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Mild Velocity Dispersion Evolution of massive galaxies since $z \sim 2$

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Abstract. Making use of public spectra from Cimatti *et al.* (2008), we measure for the first time the velocity dispersion of spheroid-like massive ($M_\star \sim 10^{11} M_\odot$) galaxies at $z \sim 1.6$. By comparing with galaxies of similar stellar mass at lower redshifts, we find evidence for a mild evolution in velocity dispersion, decreasing from $\sim$240 km s^{-1} at $z \sim 1.6$ down to $\sim$ 180 km s^{-1} at $z \sim 0$. Such mild evolution contrasts with the strong change in size (a factor of ~ 4) found for these type of objects in the same cosmic time, and it is consistent with a progressive larger role, at lower redshift, of the dark matter halo in setting the velocity dispersion of these galaxies. We discuss the implications of our results within the context of different scenarios proposed for the evolution of these massive objects.

Keywords. galaxies: evolution — galaxies: formation — galaxies: structure — galaxies: kinematics and dynamics

1. Introduction

Recent observations show that the most massive ($M_\star \gtrsim 10^{11} M_\odot$) spheroid-like galaxies at $z > 1.5$, irrespective of their star formation activity (Pérez-González *et al.* 2008), were much smaller (a factor of $\sim$4) than their local counterparts (e.g. Daddi *et al.* 2005; Trujillo *et al.* 2007; Cimatti *et al.* 2008, hereafter C08; Buitrago *et al.* 2008, hereafter B08). The near absence of such systems ($r_e \lesssim 1.5$ kpc; $M_\star \gtrsim 10^{11} M_\odot$) in the nearby Universe (<0.03%; Trujillo *et al.* 2009) implies a strong evolution in the structural properties of these massive galaxies as cosmic time evolves.

Different scenarios have been proposed to explain the dramatic size evolution of these galaxies since $z \sim 3$ (Khochfar & Silk 2006; Naab *et al.* 2007; Fan *et al.* 2008; Hopkins *et al.* 2009). The main difference among them is the role of mergers to increase the size of galaxies. Fan *et al.* (2008) support an evolutionary scheme where galaxies grow by the effect of quasar feedback, which removes huge amounts of cold gas from the central regions hence quenching the star formation. The removal of gas makes galaxies to puff up in an scenario similar to the one proposed to explain the growth of globular clusters. In the merging scenario, however, merger remnants get larger sizes than those of their progenitors by transforming the kinetic energy of the colliding systems into potential energy. Whereas both scenarios predict a strong size evolution for the most massive galaxies, they disagree on the expected evolution of the velocity dispersion of the massive galaxies at a given stellar mass. The merging scenario basically predicts no evolution (at most a 30% since $z \sim 3$; Hopkins *et al.* 2009), whereas the puffing up scenario predicts central velocity dispersions to be $\sim$2 times larger than in present-day massive galaxies.

Constraining the evolution of the velocity dispersion of spheroid-like massive galaxies over the last 10 Gyr turns therefore crucial to test the above models of galaxy evolution, as well as to determine the importance of dark matter halos in setting the velocity dispersion of galaxies as cosmic time evolves. For these reasons, in this work we measure for the first time the velocity dispersion of such massive galaxies at $z \sim 1.6$, and compare it with a compilation of velocity dispersions for similar galaxies at $z \lesssim 1.2$. In what follows, we adopt a cosmology of $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

2. The data

2.1. *Velocity dispersions at* $z \sim 1.6$

To determine the typical velocity dispersion of spheroid-like massive ($M_\star \sim 10^{11} M_\odot$) galaxies at $z \sim 1.6$, we have used the publicly available stacked spectrum of galaxies at $1.4 < z < 2.0$ ($\langle z \rangle = 1.63 \pm 0.18$ r.m.s. standard deviation) presented in C08 as part of the GMASS project. The spectrum consists of an averaged spectrum of 13 massive galaxies with a total integration time of 480 h. Only 2 of them are classified as disks, whereas the remaining 11 galaxies have either a pure elliptical morphology or show a very concentrated and regular shape (see C08). The stacked spectrum is consequently representative of massive spheroid-like objects at that redshift. Individual galaxy spectra were taken at VLT with FORS2, using the grism G300I and a 1 arcsec width slit, providing a spectral resolution of FWHM ∼13 Å in the range $\lambda\lambda 6000 - 10000$ Å ($\lambda/\Delta\lambda \sim 600$). Before stacking, each individual galaxy spectrum was previously de-redshifted and assigned to have the same weight in the $\lambda\lambda 2600 - 3100$ Å rest-frame range. The resulting rest-frame stacked spectrum was set to 1 Å/pix over the range $\lambda\lambda 2300 - 3886$ Å. Aimed at computing the velocity dispersion of the above stacked spectrum, it is required the use of reference template spectra of well known spectral resolution. In Cenarro & Trujillo (2009), we provide with a full description of these data-sets, as they are basic input ingredients of the analysis carried out in this work.

2.2. *Velocity dispersions up to* $z \sim 1.2$

We have compiled from previous work velocity dispersions estimates of spheroid-like massive galaxies at $z < 1.2$. This includes data from van der Wel *et al.* (2005) for galaxies in the ranges $0.6 < z < 0.8$ and $0.9 < z < 1.2$, and from di Serego Alighieri *et al.* (2005) for galaxies at $0.9 < z < 1.3$. These authors also provide stellar masses and effective radii for their galaxies. The vast majority of these objects present a prominent spheroidal component an are identified as either E or S0. When necessary, stellar masses have been transformed assuming a Chabrier IMF. To allow a meaningful comparison along the entire redshift interval explored in this work, only galaxies with stellar masses in the range $0.5 < M_\star < 2 \times 10^{11} M_\odot$ have been considered.

To have a local reference, we have retrieved velocity dispersions, effective radii and stellar masses (Chabrier IMF) from the SDSS NYU Value-Added Galaxy Catalog (DR6; Blanton *et al.* 2005) for those galaxies within the above stellar mass range having Sérsic indices (in the r-band) $n > 2.5$. Selecting objects with $n > 2.5$ assures that the majority of the sources have a Hubble morphological Type $T < 0$. We have estimated the average velocity dispersion of the above galaxies in two redshift bins: $0 < z < 0.1$ and $0.1 < z < 0.2$. We have not tried higher redshifts to assure individual signal-to-noise ratios (S/N) larger than 10.

3. Discussion

Fig. 1 shows our results. The fact that the velocity dispersion of $M_\star \sim 10^{11} M_\odot$ spheroid-like galaxies at $z \sim 1.6$ is $\sim 240\,\mathrm{km\,s^{-1}}$ has important consequences to understand their evolution:

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• It confirms that high-z spheroid-like massive galaxies are truly massive objects. The unexpected strong size evolution of these objects has cast some doubts about the reliability of their stellar mass estimates, which relies on the assumption that the IMF is the same at all redshifts. In fact, an appropriate change of the IMF with redshift would mitigate the problem of the strong size evolution. However, the derived velocity dispersion at $z \sim 1.6$ is similar to that of present-day galaxies with $M_\star > 10^{11} M_\odot$, consequently constraining any potential change of the IMF with redshift.

• It alleviates the problem of understanding how massive —and compact— galaxies at high-z can evolve through merging since that epoch. An extraordinarily high velocity dispersion at high-z (e.g. $\sim 500\,\mathrm{km\,s^{-1}}$) would have implied that the gravitational potential depth of the system would be so intense that it would not easily evolve in size.

To put in context the above result, Figure 1 shows the sizes (top panel) and velocity dispersions (bottom panel) for the C08 galaxies and the compilation of spheroid-like galaxies of similar mass described in Section 2.1. These galaxies follow nicely the observed strong size evolution found in other independent larger samples where completeness effects are accounted (Trujillo et al. 2007; B08; dashed line), hence probing that the sizes of the objects explored in this paper are typical of average spheroidal-like massive galaxies at those redshifts. It is also clear that, although massive spheroid-like galaxies have experienced a strong size evolution (a factor of ~ 4 since $z \sim 1.5$; Trujillo *et al.* 2007), the velocity dispersion has evolved mildly by a factor of ~ 1.3 in the same redshift interval. This result is crucial to constrain the different scenarios proposed so far to explain the dramatic size evolution since $z \sim 2$, as they disagree in the amount of evolution expected in their velocity dispersions.

In the puffing up scenario of Fan *et al.* (2008), velocity dispersions change as $\sigma_\star \propto r_\mathrm{e}^{-1/2}$. Using the observed size evolution of B08, $r_\mathrm{e}(z) \propto (1+z)^{-1.48}$, the solid line in Fig. 1 illustrates the expected $\sigma_\star$ evolution under this scenario. It increases with redshift in a way that galaxies are expected to double their $\sigma_\star$ at $z \sim 1.5$. The observed velocity dispersions are compatible —within the error bars— with this scenario up to $z \sim 0.7$. However, at $z > 1$ the discrepancy between theory and data is apparent.

In the merging scenario of Hopkins *et al.* (2009), at a fixed stellar mass, $\sigma_\star$ evolves with redshift as

$$\frac{\sigma_\star(z)}{\sigma_\star(0)} \propto \frac{1}{\sqrt{1+\gamma}}\sqrt{\gamma + \frac{r_\mathrm{e}(0)}{r_\mathrm{e}(z)}}, \tag{3.1}$$

where $\gamma \equiv (M_\mathrm{halo}/R_\mathrm{halo})/(M_\star/r_\mathrm{e})$ is the dark matter contribution to the central potential relative to that of the baryonic matter at $z \sim 0$, and R_halo is the effective radius of the halo. Again, we have used the B08 size evolution as an input into the merging model prediction. The grey area in Fig. 1 encloses the expected $\sigma_\star$ evolution when γ varies between 1 and 2. The agreement between the merging scheme and the observed evolution looks reasonably good at all redshifts.

Following Hopkins *et al.* (2009), to explain why $\sigma_\star$ has only changed weakly since $z \sim 2$ it is necessary to consider that the observed velocity dispersion is driven by two components: the baryonic matter and the dark matter halo. Both components contribute linearly to the central gravitational potential of the galaxy, hence $\sigma_\star \propto (M_\star/r_\mathrm{e} + M_\mathrm{halo}/R_\mathrm{halo})$. Assuming that R_halo evolves weakly with time (most simulations show that halos build inside-out, so the central potential is set first and just the outer halo grows with time), the dark matter effect on the central potential of the galaxy (i.e. on $\sigma_\star$) basically remains unchanged at a fixed $M_\star$. However, the influence of the baryonic matter on the gravitational potential has changed strikingly since $z \sim 1.5$, at present-day being ~ 4 times smaller due to the expansion of the object. The relative

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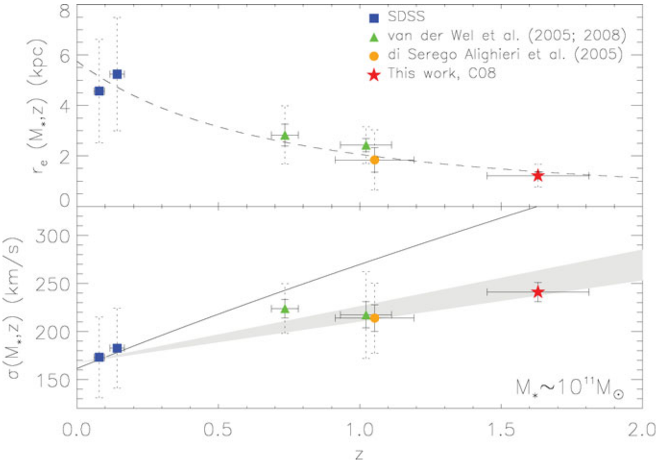

Figure 1. *Top Panel:* Size evolution of $M_\star \sim 10^{11} M_\odot$ spheroid-like galaxies as a function of redshift. Different symbols show the median values of the effective radii for the different galaxy sets considered in this work (see Section 2), as indicated in the labels. Dashed error bars, 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 B08 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. Assuming the B08 size evolution, the solid line represents the prediction from the "puffing up" scenario (Fan *et al.* 2008), whereas the grey area illustrates the velocity dispersion evolution within the merger scenario of Hopkins *et al.* (2009) for $1 < \gamma < 2$. See text for details.

influence of the dark matter on setting the inner potential increases with the decreasing effect of the baryonic matter. In fact, the data look in agreement with an almost symmetric influence of dark and baryonic matter (i.e. $\gamma \sim 1$) in setting the central gravitational potential of present-day objects.

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