites that surround the massive galaxies at every redshift. Further investigations will clarify whether this discrepancy is just

a matter of refining the models predictions or whether these observations will force us to change our main view of massive galaxy evolution.

Acknowledgments

The results presented here are due to the effort of many people over the last 5 years. I would like to particularly thank the large number of collaborators which I have had the pleasure to work with along all these years. This work has been supported by the Programa Nacional de Astronomía y Astrofísica of the Spanish Ministry of Science and Innovation under grant AYA2010-21322-C03-02.

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