The Dramatic Size Evolution of ETGs

and QSOs Feedback

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Introduction

Most of the massive (stellar mass $M_* > 3*10^{10}$ solar mass), passively evolving, galaxies at $z > 1$ observed with high enough angular resolution exhibit characteristic sizes of their stellar distributions much more compact than local early type galaxies (ETGs) of analogous stellar mass (Ferguson et al. 2004; Trujillo et al. 2004, 2007; Longhetti et al. 2007; Toft et al. 2007;Zirm et al. 2007; van der Wel et al. 2008; van Dokkum et al. 2008; Cimatti et al. 2008;Buitrago et al. 2008; Damjanov et al. 2009).A strong size evolution, by a factor ~3 or more, is indicated. We proposed that the expansion is driven by the expulsion of a substantial fraction of the initial baryons,still in gaseous form, by QSOs activity.We also discuss the other popular mechanism of increasing size by minor mergers.Observations of the mass functions of massive ETGs at high redshifts and studies of high redshift Brightest Cluster Galaxies constrain the mass increase to less than 50% since z<1.5,thus severely constraining dry minor merger as responsible for most of the size evolution.

Two main physical mechanisms for size evolution

1, Gas expulsion

If the ejection occurs on a timescale shorter than the dynamical timescale of the system $\tau_{ej} < \tau_{dyn}$ (e.g. quasar feedback), immediately after the ejection the size and velocity dispersion are unchanged but the total energy is larger because the mass has decreased. The system then expands and evolves towards a new equilibrium configuration. In the case of homologous expansion the final size R_f is related to the initial one R_i by (Biermann & Shapiro 1979; Hills 1980):

$$R_f/R_i = 1 - M_{ej}/M_f \quad (1)$$

where M_{ej} is the ejected mass and M_f is the final mass.

When the mass loss occurs on a timescale longer than the dynamical time (e.g. SN feedback) the system expands through the adiabatic invariants of the stellar orbits and one gets

$$R_f/R_i = 1 + M_{ej}/M_f \quad (2)$$

2, Minor merger

In the case of minor mergers on parabolic orbits the initial potential energy of the accreting mass is neglected in the computation. Following Naab et al. (2009) we assume that random motions are dominant in high-z ETG precursors and set $\eta = M_a/M_i$ and $\varepsilon = \sigma_a^2 / \sigma_i^2$, the i and a indices referring to initial and accreted material. The mass after merging is therefore $M_f = M_i\,(1 + \eta\,)$. If r is proportional to M_*^{α}, the virial theorem gives $\varepsilon = \eta^{1-\alpha}$. Local ETGs have $\alpha \approx 0.56$ (Shen et al. 2003) or even larger in the case of BCGs (Hyde & Bernardi 2009); in addition, a value $\alpha \approx 0.5$ is implied by the Faber-Jackson (1976) relationship. From the virial theorem and the energy conservation equation it is easily found that the fractional variations of the gravitational radius and of the velocity dispersion between the configurations before (i) and after (f) merging are:

$$R_{g,f} / R_{g,i} = (1 + \eta)^2 / (1 + \eta^{2-\alpha}) \quad (3)$$

Boylan-Kolchin et al. (2008) showed that minor mergers can be effective only if $\eta \geq 0.1$,lower mass ratios requiring too long timescales. If $\alpha = 0.5$ a sequence of mergers with $\eta = 0.05$, 0.1, and 0.2, leading to a size increase of a factor 3, increases also the mass by factors of 1.86, 1.93, and 2.05,

The limited mass evolution of ETGs

Spectral properties of local ETGs with stellar masses $M_* > 3*10^{10}$ solar mass indicate that their light-weighted age exceeds 8 – 9 Gyr, independently of the environment (see Renzini 2006 for a review and Gallazzi et al. 2006 for an extensive statistical study). Since light-weighted ages are lower limits to mass-weighted ages (e.g., Valentinuzzi et al. 2009), it is generally agreed that most of the stars of massive ETGs formed at $z_{form} \geq 1.5$–2. Moreover, all massive galaxies that formed and gathered the bulk of their stars at $z \leq 1$ are presently ETGs or massive bulges of Sa galaxies, since there are no late-type, disc-dominated galaxies endowed with so large masses of old stellar populations.

Figure 1 shows that an evolution in mass limited to less than 50% since $z \approx 1$-1.2 for ETGs with $M_* > 10^{11}$ solar mass.This is indeed consistent with the results of numerical simulations(Boylan-Kolchin et al. 2008,Stewart et al. 2008) .Ant it tightly constrains the size increase obtainable via minor dry mergers ($R_f/R_i \leq 1.6$).

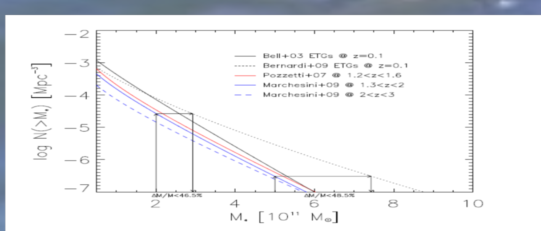


Fig. 1.— Cumulative stellar mass function. The different lines illustrate Schechter fits to the average stellar mass function at different redshifts as estimated by Bell et al. (2003),Bernardi et al. (2009), Pozzetti et al. (2007), and Marchesini et al. (2009). All estimates have been scaled to Chabrier's (2003) IMF.

Expected sizes of high-z galaxies and size evolution

If the high-z,massive galaxies formed most of their stars in a rapid,dissipative collapse of baryons inside a host dark matter halo,the effective radius R_e can be expressed in terms of the halo radius R_H and mass M_H (Fan et al. 2008,2010).

$$R_e \simeq \frac{S_s(n)}{f_\sigma^2}\frac{(M_* + M_{gas})}{M_H} R_H \simeq 1.2\frac{S_s(n)}{0.34}\frac{25}{m}\left(\frac{1.3}{f_\sigma}\right)^2\left(\frac{M_H}{10^{12}}\right)^{1/3}\left(\frac{4}{1+z_{form}}\right) kpc \quad (4)$$

where $S_s(n)$ is the coefficient converting the gravitational radius into the effective radius,in particular, $S_s(4) \approx 0.34$ (Prugniel & Simien 1997). m is the halo mass to stellar mass ratio ($m=M_H/M_*$). f_σ relates the DM velocity dispersion to the stellar velocity dispersion ($\sigma_* = f_\sigma \sigma_{DM}$). z_{form} is the redshift when the baryon collapse begins.
The equation shows that the baryon collapse naturally leads to ***kpc or sub-kpc*** effective radius(See Fig 2).It also shows the effective radius scales like $R_e \propto (1+z_{form})^{-0.75}$!

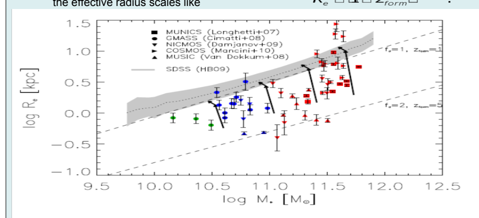
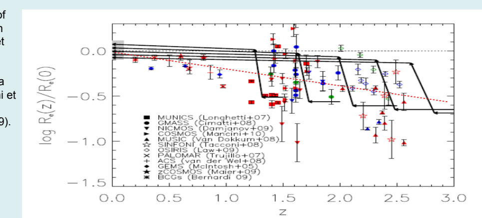


Fig. 2.— Correlation between effective radius and stellar mass. The observations of passively evolving galaxies with spectroscopic redshifts $z \geq 1$ by Longhetti et al. (2007), Cimatti et al. (2008), Damjanov et al. (2009), and van Dokkum et al. (2008) are compared with the local correlation (Hyde & Bernardi 2009; the dotted line illustrates the average and the shaded area represents the variance). The color of the data points refers to the stellar mass of the galaxy: red is for $M \geq 10^{11}M_\odot$, blue for $3 \times 10^{10}M_\odot \leq M_* \leq 10^{11}M_\odot$, and green for $M_* \geq 3 \times 10^{10}M_\odot$. The thick solid lines illustrates the outcomes of Eq. (4) for extreme values of the relevant parameters f_σ and z_{form}. The black arrows present the size evolution driven by gas expulsion:the long ones mark the contributions by quasar feedback following a slow size expansion by SN feedback (the short arrows).

We propose that most of the size evolution is due to a puffing up driven by gas expulsion. The quasar-driven winds advocated by us occur in the most massive galaxies, while below $M_* \leq 2 \times 10^{10}M_\odot$ the dominant energy input into the interstellar medium comes from supernova explosions which induce a slower mass loss. The size evolutions driven by the rapid and the slow gas loss are described with long and short arrows in Fig 2.
We compile the latest observed data to show the evolution of the effective radius with redshift (Figure 3).The black arrows describe the expectation by our reference model (Granato et al. 2001,2004,Lapi et al. 2006). The short horizontal ones represent the forming phase when stars are forming in a rapid, dissipative collapse. The upward arrows mark size expansion driven by quasar feedback. The slight slopes of the upward arrows reflect how long it takes for the stellar structure to readjust to a new equilibrium after quasar feedback. The following long horizontal arrows describe the slow size increase phase driven by SN feedback.

Fig. 3.— Evolution of the effective radius with redshift. The data points show: average sizes of $z \leq 1$ passively evolving galaxies, divided by the local sizes of galaxies of equal stellar mass, in the samples by Trujillo et al. (2007), McIntosh et al. (2005), van der Wel et al. (2008), Maier et al. (2009) and Bernardi (2009), with the associated errors; individual data and error bars for passively evolving galaxies with spectroscopic redshifts $z \geq 1$ by Longhetti et al. (2007), Cimatti et al. (2008), Damjanov et al. (2009), and van Dokkum et al. (2008); data and error bars for individual star forming galaxies with spectroscopic redshifts $z \geq 2$ by Tacconi et al. (2008) and Law et al. (2009). Color code refers to the stellar mass, as in Fig 2. The shaded area reflects the distribution of local SDSS galaxies (Hyde & Bernardi 2009). The black arrows describe our model prediction(See text for the details).And the red dotted-line shows the model expectation by dry merger(van del wel et al.,2009).



Conclusions

- The observed small sizes at high-z are indeed expected (cf. Eq. [4]) if ETG progenitors formed most of their stars in a rapid, dissipative collapse.
- The limits on the mass increase of ETGs (cf. Fig. 1) tightly constrain the size increase obtainable via minor dry mergers. Minor dry mergers can only be responsible for the mild size evolution observed since $z \leq 1$.
- Most of the size evolution is due to a puffing up driven by gas expulsion. The size expansion has two phases:a

rapid gas loss phase driven by quasar feedback following a slow one by SN feedback. The quasar feedback dominates the size evolution of massive ETGs with $M_* \geq 10^{11}\,M_\odot$ while SN feedback dominates at $M_* \leq 2 \times 10^{10}M_\odot$.

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