THE SIZE-STAR FORMATION RELATION OF MASSIVE GALAXIES AT 1.5 < z < 2.5

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ABSTRACT

We study the relation between size and star formation activity in a complete sample of 225 massive (\(M_*>5\times10^{10}\,M_\odot\)) galaxies at 1.5 < z < 2.5, selected from the FIREWORKS UV–IR catalog of the CDFS. Based on stellar population synthesis model fits to the observed rest-frame UV–NIR spectral energy distributions, and independent MIPS 24 \(\mu\)m observations, 65% of the galaxies are actively forming stars, while 35% are quiescent. Using sizes derived from two-dimensional surface brightness profile fits to high-resolution (FWHM_{PSP} \sim 0.45) ground-based ISAAC data, we confirm and improve the significance of the relation between star formation activity and compactness found in previous studies, using a large, complete mass-limited sample. At z \sim 2, massive quiescent galaxies are significantly smaller than massive star-forming galaxies, and a median factor of 0.34 \pm 0.02 smaller than galaxies of similar mass in the local universe. Thirteen percent of the quiescent galaxies are unresolved in the ISAAC data, corresponding to sizes <1 kpc, more than five times smaller than galaxies of similar mass locally. The quiescent galaxies span a Kormendy relation which, compared to the relation for local early types, is shifted to smaller sizes and brighter surface brightnesses and is incompatible with passive evolution. The progenitors of the quiescent galaxies were likely dominated by highly concentrated, intense nuclear starbursts at z \sim 3–4, in contrast to star-forming galaxies at z \sim 2 which are extended and dominated by distributed star formation.

Key words: cosmology: observations – galaxies: evolution – galaxies: formation – galaxies: high-redshift

1. INTRODUCTION

The size of a galaxy is a important property, which scales with its mass. The evolution of galaxy sizes with redshifts provides strong constraints on galaxy formation models, as it reflects the change in the distribution of stellar mass with time. Sizes of high-redshift galaxies provide the strongest constraints. Lately evidence has been accumulating for massive high-redshift galaxies having significantly smaller sizes than local galaxies of similar mass (Toft et al. 2005; Daddi et al. 2005; Trujillo et al. 2006a, 2006b, 2007; Toft et al. 2007; Zirm et al. 2007; Cimatti et al. 2008; van Dokkum et al. 2008; Franx et al. 2008). There is furthermore evidence for a relation between star formation activity and size: at z \sim 2, star-forming galaxies are on average a factor of 2 smaller than local galaxies of similar mass, while quiescent galaxies are even smaller by a factor of 3–6 (Toft et al. 2007; Zirm et al. 2007; Cimatti et al. 2008; van Dokkum et al. 2008), suggesting the existence of a significant population of massive galaxies with extremely dense old stellar populations, which are not easily explained by current galaxy formation models. All these observations are based on relatively small samples of galaxies, with a range of possible biases resulting from different selection schemes. In this paper, we present the first study focusing on the correlation between star formation activity and size in a large mass-limited sample of galaxies at z \sim 2.

Throughout the paper, we assume a flat cosmology with \(\Omega_m = 0.3\), \(\Omega_A = 0.7\), and \(h = 0.72\). Magnitudes are in the AB system.

2. FIREWORKS

This paper is based on FIREWORKS, an imaging survey of \sim 135 arcmin$^2$ in the CDFS, which combines deep multi wave band space and ground-based optical–NIR data with MIR data from the Spitzer IRAC and MIPS instruments (Wuyts et al. 2008). We adopt the photometric redshifts of Wuyts et al. (2008) which were derived from the UV–IR spectral energy distributions (SEDs; calibrated using 1477 spectroscopic redshifts) and have an accuracy of \(\Delta z/(1+z) \sim 0.05\) at \(z_{spec} > 1\), and the SED modeling of N. M. Förster Schreiber et al. (2009, in preparation) who fit Bruzual & Charlot (2003) stellar population synthesis models to derive constraints on the star formation rates (SFRs), histories, ages, stellar masses, extinction etc. We here use the results for a Calzetti extinction law, solar metallicity, and a Salpeter IMF (which we renormalized to a Kroupa 2001) IMF by multiplying derived masses and SFRs by \sim 0.2 to Franx et al. 2008). We note that the derived masses increase on average by a factor of 1.4 when Maraston (2005) models are used. There is no evidence for this factor being dependent on color, mass, or redshift (Wuyts et al. 2007). We constructed a complete (see Franx et al. 2008), mass-limited (\(M > 5 \times 10^{10}\,M_\odot\)) sample of 225 galaxies in the photometric redshift range 1.5 \leq z_{phot} \leq 2.5, which form the basis of the following analysis. More details of the fits and accuracies of the derived parameters are presented in Wuyts et al. (2008) and N. M. Förster Schreiber et al. (2009, in preparation).

3. SIZE FITTING

We fitted the two-dimensional surface brightness distribution of the galaxies in the ISAAC K-band images (pixel scale...
Using a fitting procedure identical to the one used here, Trujillo et al. (2006b) derived sizes from the FIRES ISAAC data (Labbé et al. 2003; Förster Schreiber et al. 2006) which are of similar depth and quality, and were acquired and reduced in an identical way to the data set studied here. They studied in great details the effects of low signal to noise, and small intrinsic sizes on the derived structural parameters, using simulations, and found no significant systematic biases in the derived sizes, but an increasing scatter with magnitude, in agreement with the conclusion from Figure 1.

We also fitted the sizes of the galaxies in our sample in the ACS $F606W$-band images. Based on these fits, we removed 16 galaxies from the sample which had bright blue central sources with derived sizes consistent with being unresolved, since their broadband photometry and derived sizes are likely to be contaminated by active galactic nuclei (AGNs).

### 4. RESULTS

Based on the specific star formation rates ($s\text{SFR}$s) derived from the SED fits, 65% of galaxies in the sample have $s\text{SFR} > 0.03 \text{ Gyr}^{-1}$ and are classified as “star forming” (median ($s\text{SFR})_j = 1.13 \pm 0.67 \text{ Gyr}^{-1}$), while 35% have $s\text{SFR} < 0.03 \text{ Gyr}^{-1}$ and are classified as “quiescent” (median ($s\text{SFR})_q = 0.01 \pm 0.01 \text{ Gyr}^{-1}$). These fractions are similar to those found for distant red galaxies (Kriek et al. 2006; Toft et al. 2007; Zirm et al. 2007) as expected, since most massive galaxies are red at these redshifts. The corresponding volume densities are $\phi_d = 1.7_{-0.5}^{+0.6} \times 10^{-4} \text{ Mpc}^{-3}$ and $\phi_d = 3.1_{-0.8}^{+1.4} \times 10^{-4} \text{ Mpc}^{-3}$ for quiescent and star-forming galaxies, respectively (error bars represent the estimated cosmic variance; see Marchesini et al. 2008). The results are robust with respect to small changes in the $s\text{SFR}$ threshold used for dividing the galaxies into star forming and quiescent, as relatively few galaxies ($\lesssim 10\%$) have intermediate (0.03 Gyr$^{-1} < s\text{SFR} < 0.5 \text{ Gyr}^{-1}$) derived sSFRs.

In Figure 2, we plot the mass of the galaxies versus their effective radii. At a given mass, the quiescent galaxies are significantly smaller than the star-forming galaxies. With the

![Figure 1](image-url)
Monte Carlo simulations by Wuyts et al. (2008). For each realization, we calculate the median value of a parameter, and randomly perturb it according to the uncertainty from its variation in the realizations. In this way, we find that the star-forming galaxies are a median factor of 4 denser than galaxies of similar mass locally, while the star-forming galaxies are denser by a median factor of 4.1 ± 0.2.

In the above size comparison, we compared to the local late-type relation when the best fitting Sérsic $n$ was $< 2.5$ and the local early-type relation when $n > 2.5$, consistent with the definition of the relations in Shen et al. (2003). One may worry that this could introduce systematic effects since the fitted $n$ parameter is relatively uncertain, especially for the smallest galaxies, and we do not know for sure if the $z \sim 2$ galaxies will evolve into early or late-type galaxies, however, since the local relations are very similar in the considered mass range, the derived median offsets from the local mass–size relation do not change significantly when the sizes, independently of the fitted $n$, are compared to only the local early-type (0.35 ± 0.02) or late-type (0.33 ± 0.02) relations.

As an independent confirmation of the correlation, we added MIPS 24 μm imaging to the analysis. As shown by Toft et al. (2007), the ratio of flux at 24 and 4.5 μm as measured by the Spitzer MIPS and IRAC instruments is a good empirical tracer of the sSFR (and/or AGN activity) of galaxies in this redshift range. In Figure 3, we plot this ratio ($F_{24}/F_{4.5}$) as a function of size (normalized by the local mass–size relation). The majority of the quiescent galaxies have log($F_{24}/F_{4.5}$) $\lesssim 0$ (many of them only have upper limit detections, corresponding to sSFR $\lesssim 0.2$ Gyr$^{-1}$) while most of the star-forming galaxies have log($F_{24}/F_{4.5}$) $\sim 1$, corresponding to sSFR $\sim 1.5$ Gyr$^{-1}$, independently confirming the correlation between size and star formation activity (based on SED fits), and that the quiescent galaxies are small and red due to extremely compact old quiescent stellar populations rather than dust enshrouded star formation or AGN activity.

The relation between star formation activity and size found here for a mass-selected sample at $z \sim 2$ is consistent with the relation between color, size, and mass and its evolution with redshift found by Franx et al. (2008) for a K-selected sample. At a given mass, they found galaxy sizes to evolve like $r_e \propto 1/(1+z)^{0.99 \pm 0.04}$, corresponding to a size difference of $r_{e,z=2}/r_{e,z=0} = 0.52 \pm 0.06$, which is very similar to the size difference measured here for the whole sample (quiescent+star-forming galaxies): $r_{e,z=2}/r_{e,z=0} = 0.48 \pm 0.03$. For quiescent galaxies, they found a faster evolution $r_e \propto 1/(1+z)^{1.09 \pm 0.07}$, corresponding to $r_{e,z=2}/r_{e,z=0} = 0.30 \pm 0.03$, again consistent with the value derived here for quiescent galaxies $r_{e,z=2}/r_{e,z=0} = 0.34 \pm 0.02$.

In Figure 4, we plot the Kormendy relation between size and dust corrected rest-frame $i$-band surface brightness for the quiescent galaxies. Also plotted are the Kormendy relation of early-type galaxies in SDSS and the predictions of simple passive evolution models which, if the stellar populations form at

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**Figure 2.** Top: mass–size relation for $M_{*} > 5 \times 10^{10} M_{\odot}$ galaxies with $1.5 < z_{\text{phot}} < 2.5$. Filled red circles are quiescent galaxies, blue stars are star forming. The curves represent the mass–size relation of early-type (red) and late-type (blue) galaxies in SDSS (Shen et al. 2003). Quiescent galaxies are significantly smaller than star-forming galaxies of similar mass. The quiescent and star-forming galaxies are median factors of 0.34 ± 0.02 and 0.51 ± 0.02 smaller than galaxies of similar mass locally. The arrow shows the increase in mass and size predicted from equal mass dry merger simulations (Boylan-Kolchin et al. 2006). Bottom: surface mass density vs. stellar mass. Star-forming galaxies are a median factor of 4.1 ± 0.2 denser than galaxies of similar mass locally, while quiescent galaxies are 8.8 ± 0.7 times denser. Crosses show typical error bars for galaxies, with median properties.

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exception of a few dozen galaxies with $M < 10^{11} M_{\odot}$, which within the scatter are consistent with the local relation, the galaxies are smaller than local Sloan Digital Sky Survey (SDSS) galaxies of similar mass at all considered masses.

We parameterize the evolution of the mass–size relation with log(re($M_{*}$)$_{z=2}$) = log(re($M_{*}$)) + log A, where A is the median offset between the relation at $z = 2$ and $z = 0$, and use Monte Carlo simulations to derive the most likely value of A and its uncertainty. We generate 500 realizations of the data set by varying the photometric redshifts and corresponding stellar masses randomly within their 1σ errors (derived from Monte Carlo simulations by Wuyts et al. 2008). For each photo-$z$ realization, we calculate the corresponding physical size in kpc, and randomly perturb it according to the uncertainties shown in Figure 1, derived from galfit and from the comparison to NICMOS (added in quadrature). For each realization, we then calculate the median A, and estimate its uncertainty from its variation in the realizations. In this way, we find that the star-forming galaxies are a median factor of $A_{sf} = (\text{re}/\text{re}_{\text{SDSS}})_{sf} = 0.51 \pm 0.02$ smaller than galaxies of similar mass in the local universe, while the quiescent galaxies are smaller by a median factor of $A_{q} = (\text{re}/\text{re}_{\text{SDSS}})_{q} = 0.34 \pm 0.02$.

This difference is smaller than was found for quiescent distant red galaxies (DRGs; (reDRG/ reSDSS) $\sim 0.2$; Toft et al. 2007) and K-selected galaxies without emission lines at $z \sim 2.3$ ((reDRG/ reSDSS) $\sim 0.17$; van Dokkum et al. 2008), but the scatter is large, with values ranging from $0.1 \lesssim \text{re}_{q}/\text{re}_{\text{SDSS}} \lesssim 1$. This difference is likely a consequence of the systematically higher redshifts ($2 < z < 3.5$) and brighter K-band magnitudes of the galaxies in these studies relative to the median galaxy in the present mass-selected sample. Thirteen percent of the quiescent galaxies are unresolved in the ISAAC data with re set to an upper limit of 0.5 pixel. Furthermore, from Figure 1 we concluded that the sizes of some of the smallest, faintest galaxies may be overestimated from the ISAAC data. These galaxies are included in the calculation of $A_{q}$, which should thus be considered a lower limit for the size difference. Also plotted in Figure 2 is the surface mass density $\Sigma_{0} = \frac{M_{*}}{2\pi r_e^2}$ of the galaxies as a function of stellar mass. From the Monte Carlo simulations described above, we find that the quiescent galaxies are a median factor of $[\Sigma_{0}/\Sigma_{0,\text{SDSS}}]_{q} = 8.8 \pm 0.7$ denser than galaxies of similar mass locally, while the star-forming galaxies are denser by a median factor of $[\Sigma_{0}/\Sigma_{0,\text{SDSS}}]_{sf} = 4.1 \pm 0.2$.
a common formation redshift $z_f$, just shift the relation vertically without changing its slope (if the galaxies formed at different redshifts, the passive evolution could also change the slope). The $z \sim 2$ quiescent galaxies are shifted to smaller sizes and higher surface brightnesses, than locally. The $z \sim 2$ relation appears to be steeper, but this may be due to selection effects, as indicated by the dashed line, which shows the approximate position of galaxies at the mass limit ($5 \times 10^{10} M_\odot$). Using bootstrapping, we find that the surface brightness of the $z \sim 2$ galaxies on median is $3.2 \pm 0.1$ mag arcsec$^{-2}$ brighter than similar size local galaxies. This is consistent with results from of smaller samples at similar redshifts (Toft et al. 2007; Longhetti et al. 2007; Cimatti et al. 2008; van Dokkum et al. 2008). Note that a population of small ($r_e < 1$ kpc) quiescent elliptical galaxies exists in the local universe (e.g., in the Virgo cluster; see Ferrarese et al. 2006), which is missed by SDSS selection function. However, these are typically faint, low-mass dwarf galaxies, with surface brightnesses in agreement with the local Kormendy relation shown in Figure 4. The $z \sim 2$ relation cannot evolve into the local relation through simple passive evolution, as this would result in galaxies which are too small and bright for their mass, compared to what is observed. In other words, the galaxies need to evolve in size in addition to the passive fading of their stellar light to evolve into the local population.

5. DISCUSSION

A possible formation scenario for the ultra compact quiescent galaxies is through high-redshift gas-rich mergers, which models suggest under certain circumstances can create very dense stellar populations (see, e.g., Khochfar & Silk 2006). Examples of high-redshift gas-rich mergers with intense associated star formation are submillimeter selected galaxies (SMGs), which in some cases have very high central concentrations of molecular gas and dynamical mass densities comparable to the central stellar density found here in the quiescent galaxies (e.g., Tacconi et al. 2008; Coppin et al. 2009). For this reason, an evolutionary connection between the two galaxy types has been hypothesized (Toft et al. 2007; Cimatti et al. 2008; Tacconi et al. 2008). A simple connection is, however, unlikely. In contrast to the quiescent galaxies, SMGs are among the most vigorously star-forming galaxies known in the universe. High extinction and evidence for a large fraction of interacting/merging systems among SMGs complicate the comparison of their sizes with those of more common star-forming galaxies at $z \sim 2$. Smail et al. (2004) and Almaini et al. (2005) find half light radii of a few to $\sim 10$ kpc for samples of $\sim 10$ SMGs, which are more similar to the range spanned by our star-forming subsample, and thus consistent with the SFR-size trend (but see Tacconi et al. 2008 for a contrasting view). Such large inferred sizes, together with extended disturbed morphologies and dynamics seen in a fraction of SMGs, are clearly different than for many of the quiescent galaxies studied here. It seems implausible that all SMGs could be turned off and appear as compact remnants within very short timescales (the redshift distributions are similar). The old stellar ages measured for the quiescent galaxies ($0.5$–$1.5$ Gyr; Kriek et al. 2006) and their compact structure suggest that they formed the majority of their stars in highly concentrated (nuclear) starbursts at $3 \lesssim z \lesssim 5$. This suggests that a population of very compact, intensely star-forming galaxies exists at $z \sim 4$, with properties quite different from the bulk of star-forming galaxies at $z \sim 2$, which are extended, and dominated by spatially distributed star formation. If their star formation is relatively unobscured, these galaxies may be present in $B$-band and $V$-band drop out selected samples of $z \sim 4$ and $z \sim 5$ galaxies. Interestingly, the space densities of the brightest ($L_{UV} > 2.5L_{UV}^\star$) $B$-band and ($L_{UV} > 2L_{UV}^\star$) $V$-band drop out galaxies are similar to the space density of quiescent $z \sim 2$
galaxies (Bouwens et al. 2007), however, their (rest-frame UV) sizes are considerable larger (re ≈ 1.6 kpc; Bouwens et al. 2004). Also, Lyman break galaxies at z ≈ 4, with Lyα detected in emission, have recently been shown to have compact (median rest-frame UV re ≈ 1 kpc), intensely star-forming regions, in agreement with this scenario (Vanzella et al. 2009). If their star formation is triggered by gas-rich major mergers, it may be obscured by dust, in which case these galaxies would not be present in Lyman drop selected samples, but may be detectable as a population of dense z ≈ 4 submillimeter galaxies. Identifying SMGs at these redshifts is, however, difficult, since they fall below the detection limit of the deepest radio VLA maps, needed for identifying their optical counterpart due to the poor resolution of current submillimeter facilities (e.g., Ivison et al. 2007). Therefore, only a few examples of SMGs are known at these redshifts (e.g., Younger et al. 2007; Knudsen et al. 2008; Dannerbauer et al. 2008), all of which have been detected in radio. However, a significant fraction of SMGs (about 1/3; Ivison et al. 2007) are unidentified in radio and are thus likely to be at z > 3.5. Some of these may be progenitors of the z ≈ 2 quiescent galaxies.

While the derived stellar mass densities in the quiescent galaxies (10^9–10^11 M⊙ kpc^-3) are much higher than in local massive galaxies, comparable or higher densities are found in globular clusters and ultra compact dwarf galaxies (10^{10–10^{11}} M⊙ kpc^-3; Dabringhausen et al. 2008), which are some of the oldest stellar systems known. Even though their total masses are much smaller (10^9–10^8 M⊙), and there may not be a direct connection to the compact z ≈ 2 quiescent galaxies, it is interesting to note that starbursts in the early universe can result in extremely compact stellar distributions.

The quiescent galaxies at z ≈ 2 are dominated by old extremely compact stellar populations, so it would be natural to assume that they would continue to evolve passively into local elliptical galaxies, which are the oldest, densest, most massive galaxies in the local universe. From Figures 2 and 4, it is clear that this scenario is ruled out, as passive evolution would result in too many extremely compact massive galaxies with too high surface brightnesses, compared to what is observed. Some elliptical galaxies in the local universe have super solar metallicities. Assuming super solar (2.5 Z⊙) metallicity in theSED fits, on average leads to 19% ± 1% smaller masses for the quiescent galaxies, which is not enough to explain their unusually high-mass densities.

The high masses and small sizes of the quiescent galaxies correspond to unusually high expected velocity dispersions (σ = 300–500 km s^-1; see also Toft et al. 2007; van Dokkum et al. 2008; Cimatti et al. 2008). This has been observationally confirmed from a deep rest-frame optical spectrum of a M = 2 × 10^{11} M⊙, z = 2.2 compact, quiescent galaxy which has a measured σ = 510^{165}_{-40} km s^-1 (van Dokkum et al. 2009). Recently, a small number of low-redshift galaxies with velocity dispersions σ_v > 350 km s^-1, high stellar masses (>10^{11} M⊙), and unusually small sizes (1–2 kpc) were found in the SDSS (Bernardi et al. 2006). Their derived stellar surface mass densities are, however, not as extreme as for the quiescent galaxies found here (see also Cimatti et al. 2008), and they are extremely rare, with 10^2 times smaller space densities (φ ≈ 10^{-7}–10^{-8} Mpc^{-3}), so a simple evolutionary connection is unlikely.

One of the most promising processes for decreasing the stellar mass density of the quiescent galaxies is dry merging. Simulations suggest that under favorable conditions, an equal mass dry merger can increase the size of the remnant by up to a factor of 2 (e.g., Boylan-Kolchin et al. 2006; Naab et al. 2007). As indicated in Figure 2, the compact quiescent galaxies would need to go through 2–3 successive equal mass mergers to end up near the local mass–size relation, which would result in remnant masses in excess of 5 x 10^{11} M⊙. The space density of M > 5 x 10^{11} M⊙ early-type galaxies in the SDSS sample of Bernardi et al. (2003) is ~0.2 x 10^{-4} Mpc^{-3}, a factor of 10 lower than the density of the z > 2 quiescent M > 5 x 10^{11} M⊙ galaxies considered here. Interestingly, three successive equal mass dry mergers of the quiescent z > 2 galaxies could thus result in remnants with masses and number densities comparable to those of the most massive local elliptical galaxies, but possibly not with quite as large sizes (see also, e.g., Bezanson et al. 2009; van der Wel et al. 2009).

Recent studies have explored minor dry merging as an efficient way of decreasing the central stellar mass density of the z ≈ 2 quiescent galaxies to the value observed in local ellipticals, and the possibility that the compact stellar populations of some of them could survive to the present day, hidden in centers of local ellipticals underneath lower density envelopes of stars accreted at later times (Naab et al. 2009; Bezanson et al. 2009; Hopkins et al. 2009). Finally, if the IMF evolves with time and were more top heavy in the past as suggested by, e.g., van Dokkum (2008), part of the offset from the local mass–size relation could be explained by a systematic over estimation of the masses at z ≈ 2.

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