SIZE EVOLUTION OF THE MOST MASSIVE GALAXIES AT 1.7 < z < 3 FROM GOODS NICMOS SURVEY IMAGING

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ABSTRACT

We measure the sizes of 82 massive (M ≥ 10^{11} M_\odot) galaxies at 1.7 ≤ z ≤ 3 utilizing deep HST NICMOS data taken in the GOODS North and South fields. Our sample is almost an order of magnitude larger than previous studies at these redshifts, providing the first statistical study of massive galaxy sizes at z > 2, confirming the extreme compactness of these systems. We split our sample into disk-like (n ≤ 2) and spheroid-like (n > 2) galaxies based on their Sérsic indices, and find that at a given stellar mass disk-like galaxies at z ∼ 2.3 are a factor of 2.6 ± 0.3 smaller than present-day equal-mass systems, and spheroid-like galaxies at the same redshifts are 4.3 ± 0.7 smaller than comparatively massive elliptical galaxies today. At z > 2 our results are compatible with both a leveling off, or a mild evolution in size. Furthermore, the high density (~2 × 10^{10} M_\odot kpc^{-3}) of massive galaxies at these redshifts, which are similar to present-day globular clusters, possibly makes any further evolution in sizes beyond z = 3 unlikely.

Subject headings: galaxies: evolution — galaxies: high-redshift — infrared: galaxies

1 INTRODUCTION

One of the most exciting discoveries in extragalactic astronomy in the last few years is that massive (M ≥ 10^{11} M_\odot) galaxies at z > 1 were extremely compact (Daddi et al. 2005; Trujillo et al. 2006b, 2007; Longhetti et al. 2007), particularly those with the lowest estimated star formation rates (Zirm et al. 2007; Toft et al. 2007; Cimatti et al. 2008; van Dokkum et al. 2008; Pérez-González et al. 2008). Since only a very few dense and massive objects are found at z ∼ 0 (Bernardi et al. 2006; cf. with none at z ≤ 1 kpc) it is clear that significant growth in the sizes of these galaxies has occurred during cosmic history.

Within the current galaxy formation paradigm, the origin of these galaxies can be described by the collapse and merging of dark matter halos. Models suggest that at very early times galaxies contain large amounts of cold gas, resulting in efficient starbursts (e.g., Khochfar & Silk 2006). As star formation occurs, the gas in these galaxies becomes heated due to various feedback processes (e.g., Granato et al. 2004; Menci et al. 2006), leading to reduced star formation rates, creating compact and massive remnants. Observationally, we know that at z < 2 there are few gas-rich mergers in massive galaxies based on structural analyses (e.g., Conselice et al. 2003, 2008; Conselice 2006) preventing significant starbursts and new star populations from forming. Since at these lower redshifts the amount of available gas has decreased, “dry” mergers are expected to be the dominant mechanism for size and stellar mass growth (Ciotti & van Albada 2001; Domínguez-Tenreiro et al. 2006; Boylan-Kolchin et al. 2006), although other processes are possible (Nabz et al. 2007; Pipino & Matteucci 2008).

One of the ways to trace this evolution is through measuring the sizes of galaxies throughout time. At z < 2, the size evolution of the most massive galaxies has been well characterized with large samples of objects. Recently, Trujillo et al. (2007) using ~800 sources found that, at a given stellar mass, disk-like objects at z ∼ 1.5 were a factor of 2 smaller than their present-day counterparts. For spheroid-like objects the evolution is even stronger. The spheroidal objects are a factor of 4 smaller at z ∼ 1.5 compared with similar mass modern ellipticals. This evolution is also in qualitative agreement with hierarchical semianalytical model predictions which find a factor of 1.5–3 evolution in size since that redshift (e.g., Khochfar & Silk 2006).

At z > 2, however, our knowledge of the size evolution of the most massive objects is much more scarce. There are only a few attempts to explore this issue using small samples of massive galaxies at z ∼ 2.5 (Zirm et al. 2007; Toft et al. 2007; van Dokkum et al. 2008). This is due to the intrinsic scarcity of distant massive galaxies, and the relative small sizes of previous deep NIR imaging surveys. With the aim of substantially increasing our knowledge of the size evolution of massive galaxies in the redshift interval 1.7 ≤ z ≤ 3, we have imaged a sample of 82 very massive galaxies in the GOODS North and South fields within the H-band filter as part of the GOODS NICMOS Survey (C. Conselice et al. 2008, in preparation).

To allow a comparison with both the local SDSS stellar mass-size relations, and the results obtained at lower redshifts (z < 2), we split our sample according to light concentration using the Sérsic index n to separate disk-like galaxies from more concentrated spheroid-like systems. We find that both types continue, and perhaps level off, in their size evolution at z > 2. We assume the following cosmology throughout: H₀ = 70 km s^{-1} Mpc^{-1}, Ωₗ = 0.7, and Ωₘ = 0.3, and use AB magnitude units.

2 DATA AND SAMPLE

Our sample of galaxies originates from the GOODS North and South fields and are imaged as part of the GOODS NICMOS survey (GNS; PI C. Conselice). The GNS is a large HST NICMOS-3 camera program of 60 pointings centered around massive galaxies at z = 1.7–3 at 3 orbits depth, for a total of 180 orbits in the F160W (H) band. Each tile (52" × 52", 0.203° pixel^{-1}) was observed in six exposures that were combined to produce images with a pixel scale of 0.1", and a point-spread function (PSF) of ~0.3" full width at half-maximum (FWHM). The details of the data reduction procedure are discussed in Magee et al. (2007). We optimize our pointings to obtain as many high-mass
$M_*>10^{11}M_\odot$ galaxies as possible, with the selection of these targets described in C. Conselice et al. (2008, in preparation). These galaxies consist of distant red galaxies from Papovich et al. (2006), IEROs from Yan et al. (2004), and BzK galaxies from Daddi et al. (2007). Within our NICMOS fields we find a total of 82 galaxies with masses larger than $10^{11}h_{70}^{-2}M_\odot$ with photometric and spectroscopic redshifts in the range $1.7 \leq z \leq 3$. In addition to these data, and to allow a comparison with the sizes obtained in the $H$ band, we measure, whenever possible, the sizes of the same galaxies using the $z$-band (F850LP, 5 orbits/image) HST ACS data. The $z$-band data is drizzled to a scale $0.03''$ pixel$^{-1}$ and has a PSF FWHM of $\sim0.1''$. Limiting magnitudes reached are $H \sim 26.8$ (5 $\sigma$) and $z = 27$ (15 $\sigma$ in a 0.2'' aperture) (Giavalisco et al. 2004).

3. DETERMINATION OF STELLAR MASSES AND PHOTOMETRIC REDSHIFTS

The masses and photometric redshifts of our objects are calculated using the large suite of GOODS data from the $B$ band to the infrared (e.g., Giavalisco et al. 2004). For our work we used the filters $BVRIizJHK$. Stellar masses are measured using standard multicolor stellar population fitting techniques, producing uncertainties of $\approx0.2$ dex. Details of the procedure for stellar mass determinations are in, e.g., Papovich et al. (2006), Bundy et al. (2006), Yan et al. (2004), Conselice et al. (2007), and C. Conselice et al. (2008, in preparation). Our stellar masses are calculated by assuming a Chabrier (2003) initial mass function (IMF) and producing model spectral energy distributions (SEDs) constructed from Bruzual & Charlot (2003)
stellar populations synthesis models parameterized by an exponentially declining star formation history. These model SEDs are fit to the observed SEDs of each galaxy to obtain a stellar mass. Issues concerning newer models utilizing AGB stars (see Maraston et al. 2006) are discussed in Conselice et al. (2007) and Trujillo et al. (2007), although we find that these newer models do not significantly alter our measured stellar masses.

Another source of uncertainty are the photometric redshifts we use in our sample which originated from standard techniques (e.g., Conselice et al. 2007). From the literature we find seven spectroscopic redshifts for our sample. Using the GOODS/VIMOS DR1 (details in Popesso et al. 2008) we find three matches with $\delta z/(1 + z) = 0.026$, and four more from the compilation of GOODS-S spectroscopic redshifts Wuyts et al. (2008) giving $\delta z/(1 + z) = 0.034$.

4. DETERMINATION OF GALAXY SIZES

Sérsic indices and sizes, as parameterized by the effective radius along the semimajor axis $a_e$, were measured using the GALFIT code (Peng et al. 2002). Our measured sizes are circularized, $r = a_e(1 - e)$, with $e$ the projected ellipticity of the galaxy. GALFIT convolves Sérsic (1968) $r^{n}$ 2D models with the PSF of the images and determines the best fit by comparing the convolved model with the observed galaxy surface brightness distribution using a Levenberg-Marquardt algorithm to minimize the $\chi^2$ of the fit. We use single Sérsic models to compare our size estimations with previous work at lower redshifts. We first estimate the apparent magnitudes and other useful parameters of our galaxies using SExtractor (Bertin & Arnouts 1996) which were then used as inputs to the GALFIT code.

Before we carry out our fitting we remove neighboring galaxies using an object mask. In the case of very close galaxies we select five (non-saturated) bright stars to estimate the apparent magnitudes and other useful parameters of our galaxies. In the NIC3 images we select five (non-saturated) bright stars to gauge the accuracy of our parameter estimations. The structural parameters of each individual galaxy are measured five times, using each time a unique star. The uncertainty ($1 \sigma$) on the structural parameters due to changes in the PSF is $\sim 10\%$ for $r_e$ and $\sim 20\%$ for the Sérsic index $n$.

Surface brightness dimming is one of the main concerns when measuring sizes and Sérsic indices at high redshift, which in principle could bias our measured sizes. In previous papers we conduct many simulations in order to check the importance of surface brightness dimming at different observational conditions (NIR ground-based; Trujillo et al. 2004; 2006a, 2006b; and using ACS data Trujillo et al. 2007). Trujillo et al. (2006a) show through extensive simulations of galaxies with various sizes and magnitudes, within observing conditions and depth worse than the NIC3 data we use, that sizes can be retrieved easily within the magnitude ranges of our objects ($K_{AB} \sim 21.5$).

We check in addition the accuracy of our structural parameter determinations by comparing our $H$-band measurements (giving optical rest-frame) against the results obtained using the $z$-band (NUV rest-frame) from the ACS imaging, where the spatial resolution is a factor of 3 better. Unfortunately, at $z \geq 2$ a large fraction (49 out 82) of our galaxies are not detected in the $z$-band, and cannot be used for the comparison. For the 33 objects remaining we find a good correlation (Pearson correlation coefficient 0.59) between sizes measured in both bands, with a small possible bias toward smaller sizes (4% $\pm$ 6%) in the $H$-band compared to the $z$-band measurements. This potential bias toward smaller sizes at longer wavelengths is as expected (see, e.g., Barden et al. 2005; McIntosh et al. 2005; Taylor-Mager et al. 2007; Trujillo et al. 2007). Comparing the Sérsic index $n$ is less straightforward, since the patchy distribution of UV light makes the measurement of the index $n$ (i.e., the shape of the surface brightness profile) very different from the light coming from more evolved stellar populations. We however find a correlation between the Sérsic index as measured in ACS and in NICMOS imaging (Pearson correlation coefficient 0.36). The Sérsic indices measured with NICMOS are 13% $\pm$ 12% smaller than those in the ACS $z$-band imaging. Part of the reason for the smaller value of the index $n$ in the NICMOS images is due to the larger PSF size in the infrared images compared to the PSF in the ACS data.

5. THE OBSERVED STELLAR MASS VERSUS SIZE RELATION

The stellar mass-size relation for our sample is shown in Figure 1, where we have split our sample into 3 redshift bins. Overplotted on each panel is the local value of the mean half-light radii and its dispersion at a given stellar mass (based on Sloan Digital Sky Survey data; Shen et al. 2003). SDSS sizes were determined using $r^\prime$-band data, which is equivalent to the $V$-band rest-frame at $z \sim 0.1$, the mean redshift of the galaxies in SDSS, and using a circularized Sérsic model. Stellar mass determinations of the galaxies in the local reference relation were measured using a Kroupa (2001) IMF which gives nearly the same stellar masses as using a Chabrier IMF.

Our galaxies are split into two types using our measured Sérsic indices. As shown by, e.g., Ravindranath et al. (2004) there is a correlation between the Sérsic index $n$ and Hubble type. Following this correlation, galaxies are usually segregated into late-type galaxies (with $n < 2$–2.5) and early-type (with $n > 2$–2.5). The effect of using either $n = 2$ or $n = 2.5$ does not significantly alter the derived mass-size relation for the local galaxies. We use $n = 2$ as our limit to account for the systematic bias toward smaller values of the measured Sérsic index when the PSF size is similar to the sizes of the objects measured (see a detailed explanation of this effect in Trujillo et al. 2006a; see also Marleau & Simard 1998). To obtain a realistic comparison between the local relation and the size evolution of massive galaxies at $z < 2$, Trujillo et al. (2007) use $n = 2.5$ to separate disk-like and spheroid-like systems. Trujillo et al. (2007) use a larger Sérsic index for their cut, as their PSF sizes are much smaller than the galaxies they measure, unlike in our present sample. Our choice of $n = 2$ is further reinforced by exploring the Sérsic distribution of the index $n$ in our sample, where two peaks are found at $n \approx 1$ and at $n \approx 2.3–2.5$.

Figure 1 shows that at a given stellar mass our massive galaxies are progressively smaller at high $z$. Remarkably, none of our galaxies at $z > 1.7$ fall in the mean distribution of the local relation. Moreover, if our stellar masses were overestimated by a factor of

| Redshift | $\alpha$ ($\pm 1 \sigma$) | $\beta$ ($\pm 1 \sigma$) |
|----------|--------------------------|--------------------------|
| Disk-Like Galaxies | | |
| 0.0–2.0 | 1.08 (0.02) | -0.78 (0.04) |
| 1.7–3.0 | 1.85 (0.28) | -1.34 (0.59) |
| 0.0–3.0 | 1.08 (0.01) | -0.82 (0.03) |
| Spheroid-Like Galaxies | | |
| 0.0–2.0 | 1.16 (0.01) | -1.51 (0.04) |
| 1.7–3.0 | 1.42 (0.29) | -1.66 (0.92) |
| 0.0–3.0 | 1.15 (0.01) | -1.48 (0.04) |

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of stars in the local universe—globular clusters. This comparison is an interesting one, since globular clusters are also expected to be form either very early, or more recently as a result of mergers of gas clouds during galaxy collisions.

A typical spheroid-like galaxy in our sample at \( z \sim 2.75 \) has a stellar mass of \( \sim 2 \times 10^{11} M_\odot \), and a size of \( r_e \sim 1 \) kpc. The stellar density for this object, assuming spherical symmetry, is \( \rho = (0.5M_\odot)/(4/3\pi r_e^3) \sim 2.4 \times 10^6 M_\odot \) kpc\(^{-3} \). A disk-like galaxy at \( z \sim 2.75 \) has a typical mass of \( 2 \times 10^{10} M_\odot \) and size \( r_e \sim 2 \) kpc.

Assuming a disk symmetry, the stellar mass density within these disk-like systems is \( \rho = (0.5M_\odot)/(\pi r_e^2 h) \sim 2.6 \times 10^8 M_\odot \) kpc\(^{-3} \), where we have used \( h \sim 0.3 \) kpc. In both cases the stellar mass densities are similar. A typical global stellar cluster (\( r_e = 10 \) pc and \( M \sim 10^4 M_\odot \)) has a density of \( \sim 1.2 \times 10^6 M_\odot \) kpc\(^{-3} \). This is remarkably similar to our massive galaxies at \( z > 2 \), and reveals that these high-z galaxies may in principle have an origin similar to globular clusters. This further suggests that their stellar mass densities do not likely become much larger at high redshifts \((z > 3)\). A massive galaxy at \( z > 2 \) must also have formed very quickly, and consequently these high stellar densities could reflect the high gas densities in the primeval universe. The compactness of our objects, and their similar densities to globulars, is consistent with a scenario whereby more massive halos start collapsing earlier and drag along a large amount of baryonic matter that later forms into stars.

If, as suggested by the high density of our galaxies, the size evolution is stopped or diminished at \( z > 2 \), this perhaps reveals a different evolutionary mechanism for massive galaxies at \( z < 2 \). A faster size evolution is in agreement with theoretical models, which predict that the amount of gas involved in galaxy mergers decreases with lower redshifts. A lower amount of gas results in a more efficient size growth, as the energy of the collision is not dissipated into the formation of new stars (e.g., Khochfar & Silk 2006).

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