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THE MORPHOLOGICAL DIVERSITIES AMONG STAR-FORMING GALAXIES AT HIGH REDSHIFTS IN THE GREAT OBSERVATORIES ORIGINS DEEP SURVEY [1]

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ABSTRACT

We have used the deep, multi–wavelength images obtained with the Advanced Camera for Surveys (ACS) on the *Hubble Space Telescope (HST)* by the Great Observatories Origins Deep Survey (GOODS) to identify ~ 4700 Lyman-break galaxies (LBGs) at redshifts $2.5 < z < 5$, and 292 starburst galaxies at $z \sim 1.2$. We present the results from a parametric analysis of the two-dimensional surface brightness profiles using a Sérsic function, for the 1333 brightest LBGs with rest-frame $M_{1600} \leq -20.5$ AB magnitudes. We distinguish the various morphological types based on the Sérsic index, *n*, which measures the profile shape. About 40% of LBGs at $z \sim 3$ have light profiles close to exponential, as seen for disks, and only about 30% of the galaxies have the high central concentrations seen in spheroids. We also identify a significant fraction ($\sim 30\%$) of galaxies with shallower than exponential profiles, which appear to have multiple cores or disturbed morphologies suggestive of close pairs or on-going mergers. The fraction of spheroid-like ($n > 2.5$) LBGs decreases by about 15% from $z \sim 5$ to 3. A comparison of LBGs with the starburst galaxies at $z \sim 1.2$, shows that disk-like and merger morphologies are dominant at both redshifts, but the fraction of spheroid-like profiles is about 20% higher among LBGs. The ellipticity distribution for LBGs exhibits a pronounced skew towards high ellipticities ($\epsilon > 0.5$), which cannot be explained by galaxy morphologies similar to the local disks and spheroids viewed at random orientations. The peak of the distribution evolves toward lower ellipticities, from 0.7 at $z = 4$ to ~ 0.5 at $z = 3$. The ellipticity distribution for the $z \sim 1.2$ galaxies is similar to the relatively flat distribution seen among the present–day galaxies. The dominance of elongated morphologies among LBGs suggests that in a significant fraction of them we may be witnessing star-formation in clumps along gas-rich filaments, or the earliest gas-rich bars that encompass essentially the entire visible galaxy. Similar features are found to be ubiquitous in hydrodynamical simulations in which galaxy formation at high redshifts occurs in filamentary inflows of dynamically–cold gas within the dark matter halos, and involves gas-rich mergers.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift — galaxies: fundamental parameters — galaxies: structure

1. INTRODUCTION

Galaxy morphologies at various look-back times provide important insights into the physical process associated with galaxy assembly. In the local Universe, the morphologies seen among the galaxy population are well described by the Hubble sequence (Hubble 1936) and both the physical, and kinematic properties of galaxies are known to vary systematically with the Hubble type (Roberts & Haynes 1994). Quantitative morphological analysis of galaxies at *HST* resolution ($\sim 0.''1$) suggest that the Hubble sequence was already in place by $z \sim 1$ (Abraham et al. 1996; Schade et al. 1999; Brinchmann et al. 1998; Lilly et al. 1998; Marleau & Simard 1998; Im et al. 1999; van den Bergh 2001; Trujillo & Aguerri 2004; Conselice, Blackburne, & Papovich 2005). There is growing evidence that a significant fraction of the present–day spirals and ellipticals were formed beyond $z = 1$, and very little size evolution has occurred after this epoch (Lilly et al. 1998; Simard et al. 1999; Im et al. 2002; Stanford et al. 2004; Ravindranath et al. 2004; Barden et al. 2005). Therefore, the assembly of the spheroid and disk components that define the morphological types appears to have occurred at much higher redshifts ($z > 1$). Although based on small samples, the morphological analysis of galaxies with spectroscopic redshifts $1 < z < 3$, have shown that the regular Hubble types can be identified out to $\sim z = 1 - 1.5$. However, at $z > 1.5$ the Hubble sequence is no longer clearly discernible, even in deep *HST*/NICMOS infrared images which measure the rest-frame optical light. At $z > 1.5$, the galaxies are often irregular and compact, and show tidal features, double nuclei, or disturbed morphology suggesting that mergers may be dominant at these redshifts (Papovich et al. 2005; Conselice, Blackburne, & Papovich 2005). Several earlier studies (Abraham et al. 1996; Glazebrook et al. 1994; Griffiths et al. 1994; Driver et al. 1995; Cowie, Hu, & Songaila 1995) have also emphasised the dominance of peculiar and irregular galaxies at the faintest

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magnitudes in optical *HST* surveys.

For almost a decade, star-forming galaxies at higher redshifts ($z > 2.5$) have been identified in deep, multi–wavelength surveys by using color criteria that are sensitive to the Lyman-break and Lyman-α forest absorption features in their otherwise flat ultraviolet spectral continuum (Steidel et al. 1996; Giavalisco 2002; Giavalisco et al. 2004). The robustness and efficiency of the "Lyman-break" technique to identify $z > 2.5$ galaxies has been established through extensive spectroscopic redshift determinations (Steidel et al. 2003). Although Lyman-break galaxies (LBGs) are among the largest samples of high-z galaxies that have been identified, until recently, the high resolution *HST* images required to study their morphological properties were available only for small samples of LBGs (Giavalisco, Steidel, & Macchetto 1996; Giavalisco et al. 1996; Lowenthal et al. 1997). The previous morphological analysis using 19 LBGs have suggested that they have a range of morphologies, and their surface brightness profiles in most cases show a core that can be represented by the $r^{1/4}$ profile seen for spheroids (Giavalisco, Steidel, & Macchetto 1996). About 90-95% of the stars are formed in these compact cores with sizes in the range 2.4–3.6 h_{50}^{-1} kpc. Ferguson et al. (2004) used the *HST*/ACS images from the initial three epochs of GOODS observations to measure the concentration index, ellipticity, and sizes of 386 LBGs at $z \sim 4$. Although the concentration index measures favor a significant fraction of spheroid-like systems among the LBGs at $z \sim 4$, their ellipticity distributions seemed to suggest that extended disk-like morphology was more dominant. In a recent analysis, Lotz et al. (2005) used GOODS images to study morphology of 82 LBGs at $z \sim 4$ with sizes $r_p > 0.''3$, where r_p is the Petrosian radius. They measured the Gini coefficients, and the second–order moment of the brightest 20% of the galaxy light (M_{20}), and find that only 30% have bulge-like morphology and more than 50% of the galaxies have morphologies that are disk-like, minor mergers, or post–mergers.

In this paper, we use the surface-brightness profile shape, and ellipticity measurements to characterize the rest-frame UV morphologies among the high redshift, star-forming galaxies in the GOODS images. Our aim is to quantify the frequency of spheroid, disk, or merger-like morphology among LBGs at $z > 2.5$ in a statistical manner, and to study the morphological evolution of actively star-forming galaxies through a comparison of LBGs at $z > 2.5$ and starbursts sample at $z \sim 1.2$. These redshifts are particularly interesting because they correspond to two widely separated epochs marked by lack of the Hubble type morphologies at $z = 3$, to their appearance by $z = 1.2$.

The central concentration of the light profiles (Abraham et al. 1996; Conselice et al. 2003), and axial ratios (Im et al. 1995; Odewahn et al. 1997; Alam & Ryden 2002) are among the commonly used measurements to characterize the morphological types among faint, distant galaxies. The interpretation of these quantities is based on the observed trends with galaxy morphology in the local Universe. Elliptical galaxies and bulges of spiral galaxies tend to have steep ($r^{1/4}$) light profiles, while disk-dominated galaxies have exponential or even shallower light profiles. The apparent axial ratio (b/a) or ellipticity ($\epsilon = 1 - b/a$), of a galaxy is related to its intrinsic three-dimensional structure, and elliptical and spiral galaxies are known to have different observed axial ratio distributions locally (Sandage, Freeman, & Stokes 1970; Lambas, Maddox, & Loveday 1992). The distribution for local ellipticals peaks around $\epsilon = 0.2$ and declines rapidly beyond $\epsilon > 0.5$, while spiral galaxies show a relatively flat distribution from $\epsilon = 0.2$ to 0.7 and falls off at higher ϵ (Lambas, Maddox, & Loveday 1992).

Most of the morphological studies of low redshift galaxies are done at rest-frame optical wavelengths, but the *HST* optical images of the LBGs at $z > 2.5$ sample the rest-frame UV wavelengths where the contribution from actively star forming regions dominates the light. It is known that morphological *k*–correction or the wavelength dependence of galaxy morphology can be significant for local galaxies (Kuchinski et al. 2000, 2001), and Giavalisco et al. (1996) have examined how this may influence the morphologies inferred for the high redshift galaxies. Galaxies tend to be classified as later Hubble types in the UV, because the redder bulge and bar components which are pre-dominantly made of evolved stellar populations and low-mass stars, become extremely faint with respect to the actively star-forming disk component. However, a comparison of the optical and near-infrared *HST* images which sample the rest-frame UV and optical light respectively for LBGs at $z > 2.5$, show very similar morphology implying that the morphological *k*–correction is negligible (Dickinson 2000; Papovich et al. 2003). Quantitative measurements of the internal color gradients also show that this effect is more severe at low redshifts ($z \leq 1$) than at high redshifts (Papovich et al. 2005). Therefore, the UV morphologies derived for the LBGs are likely to be representative of the typical morphological mix among this population.

In the present study, we perform a parametric analysis of the galaxy surface brightness distribution, in order to measure the profile shape that quantifies the central concentration, and the ellipticity which allows to infer the intrinsic shape. We use the deep, multi-wavelength *HST*/ACS images for a large sample (≈ 4700) of LBGs available from GOODS, with unprecedented high spatial resolution ($\sim 700-800$ parsecs at $2.5 < z < 5.0$) which is essential for exploring the morphology of high redshift galaxies. We also make use of the Hubble Ultra Deep Field (HUDF) images to understand the selection effects, and use the UV images from GALEX to redshift local galaxies to high-z for comparison with the morphology of LBGs. The UV morphology is dominated by the actively star-forming regions which are often clumpy and irregular, and cannot be well-described by a smooth analytical function. However, we use the Sérsic function (Sérsic 1968) to model the light profile because it is sensitive to the central concentration, and can help to broadly distinguish between a bulge-dominated and disk-dominated galaxy. Also, we obtain a measure of the ellipticity for the overall galaxy light distribution from the parametric model. We describe the observations, and sample selection in § 2, and the morphological analysis is detailed in § 3. The simulations that were performed in order to assess the selection biases and measurement errors are described in (§ 4). We discuss the observed morphological diversities among LBGs, and its implications for galaxy formation in § 5, and § 6. We adopt the cosmology defined by $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\lambda = 0.7$ throughout this paper. All magnitudes are in units of AB magnitudes (Oke & Gunn 1983).

2. THE STAR-FORMING GALAXIES SAMPLE

The GOODS *HST* treasury program (Giavalisco et al. 2004a) is a multi–wavelength, deep imaging survey in the B(F435W), V(F606W), *i*(F775W), and *z*(F850LP) filters using the ACS instrument. The Survey covers an area of $\approx$ 316 sq. arcmin in two fields, one centered on the Chandra Deep Field-South (GOODS-S) and the other centered on the Hubble Deep Field-

North (GOODS-N). The basic image reduction procedures and creation of the drizzled image mosaics is described in Giavalisco et al. 2006 (in preparation). The final image scale of the GOODS ACS images is 0.″03 pixel^{-1}, and spatial resolution is $\sim$ 0.″11 (in the *z*-band) corresponding to the full width at half maximum of the point spread function (PSF). The GOODS ACS program does not include the U-band imaging required for the color selection of LBGs at $z \sim 3$. For this purpose, we used deep ground-based multi–wavelength images of the GOODS fields observed with the MOSAIC II camera at CTIO 4-m telescope, and the prime focus MOSAIC camera on the KPNO Mayall 4-m telescope (Giavalisco et al. 2004a).

The source catalogs for all images were created using the SExtractor (Bertin & Arnouts 1996) software, by using the F850LP image for detection. Photometry was done in common apertures for all the four ACS bands using the SExtractor dual–image mode. The samples of LBGs were extracted from the catalog by applying a set of color criteria that were defined based on the spectral energy distributions (SEDs) of star-forming galaxies at high redshifts, convolved with the detector efficiency and transmission in the various filters used for the survey. The color criteria adopted for the selection of LBG samples used in the present analysis is discussed in Giavalisco et al. (2004b) and Lee et al. (2006). The sources that satisfied the color criteria were culled by visual inspection to reject artifacts, such as, satellite trails, diffraction spikes of bright stars, etc. The final LBG sample consists of 1409 U-dropouts at $z \sim 3.1$, 2440 B-dropouts at $z \sim 3.8$, and 845 V-dropouts at $z \sim 4.9$.

In order to look for evolution between redshifts $z = 1.2$ and $z > 2.5$, we selected galaxies at $0.95 < z < 1.5$ using the spectroscopic redshifts available for the GOODS fields, mostly from the VIMOS VLT Deep Survey (VVDS; Le Févre et al.2004), the Team Keck Redshift Survey (TKRS; Wirth et al. 2004), and Vanzella et al. (2005). We use this as our low–*z* sample that represents the general galaxy population at $z = 1.2$. We also have information on the best-fitting spectral templates for these galaxies, derived as a by–product of the photometric redshift determinations based on the Bayesian method (Benítez 2000) using 10–band optical and near–infrared photometry for galaxies in the GOODS fields (Mobasher et al. 2004). From the spectroscopic sample at $0.95 < z < 1.5$, we have selected a subset of 292 galaxies whose SEDs are best fit by the starburst galaxy templates of Kinney et al. (1996). While choosing this subset, we only considered galaxies whose photometric redshifts agree with the spectroscopic redshifts to within 10%, in order to avoid errors in the spectral type fitting. This serves as our starburst galaxies sample at low–*z* for a fair comparison with the actively star-forming LBGs at $z > 2.5$ which have similar SEDs (Papovich et al. 2001).

In addition to the GOODS data, we have used the HUDF images obtained by using the Director's Discretionary time (S. Beckwith & collaborators) [10], in order to address issues related to selection biases and measurement errors. The HUDF overlaps with the GOODS-S field over a smaller area, $\approx$ 11.5 arcmin^2, and is about 2 magnitudes deeper than the GOODS data. The HUDF images have been obtained with the *HST*/ACS using the same filters, and processed using the same reduction pipelines as the GOODS images. Also, the HUDF images are on the same world co-ordinate system as the GOODS images, and have the same image scale of 0.″03 pixel^{-1}. Therefore, we apply the same color selection used to identify the LBGs in the GOODS fields to the HUDF data and perform the morphological analysis in exactly the same manner for the two datasets. The 1-σ isophote in the *z*-band corresponds to surface brightness of 25.46 magnitudes arcsec^{-2} and 27.60 magnitudes arcsec^{-2} for the GOODS and HUDF images respectively. Because the GOODS data provide a large statistical sample of LBGs, we mainly base our analysis on this dataset and use the HUDF data only to check for any systematic bias in the measured structural parameters.

[10] *http://www.stsci.edu/hst/udf*

3. MORPHOLOGICAL ANALYSIS

We measure the structural parameters of LBGs by modeling the two-dimensional (2-D) surface brightness distribution using a Sérsic function. The Sérsic function can be expressed in the analytical form, $\Sigma(r) = \Sigma_e exp\left[-\kappa\left((\frac{r}{r_e})^{1/n} - 1\right)\right]$. The flexibility of the Sérsic index, *n*, allows accomodation of exponential disks ($n = 1$), $r^{1/4}$ spheroids ($n = 4$), and the range of profile shapes in between. The 2-D surface brightness fitting was done using the *Galfit* software (Peng et al. 2002), which convolves the 2-D analytical models with the point spread function (PSF), and optimizes the fits using a Levenberg-Marquardt algorithm for χ^2 minimization. The output parameters include the object centroid, the total magnitude, the effective radius r_e, the profile shape or index, *n*, the ellipticity, ϵ, and position angle, θ. The initial guess parameters for the fits were provided from the SExtractor catalogs and all the parameters were allowed to vary during the fitting procedure. The value of *n* was constrained between 0.0 and 8.0, to avoid arbitrarily large values for LBGs with very compact, central point sources or active galactic nuclei. One of the main advantages of the 2-D analysis method is that it accounts for effects of the PSF in contrast to commonly used aperture-based measurements for morphological analysis (Abraham et al. 1996). The PSFs required for convolving the generated Sérsic models was derived from the observed field stars using the tasks available under the IRAF/*daophot* package. The noise maps required for computing the errors were generated from the variance maps produced during the drizzling process, and includes only the sky noise. The Poisson noise from the sources cannot be easily incorporated into the RMS maps because the drizzling procedure introduces pixel-to-pixel correlations. The 2–D fitting is weighted by the signal-to-noise per pixel, and sky noise dominates for most of the faint, high-*z* galaxies analysed here. The analysis is summarized in Figure 1 where we show the observed image, the 2-D model, and residuals, along with 1-D profiles which help to visualize the agreement between the observed and model light profiles. The scale of 0.″03 per pixel for the drizzled ACS images provides adequate sampling of the light profiles of LBGs which typically have half-light radii $< 0.''5$. We reject about 8% of the LBGs for which the 2–D fits give high values of reduced χ^2 ($\chi^2_\nu > 1.0$; the mean value of the χ^2_ν distribution is 0.45). We have visually examined the rejected galaxies and find that they are mostly close pairs, chain galaxies, and low surface brightness disks. The fraction of objects that are rejected from our analysis because they have large χ^2_ν, or the fits did not reach convergence is $< 10\%$ among the LBGs, and 15% at $z = 1.2$. Therefore, the results presented here are not significantly affected by the relatively small fraction of galaxies that are rejected.

The profile shapes of LBGs reveals the morphological diversities among these high-*z* star-forming galaxies as shown in

Figures 2 and 3. In order to perform the analysis consistently at the same rest-frame UV ($\sim 1400-1600$Å) wavelengths at all redshifts, we use the V, *i*, and *z* GOODS images for the LBGs at $z = 3, 4$, and 5 respectively. For the low redshift sample, we use the B images for which the central wavelength corresponds to rest-frame ≈ 1990 Å at $z \sim 1.2$, and is the closest wavelength that is available for comparison with the high redshift sample. Because the rest-frame morphologies of LBGs are known to be very similar at UV and optical wavelengths (Dickinson et al. 2000; Papovich et al. 2005), the comparison with the low-*z* sample at slightly longer wavelengths in the UV is not expected to bias our results significantly.

4. SELECTION BIASES AND MEASUREMENT ERRORS

4.1. *Selection of star-forming galaxies*

Ideally, while comparing the morphologies of star-forming galaxies at high and low redshifts, one would like to use samples with similar luminosties, sizes, and colors. This is important to distinguish the evolution in galaxy properties, from the trends that result from the correlations between galaxy properties. However, the LBGs and starbursts at $z \sim 1.2$ have different range of intrinsic UV luminosities. LBGs have high UV luminosities ($M^*_{UV} < -21.02$; Steidel et al. 1999) and the star-forming galaxies at $z = 1.2$ overlap with LBGs only at the faint luminosities; there are only three galaxies in the low–*z* sample that are brighter than $M_{UV} = -21$. The LBGs and $z \sim 1.2$ starbursts also differ in their intrinsic sizes. In the adopted cosmology (§ 2), the ratio of the physical size to angular scale changes only by small factor ($< 10\%$) from 7.63 kpc arcsec^{-1} at $z = 3.1$ to 8.29 kpc arcsec^{-1} at $z = 1.2$. But, the mean sizes of LBGs as measured in terms of the half-light radius is ~ 2.1 kpc which is only about 40% that of star-forming disk galaxies at $z \sim 1.4$ (Ferguson et al. 2004). Unlike for LBGs, the star-forming knots and merging clumps can be fairly easily distinguished within the disks with large scalelength at low-*z*. If the light from the star–forming knots and clumps in the low surface–brightness disk is more dominant, the model profiles can appear flatter than exponential ($n < 1$) as seen in the clump–cluster galaxies and chain galaxies reported by Elmegreen, Elmegreen, & Sheets (2004).

As discussed in § 2, we have selected the high–*z* LBGs at $z > 2.5$ and the low–*z* starburst sample at $z \sim 1.2$ by using different criteria to identify the actively star-forming galaxies at these redshifts. Therefore, differences are expected to exist between the two samples owing to the selection criteria, and due to the evolution of intrinsic properties of galaxies between the two epochs. There is evidence for possible evolution in the dust content and stellar populations between $z > 2$ and $z \sim 1$, as revealed by the increase in the internal UV–optical color dispersions at lower redshifts (Papovich et al. 2005). LBGs are selected based on their UV colors and are known to have very small internal UV-optical color dispersion. They have only low or moderate dust extinction, and are dominated by the young stellar population both at rest-frame UV and optical wavelengths. The low-*z* starbursts which are selected based on the template fitting to the UV-optical SEDs are likely to have large color gradients arising from higher dust obscuration, and larger range in the ages of the stellar populations. Therefore, the morphologies of the low-*z* starbursts may show some wavelength dependence, and the UV morphology may only trace the regions where most of the recent star-formation is located.

In spite of these intrinsic differences, a comparison of the high and low redshift star-forming galaxies is warranted in order to begin to understand how the configuration of star-forming galaxies have evolved with time. Our aim is to quantify what fraction of the active star-formation is centrally concentrated as opposed to star-formation in an extended disk in the two redshift regimes. As discussed above, the small differences arising from different methods of selection for the high–*z* and low–*z* samples are not likely to introduce a significant systematic bias in the profile shapes, and ellipticity measures which are used here for comparing the morphologies at $z > 2.5$ and $z = 1.2$.

4.2. *Errors on the structural parameters*

The reliability of morphological parameters derived from 2-D fitting of the galaxy light distribution depends critically on the signal-to-noise ratio (S/N) of the images. We have carried out extensive Monte-Carlo simulations to estimate the measurement errors and biases in the 2-D fitting, which vary with the signal-to-noise ratio of the images. The simulations were done using artificial optically–thin models of spheroids and disks with pure $n = 4$ and $n = 1$ profiles respectively, with uniform distribution of magnitudes (21-27 magnitudes) and half-light radii ($0.''01$ to $5.''0$), and random ellipticities and position angles. The artificial galaxies were convolved with the ACS PSFs and inserted into the observed GOODS ACS images, after adding Poisson noise. The galaxies were then re-detected, and 2-D analysis was done exactly as with the observed data. From the grid of uniform magnitudes and sizes used in the simulations, we extracted the results for galaxies whose magnitude–size distribution matched the observed LBGs, thereby accounting for the incompleteness arising from the surface brightness limit of the survey. The LBG samples used in our analysis (typically, apparent magnitude $m_{UV} < 26.6$, and half-light radii, $r_e < 0.''5$) do not suffer from severe incompleteness; we have verified that the GOODS data are complete down to lower surface brightnesses[11]. We have compared the input and recovered profile shapes and ellipticities to quantify the selection effects and measurement biases at the typical S/N for LBGs observed in the GOODS images. Most of the LBGs at $z \sim 3$ and 4 have S/N > 15 for which the simulations show that the parameters can be well-recovered, while some of the LBGs at $z \sim 5$ have S/N ≤ 10 and the derived parameters are likely to have large errors. We note that our simulations do not account for the effect of clumpiness or internal structure seen in real galaxies, but only provides an estimate of how the S/N affects the measured structural parameters.

Profile shape measurements: In Figure 4, we show the distribution of recovered *n* values from the Monte-Carlo simulations for $\sim 50,000$ galaxies which includes about equal numbers of $r^{1/4}$ spheroids (*black points*), and exponential disks (*red points*) and correspond to two fixed input values of *n* (4, and 1). Over the range of magnitudes and sizes observed among LBGs, the output *n* distribution for the simulated galaxies has mean value, $< n >= 3.83$, with dispersion $\sigma_n = 1.4$ for the spheroids, and $< n >= 1.1$ with $\sigma_n = 0.74$ for the disks. Although the output *n* distribution is broad and extends towards low values for the spheroids, it is possible to distinguish the two populations using $n > 2.5$ to classify the spheroids and

[11]The GOODS data release document contains plots showing the completeness of the survey in the magnitude–size plane. *http://archive.stsci.edu/pub/hlsp/goods/*

$n < 2.5$ for the disks. This broad classification of galaxy types does not suffer from strong biases arising from measurement errors. Our simulations show that the n values are well-recovered for the bright ($m < 25.0$ magnitudes), and large ($r_e > 0.''2$) galaxies. The mean difference, Δn, between the input and output n values for bright galaxies ($m < 25.0$) is -0.14 ± 0.39 for spheroids, and -0.004 ± 0.09 for the disk. At fainter magnitudes ($25 < m < 26$), Δn is 0.18 ± 0.83 for the spheroids and 0.02 ± 0.20 for the disks. For large sizes ($r_e > 0.''2$), Δn = -0.11 ± 0.48 and 0.017 ± 0.16 for spheroids and disks respectively. For small sizes, the scatter increases considerably only at the fainter magnitudes, $25.0 < m < 26.0$.

Ellipticity measurements: The results from a similar test for the biases in the measured ellipticities is shown in Figure 5. For both spheroids (*black points*) and disks (*red points*), the input axial ratios are well–recovered for almost all ellipticities, over the range of S/N seen for the LBG sample. We find from the simulations that for the low input ellipticities ($\epsilon < 0.2$), the measured values tend to scatter to higher ϵ. At very high ellipticities of $\epsilon > 0.8$ a small fraction of the measurements tend to be scattered to lower values. These biases are significant for galaxies with small radii and faint magnitudes, for which the photometric errors tend to scatter objects away from the extreme limits that the axial ratios ($b/a = 0$ and 1) can have. As seen from Figure 5, the ellipticities can be reliably measured for the range of observed magnitudes ($24 < m < 26$) and sizes (typically $0.''1$ - $0.''5$) among LBGs. The mean difference between the input and output ϵ values, $\Delta\epsilon$, is $\approx 0.0013\pm0.02$ for the spheroids, and 0.0014 ± 0.02 for disks with $m < 25.0$ magnitudes. The $1-\sigma$ scatter increases to ~ 0.05 for fainter magnitudes. For large galaxies ($r_e > 0.''2$), $\Delta\epsilon = 0.005\pm0.03$ for spheroids and disks, while for smaller sizes $\Delta\epsilon = 0.007\pm0.05$ for spheroids and 0.001 ± 0.03 for disks.

We have also compared the ellipticities derived through the 2-D modeling procedure to the ellipticities derived by the SExtractor software used for object detection. We find that the measurement biases are much smaller for ϵ from the 2-D modelling procedure (Figure 6). The ellipticities provided by SExtractor are directly measured using the second moments of the image pixels within the isophotal limit of a detected object. These ϵ measurements are systematically underestimated at small radii ($< 0.''5$) because they do not account for the effects of PSF convolution. Similarly for galaxies with large radii, the light distribution is artificially truncated by the chosen isophotal detection threshold. The ϵ measurements at faint magnitudes ($m > 25$) are also significantly underestimated. The ability to account for the PSF effects in the parametric 2-D models, results in a better estimate of the projected axial ratio for the LBGs whose sizes are often comparable to the size of the PSF. Secondly, the 2-D analytical profiles extends to about five times the half-light radius, which is beyond the truncation set by the detection threshold isophote used by SExtractor, thereby allowing to estimate the shape parameters more accurately.

4.3. *Effect of surface–brightness dimming at high redshifts*

The ability to derive the morphological parameters is clearly dependent on the signal-to-noise (S/N) ratio of the images. As a result of the $(1+z)^4$ cosmological surface–brightness dimming, the S/N in the wings of the galaxy light profiles decreases rapidly for the high–z galaxies. The light profiles have high S/N out to larger radii for the low–z galaxies compared to the LBGs, and this may bias the measured parameters. An empirical assessment of the severity of this effect can be obtained by comparing the structural parameters measured from the GOODS images to that from the much deeper HUDF images for the galaxies that overlap in the two fields. The 1-σ isophote of the GOODS images correspond to a surface brightness of 25.5 magnitudes arcsec^{-2} in the z-band, while for the HUDF it reaches a much fainter isophote which corresponds to 27.6 magnitude arcsec^{-2}. The depth of the HUDF almost compensates for the surface brightness dimming from $z = 1.2$ to $z = 3$, and allows us to assess the impact on the measured parameters for real galaxies with internal structure such as, spiral arms, star-forming knots, and dust. In other words, a comparison of the structural parameters measured from GOODS and from the HUDF for the same galaxies shows how the measurements would change if the $z = 3$ galaxies were observed to the same outer isophotal limit as the $z = 1.2$ galaxies in GOODS. In Figure 7, we show the comparison of structural parameters derived from GOODS and the HUDF for 760 galaxies common to both fields, as a function of the average S/N in the GOODS image. We also show the comparison for LBGs at $z = 3$ (*blue triangles*), $z = 4$ (*green triangles*), and $z = 5$ (*red triangles*) in the F606W, F775W, and F850LP bands respectively, which corresponds to the rest-frame ~ 1600 Å at these redshifts. We find that the magnitudes and sizes that are measured from the GOODS and HUDF images agree to within $< \Delta m(UDF-GOODS) >= 0.09$ magnitudes and $< \Delta\log r_e(UDF-GOODS) >= 0.002$ with dispersions of $\sigma\Delta m = 0.31$ and $\sigma\Delta\log r_e = 0.11$. There is also good agreement in the profile shapes and ellipticities, $< \Delta n(UDF-GOODS) >= -0.06$ with $\sigma\Delta n = 0.72$, and $< \Delta\epsilon(UDF-GOODS) >= 0.03$ with $\sigma\Delta\epsilon = 0.20$. Contrary to the expected behaviour, we find that at low S/N (< 15) the n values, and r_e is higher in the GOODS images compared to the HUDF images. Visual examination of the galaxies for which $\Delta n(UDF-GOODS) < -2$ show that they mostly appear to have two or more close companions on the GOODS images. However, in the deeper HUDF data they have a common envelope at the fainter isophotes, and are revealed as a single object. In few other cases, only a few of the central pixels in the GOODS images have sufficient S/N, and the fit is weighted by these pixels resulting in a best–fit model which has high n and r_e. The overall agreement between the two datasets shows that at least for the bright LBGs used in the present analysis, the S/N is sufficiently high out to a few scalelengths (with S/N > 15) to provide a reliable measure of the structural parameters. Therefore, it appears that the measurements from the 2-D analysis used here are not severely biased, even though the the $< S/N >$ is sufficiently high over a larger radial extent for the galaxies at low–z compared to that at high–z.

4.4. *Restframe UV morphology of local galaxies sample*

The Hubble sequence of galaxy morphologies used to classify nearby galaxies is primarily based on the observed rest-frame optical properties, and cannot be directly adopted to describe the rest-frame UV morphology. This is because the morphological k–correction is significant for local galaxies where the bulge and disk components are known to have stellar populations with widely varying ages, metallicities, and dust content (Kuchinski et al. 2000, Giavalisco et al. 1996). The appearance of late-type galaxies (Sc and later) are similar in the optical and UV images, because star-forming regions dominate at both wavelengths. Early-type spiral galaxies (Sa-Sbc) tend

to be classified as later types because the bulges and/or bar components, which are pre-dominantly made of evolved stellar populations, become extremely faint with respect to the disk component in the UV. Ellipticals on the other hand retain their smooth appearance, but are generally more compact in the UV.

In order to relate the observed UV morphologies of high redshift galaxies to that of regular Hubble types seen among local galaxies, we carried out simulations using the rest-frame UV images of nearby galaxies observed by the Galaxy Evolution Explorer (GALEX; Martin et al. 2004). We used 15 galaxies covering the range of Hubble types from E to Sd which were observed as part of the Nearby Galaxies Survey (Bianchi et al. 2004). Our aim is to find whether the high redshift galaxies exhibit the same range of morphological types, and to examine the effect of low S/N and low spatial resolution on the rest-frame UV morphologies. In the simulations, the GALEX images were redshifted to $z = 1.2$ and $z = 3$ by applying the required surface brightness dimming and reduction in angular sizes as described in Lotz et al. (2005). The images were convolved with the ACS PSFs, and then added to a sky template created from the GOODS ACS images to account for the typical background and noise characteristics of the *HST* images.

Most of the redshifted nearby galaxies are difficult to detect on the ACS images, since the local star-forming galaxies are mostly late-type, sub-L* galaxies at UV wavelengths ($M_{UV} > -18$ magnitudes). The LBGs at $z > 2.5$ that are observed in the ACS images are luminous galaxies, typically $M_{UV} < -21$ magnitudes, with high UV surface-brightness. Therefore, it is important to account for the intrinsic luminosity and size evolution with redshift in the simulations. As a close approximation, we boosted the brightness of the simulated images and allowed for size evolution based on the published UV luminosity evolution (Arnouts et al. 2005) and size evolution (Ferguson et al. 2004) from $z = 0$ to 3. Recent results from GALEX provide the luminosity function at rest-frame ≈ 1500Å at low–z from $z = 0$ to 0.1, with $M^*_{UV} = -18.04 \pm 0.11$ magnitudes (Wyder et al. 2005). The value of M^*_{UV} brightens by 2.0 magnitudes between $z = 0$ and $z = 1$, and by 1.0 magnitude from $z = 1$ to $z = 3$ (Arnouts et al. 2005). The half-light radii of LBGs at $z > 2.5$ (Ferguson et al. 2004) is on average about 1/3 of that observed for local UV luminous galaxies (Heckman et al. 2005). By incorporating the above luminosity and size evolution, if the surface brightness of the redshifted nearby galaxies is boosted by ≈ 3.0 magnitudes, they become visible on the ACS images (except M82). Many of the LBGs at $z > 2.5$ (Figure 2 & 3) appear to have local analogues (Figure 8) in terms of morphology, albeit with much lower surface brightness.

We performed the 2-D analysis on the redshifted GALEX UV images at $z = 1.2$ and $z = 3$ using Sérsic function as was done for the LBGs. A comparison of the morphologies derived at the two redshifts are largely consistent (Table 1) between the two redshifts, implying that the measured n and ϵ are not severely biased because of the lower S/N and lower spatial resolution at these redshifts. However, the morphologies inferred from the n values is significantly different from that expected for the Hubble types of the nearby galaxies used in the simulations. None of the redshifted galaxies have the steep profiles observed for local spheroids, and only two galaxies (NGC 1399 and NGC 1068) with significant UV emission in the bulge have $n > 1.5$. It is important to note that the local galaxies host a spheroid component that is dominated by the redder old stellar populations, and the classical $r^{1/4}$ spheroids are not seen among their GALEX morphologies. Therefore, galaxies with early-type optical morphologies tend to be classified as later type at rest-frame UV wavelengths. For example, a bulge-dominated spiral, such as M81 with Hubble type SA(s)ab, would be classified as late-type based on its UV morphology, due to the negligible contribution from the bulge component. If LBGs have color gradients like that seen in local galaxies, our redshifted local galaxy sample suggests that we would be biased against $n = 4$ (bulge) profiles. However, this is not likely to be the case for LBGs because there is no clear evidence for significant internal color dispersion (Papovich et al. 2004). Even the spheroidal component, if it exists, is expected to be young at these very early epochs. This makes it difficult to directly map the UV morphologies at high-z to the regular Hubble types seen locally, although as discussed in § 4.2, the measured profile shapes will allow us to quantify the fraction of young spheroids among the high-z galaxies.

5. RESULTS

The profile shape, n, and the ellipticity, ϵ, provide different perspectives about the morphological diversity among a galaxy population. The profile shape is sensitive to the presence of a bulge or degree of central concentration in an individual galaxy. The ellipticity distribution, on the other hand, is useful in a statistical sense to determine whether the population is, on average, disk-like, oblate, prolate, or triaxial. Our analysis is restricted to the brightest LBGs ($L > 0.5L^*_{UV,z=3}$), where $L^*_{UV,z=3}$ is defined in terms of the characteristic luminosity of LBGs at $z = 3$ as in Steidel et al. (1999; $M^*_{UV} = -21.02$). Therefore, out of the ~ 4700 LBGs detected at redshifts $z > 2.5$, only 1333 of them with $M_{UV} < -20.5$ are included in the analysis. This ensures that the sample does not suffer from incompleteness and has the sufficient S/N to be able to yield reliable measurements for the LBGs available in the GOODS images.

5.1. *Profile shapes of LBGs at rest-frame UV wavelengths*

A visual inspection reveals that LBGs exhibit a wide range of morphologies (Figures 2 and 3), as also seen from the large range of measured Sérsic indices. The observed distribution of Sérsic indices for LBGs is shown in Figure 9. Since all the ACS bands sample the rest-frame UV light for the LBGs at $z > 2.5$, the derived n values are not expected to be very different in the various bands. We checked the derived n values with that for longer wavelengths in order to verify the robustness of the fit. We adopt a simple quantitative morphological classification based on the profile shapes implied by n. We identify the following galaxy types; $n > 4$ are centrally-concentrated, steep profile galaxies, $4.0 > n > 2.5$ are spheroid-like, $2.5 > n > 0.8$ are exponential or disk-like, and $n < 0.8$ which appear to have clumpy morphology. The fraction of galaxies belonging to the different morphological types is listed in Table 2. From the Monte–Carlo simulations it is clear that the recovered n values (Figure 9) for the spheroids with $r^{1/4}$ profile (*red dashed line*) show a large spread, but generally have $n > 2.5$ while the exponential disks have a narrow distribution around $n = 1$ (*blue dashed line*). We adopt the $n > 2.5$ criteria to distinguish spheroid-like galaxies from disk-like galaxies, which is also the classification used for low-z galaxies in the SDSS (Shen et al. 2003). Close to about 30% of the galaxies have bulge-dominated profiles with $n > 2.5$ that are as steep as the low-z bulges. Almost 40% of the LBGs at $z \sim 3$ can be fit by exponential light profiles ($2.5 > n > 0.8$) over the spatial scales (resolution ~ 700 parsecs) probed by the ACS images simi-

lar to the disk-dominated galaxies. Note that our classification into spheroids and disks is based exclusively on the value of n. Such galaxies can, and indeed many do, show clumpy or asymmetric features characteristic of tidal interaction or minor mergers. Nevertheless, they are not disrupted to the extent that the overall profile shape has departed from the normal disk and spheroid morphologies observed locally. A significant fraction (30%) of the LBGs have surface brightness profiles that are shallower than an exponential profile ($n < 0.8$). A visual examination of these galaxies show that they often have multiple cores, tadpole, or chain morphology. This class also includes diffuse, low surface-brightness galaxies which lack a prominent central concentration. We group the galaxies with $n < 0.8$ as a separate class to distinguish them from galaxies which have a well-defined central peak in their light profiles. Similar types of galaxies with low n or flatter than exponential profiles have also been identified previously in deep *HST* surveys (Marleau & Simard 1998; Elmegreen, Elmegreen, & Sheets 2004; Elmegreen, Elmegreen, & Hirst 2004; Elmegreen & Elmegreen 2005).

The fraction of LBGs with spheroid-like profile is higher by $\approx$ 15% at $z \sim 5$ than at $z \sim 3$. We examined the images of these LBGs and found that they have a dominant central core with a diffuse halo, and have tadpole-like morphology in some cases. Based on the simulations, it appears that the increase in the fraction of bulges at $z \sim 4$ compared to $z \sim 3$ is not due to measurement bias, because these LBGs typically have S/N > 15. The measurement bias can be important for the $z \sim 5$ LBGs, most of which have S/N ≈ 10 and the errors in the measured parameters become large. At $z \sim 5$, the typical observed magnitudes are $z_{850} > 26$ AB magnitudes, and the simulations show that the incompleteness for the detection of low–surface brightness disks is larger than for the spheroids (§ 4.2). Hence, the morphologies at $z \sim 5$ is likely to be biased in favor of the spheroids that have higher surface brightness than disks.

The distribution of n for the low–z sample at $z \sim 1.2$ galaxies is also shown in Figure 9, and the fraction of galaxy types based on n is listed in Table 2. Only 20 galaxies at $z \sim 1.2$ have $M_{UV} < -20.5$ which is the magnitude limit we have used for the LBGs. The small numbers among the low–z starbursts with overlapping UV luminosities is likely to be due to the luminosity evolution by ≈ 1 magnitude from $z > 2.5$ to $z \sim 1.2$. In order to define the low–z sample along the same lines as we have done for the LBGs, we use a sample of galaxies and starbursts at $z \sim 1.2$ which are brighter than 0.5 L^*_{UV} defined at $z \sim 1.2$, for which M^*_{UV} = -20.04 (Wyder et al. 2005; Arnouts et al. 2005). Therefore, we restrict the analysis at $z \sim 1.2$ to galaxies and starbursts with $M_{UV} < -19.3$. The overall population is dominated by disk-like or low concentration ($n < 2.5$) systems at $z = 1.2$ as is also the case for LBGs at high-z. However, the distribution of n values for the galaxies at $z = 1.2$ is more skewed towards lower values implying that most of the galaxies are irregulars, mergers, or low surface brightness galaxies. These are similar to the "Luminous Diffuse Objects" (LDO's) at $1 < z < 2$ reported by Conselice et al. (2004). We also show separately in Figure 9 the n distributions for the sub-sample of starburst galaxies at $z \sim 1.2$, which as mentioned in § 2 are the likely low-z analogues of LBGs. We find that the distribution for starbursts is very similar to that for the entire $z \sim 1.2$ population taken together. Although the overall UV–bright galaxies population at low–z and high–z appear to dominated by disk-like morphologies, a Kolmogrov–Smirnov (K–S) test shows that the $z > 2.5$ LBGs are a different population than the UV–bright starbursts at $z = 1.2$ at a high significance level (Table 3). The difference arises mainly from the larger fraction of steep–profile sources among the LBGs. Adopting a broad classification of galaxy types into spheroid-like profile sources with $n \geq 2.5$, their fraction increases from $\sim$ 15% at $z \sim 1.2$ to about >25% at $z > 2.5$. In order to verify whether the decrease of spheroid-like sources at low-z is because of morphological k–correction, we compared the n values derived for the $z \sim 1.2$ sample in the F435W (rest-frame UV) and the F850lp (rest-frame B) images. We find that the fraction of $n > 2.5$ galaxies is almost the same in both cases, implying that we are not missing significant numbers of the low-z bulges with evolved stellar population by using the rest-frame UV for our analysis. However, for the more shallow ($n < 2.5$) profile sources, such as, exponential disks, and merger or irregulars, their fraction decreases from $\sim$ 80% at $z \sim 1.2$ to about $\leq$ 70% at $z > 3$. The flattening of the profiles at the lower redshift may be because of reduced star-formation in the bulge, and the UV emission is mainly from the individual star-forming clumps that are fairly resolved within these disks which have scalelength more than twice that of LBGs at $z > 3$.

5.2. *Distribution of ellipticities*

In Figure 10, we present the distribution of ellipticities for the luminous LBGs and for the low-z samples. For comparison, the distribution of ϵ for local galaxies from Lambas, Maddox, & Loveday (1992) is also shown which is the sum of 2135 ellipticals and 13482 spiral galaxies from the APM survey. Clearly, the population of $z \sim 1.2$ objects have ϵ distribution that closely matches that for local galaxies. But for the LBGs at $z > 2.5$, the ϵ distribution is skewed towards higher ellipticities. Interestingly, the peak of the ellipticity distribution shifts from $\epsilon \sim 0.7$ at $z > 4$ to $\epsilon \sim 0.5$ at $z \sim 2.5$. We also show in Figure 10, the input and output ellipticity distribution from Monte Carlo simulations using galaxies with pure $n = 4$ and $n = 1$ profiles. The simulations show that for galaxies having (S/N) typical of our LBG sample, there is no significant measurement bias or selection effects that can cause the skew that is observed for the LBG ellipticity distribution.

In Figure 11, the ellipticity distributions are shown separately for the steep profile sources ($n > 2.5$) which we refer to as spheroid-like, and the shallow profile sources ($n < 2.5$) which we refer to as disk-like. For comparison, the ellipticity distribution for local spheroids (*red dotted curve*) and disks (*blue dotted curve*) from Lambas, Maddox, & Loveday (1992) are also shown separately in each panel. Overall, majority of the LBGs have large ellipticities independent of the profile types. Even the LBGs with $n > 2.5$ have high ϵ contrary to that seen for the spheroids in the local Universe. In the local Universe, such a skewed distribution has been observed only for populations of edge-on disk galaxies with very small intrinsic b/a, as in very late Hubble types, T $\geq$ Sd (Odewahn et al. 1997; Alam & Ryden 2004; Ryden 2004). At intermediate and high redshifts, a peaked ellipticity distribution with large ellipticities has been reported for chain galaxies (Cowie et al. 1995; Dalcanton & Shectman 1996; Elmegreen, Elmegreen, & Hirst 2004). Elmegreen, Elmegreen, & Hirst (2004) find that chain galaxies, which usually have large ellipticities, are likely to be clumpy galaxies viewed edge-on. Given that the LBGs are viewed at random orientations, the scarcity of low ellipticity, face–on galaxies imply that the majority of LBGs have an intrinsic shape which is preferably prolate or filamentary. In our

analysis, LBGs with clumpy, chain-like morphology have low n values, typically $n < 0.8$. In order to check whether the observed skewed distribution is dominated by the chain galaxies in our sample, we examined the distribution for the LBGs with $n > 0.8$. In Figure 11, we show the distribution of ϵ for the LBGs with nearly exponential profiles ($2.5 > n > 0.8$) separately, in order to distinguish them from the chain-like LBGs with $n < 0.8$ (*magenta histogram*). It appears that the skewness towards high ϵ for the LBGs is not dominated by the chain-like morphologies, and even the spheroids ($n > 2.5$) and nearly exponential disks ($2.5 > n > 0.8$) show the prominent skew towards $\epsilon > 0.5$.

The ϵ distribution for the spheroids ($n > 2.5$), and disks ($n < 2.5$) among the galaxy population at the lower redshift of $z \sim 1.2$ is consistent with the spheroids and disks in the APM survey. When the UV-bright starbursts at $z \sim 1.2$ are considered separately, the distribution for the $n < 2.5$ galaxies is fairly consistent with that for the local spirals. The starbursts at $z \sim 1.2$ with $n > 2.5$ have a flatter ϵ distribution than for the local spheroids. In either case, the $z \sim 1.2$ distribution does not have the skew towards higher ϵ as seen in the case of LBGs, which implies that there is a significant evolution in the overall morphology of star-forming galaxies from $z > 2.5$ to $z \sim 1.2$. A K–S test gives low probability that the $z \sim 1.2$ starbursts and LBGs are drawn from the same parent population (Table 3).

6. DISCUSSION

6.1. *Morphological Diversity among LBGs*

We have used the deep, high spatial resolution images for a subsample (≈ 1333) of the brightest LBGs which were selected from the large sample of 4700 LBGs available for the first time from GOODS, in order to characterize their morphologies in a statistical sense, and to look for morphological evolution among star-forming galaxies from $z = 5$ to $z = 1.2$. We find that more than half of the LBGs have surface brightness profiles that can be represented by the $r^{1/4}$-like and exponential profiles commonly used for normal galaxies at low redshifts. The overall LBG population at all redshifts, $z > 2.5$, is dominated by the extended disk-like galaxies and irregulars or merger-like systems ($\approx 70\%$), and only about 30% have spheroid-like profile shapes. It is interesting to note that previous studies have suggested that the LBGs are predominantly spheroids. Giavalisco, Steidel, & Macchetto (1996) used a similar analysis of the surface brightness profiles and found that the luminous LBGs exhibit a wide range of morphologies, but is dominated by spheroid-like morphology with $r^{1/4}$ light profiles. We note that the earlier study was based on small sample of about few tens of the brightest LBGs. From our analysis, we find a correlation between the morphology and luminosity of LBGs, such that, the more luminous LBGs have steeper profiles. Also, their study was done using images with $0.''1$ spatial sampling, as opposed to the present analysis which is based on a much larger sample, and uses images with higher sensitivity that offers higher S/N and better spatial sampling ($0.''03$). Morphological analysis based on the concentration index measured from GOODS images have also suggested a higher fraction of spheroids among the $z = 4$ LBGs (Ferguson et al. 2004). Unlike in the 2-D surface brightness analysis, the concentration index measurement does not account for the PSF convolution, and is measured in terms of the ratio of the flux in fixed apertures which are limited by the radial extent of the galaxy profile above the detection isophote. This may partly explain the difference between the morphologies inferred from our 2-D analysis and those presented in Ferguson et al. (2004) using the GOODS data.

We have checked for consistency between the morphological types based on other measurements and that infered from the present analysis using the same set of GOODS images. We have compared the n values and the concentration indices (Conselice et al. in preparation) measured for LBGs used in this study, and find that there is a correlation between the two parameters but with considerable scatter. We have also compared the n–based morphological types against the independent analysis based on the Gini coefficients (Lotz et al. 2005) for the $z \sim 4$ LBGs in the GOODS data. We find that the classifications are fairly consistent in terms of the morphological class that is assigned and the fractions derived for the various galaxy types. The merger fractions that we find for the LBGs at $z > 2.5$ is consistent with the results from other studies (Conselice et al. 2003, Lotz et al. 2005). Lotz et al. (2005) found that about 30% have fairly undisturbed bulge-like morphologies, $\sim$ 10–25% are likely to be major mergers, and the remaining $\sim 50\%$ are likely to be exponential disks or minor mergers. This is consistent with the fraction of morphological types that we find based on profile shapes. However, we note that our method of analysis cannot unambiguously quantify the fraction of major mergers among the LBGs, because the class of galaxies with very shallow ($n < 0.8$) light profiles include a mix of galaxy types, such as, major mergers, low surface brightness galaxies, and disks with clumpy star formation. Even the LBGs whose profiles are broadly described by the $r^{1/4}$ law, or the exponential profile do show signatures of minor mergers and tidal interactions. We find that based on the profile shapes alone, the fraction of UV-bright spheroid-like LBGs decreases from 44% at $z \sim 5$ to about 27% at $z \sim 3$, and only 16% of the UV-bright starbursts at $z \sim 1.2$ have profile shapes similar to that of spheroids. Lotz et al. (2005) also find that there are fewer spheroids among the starbursts at $z \sim 1.5$, compared to the $z = 4$ LBGs, but the fractions of mergers and transition objects do not show significant evolution in this redshift range. We find a similar result that the fraction of $n < 2.5$ galaxies are comparable at $z \sim 1.2$ and $z \sim 3$.

As discussed in § 5.2, the ellipticity distribution for LBGs does not resemble the distribution seen among local spheroids and disks, and is clearly skewed towards larger ellipticities ($\epsilon > 0.5$) at $z = 3, 4$, and 5. This result is particularly interesting because it implies an intrinsic shape distribution that is unique for the galaxy populations at high redshifts. In particular, the high ellipticities of the LBGs that have the centrally concentrated profiles is in stark contrast to the low ϵ that is typically seen for low-z spheroids, suggesting that the spheroids at $z > 2.5$ are intrinsically more elongated than the local spheroids.

The peak of the ellipticities of the LBGs tends to shift toward lower ϵ with decreasing redshift, from ~ 0.7 at $z = 5$ to 0.5 at $z = 3$. As discussed in § 5, even if possible chain or merger–like morphologies are excluded, the LBGs with exponential disk-like profiles have the skewed ellipticity distribution which appears to evolve with redshift. Interestingly, at $z = 4$, the ϵ distribution for the exponential disk-like LBGs, closely match that of the merger-like galaxies and have the same peak ϵ value (~ 0.7). At $z = 3$, the LBGs with disk-like profiles peak at lower ϵ (~ 0.5) and the distribution begins to depart from the highly skewed distribution which peaks at $\epsilon = 0.7$ for the shallow profile or merger-like galaxies. These may be the initial signatures of the transformation from a predominantly clumpy

or merger morphology at $z = 4$ to more smooth disks at $z = 3$, which finally evolves to the relatively flat distribution at $z \sim 1.2$ that resembles the local Hubble type spirals more closely. From our simulations (§ 4), it does not appear that the observed evolution of ellipticities is likely to be due to selection effects or measurement biases. Although, there is a tendency for small ellipticities ($\epsilon < 0.1$) to be scattered to slightly higher values, that alone does not seem to account for the large skew that is observed at high redshift.

6.2. *Implications for Galaxy Formation Scenarios*

Ever since their discovery a decade ago, the morphologies of LBGs have been a topic of great interest and speculation. Are they proto-elliptical galaxies? Are they young disks? Are they mergers in progress? Some of the observed LBG properties, such as comoving number densities, sizes, and LBG clustering have led to interpretations that they may reside in the most massive dark matter halos ($M \geq 10^{12} M_{\odot}$), and may be the direct progenitors of present day massive ellipticals and spheroids (Steidel et al. 1996; Giavalisco, Steidel, & Macchetto 1996; Adelberger et al. 1998; Steidel et al. 1998; Giavalisco et al. 1998; Giavalisco & Dickinson 2001; Porciani & Giavalisco 2002; Adelberger et al. 2005; Lee et al. 2005). The present analysis shows that the fraction of spheroids among the LBGs is about 30%, and their high ellipticities compared to the spheroids at low-z make them a unique population at $z > 2.5$. A visual inspection of the LBGs which have close to $r^{1/4}$ or steeper light profiles shows that in most cases there is a bright core which has elongated isophotes and diffuse halo around it, and some have double–nuclei, while a significant fraction show tadpole-like morphology. Thus, it appears that these are not relaxed systems and are likely to be protobulges that are undergoing minor mergers. The young bulges seen among the LBGs may have assembled from merging of massive clumps ($M \sim 10^9 M_{\odot}$) that form from gravitational instabilities in gas-rich disks of young galaxies (Noguchi 1999). The appearance of the primeval disks in this case is expected to be similar to chain galaxies, with clumpy star formation in elongated disks. The semi-analytical models of hierarchical galaxy formation by Somerville, Primack, & Faber (2001) suggest that LBGs are collisional starbursts triggered by mergers and are expected to be merger-like systems or bulgeless disks. The fraction of such likely mergers or clumpy galaxies ($n < 0.8$) among our LBG sample, is significantly large, about 30%, and they can end up in ellipticals or bulges of spirals at lower redshifts. We find that more than half of the LBG population at $z > 2.5$ comprise of disk-like and minor mergers; a similar result was also obtained by Lotz et al. (2005) for the $z = 4$ LBGs. There is an observed decrease in the fraction of bulges ($n > 2.5$) from 35% at $z \sim 4$ to 27% at $z \sim 2.5$, and 16% at $z \sim 1.2$ which is not likely to be due to selection effects (see § 4). This may reflect a transformation among the galaxy types, as the spheroids accrete gas and rebuild disks around them (Steinmetz & Navarro, 2002). In fact, most of the spheroids do show halos around their compact cores, and tadpole-like morphologies which suggest on-going minor mergers and formation of disk-like structure.

Mo, Mao, & White (1999) have discussed the expected morphological diversity among LBGs within the framework of disk formation in hierarchically merging cold dark matter halos (Fall & Efstathiou 1980), and adopting the star formation law from Kennicutt (1998). The range of morphologies in their models is dictated by the angular momentum distribution of the dark matter halos which is usually expressed in terms of the spin parameter. These models suggest that since LBGs have high gas-densities and star formation rates, they are likely to reside in dense halos with low spin parameters. The gas in these halos becomes self-gravitating before it can settle into a centrifugally supported disk. In such cases, LBGs would have compact, and less flattened, spheroid-like morphologies. We find that the observed LBG morphology shows a broad range of ellipticities and profile shapes which imply that LBGs are not preferentially located in low the spin halos.

One of the main results from the present analysis is the dominance of elongated morphology among the LBGs. The light profile shapes also suggest an extended configuration for the LBGs which are predominantly exponential disk-like galaxies, merger-like galaxies, or have clumpy morphology. Interestingly, even the galaxies with high central concentrations and close to $r^{1/4}$ light profiles, have significantly flattened intrinsic shapes contrary to that observed locally. The peak at high ellipticity ($\epsilon > 0.5$) for LBGs effectively rules out the possibility that LBGs are drawn from a population of circular disks or a population of oblate spheroids. Intrinsic shapes that are, to first order, prolate or triaxial, would be required to account for the observed peak and skew of the ellipticity distribution. The observed excess of flattened LBGs seen at high redshift suggests various possibilities about the morphology and dynamics of these star-forming galaxies; they may be rotating disks, or star-forming clumps that are formed along filamentary gas inflows in dark matter halos, or they may be gas–rich bars that essentially encompass the entire galaxy.

6.2.1. *Rotationally-supported disks at High-z*

We find that the dominant disk–like morphology alone cannot explain the excess of high ellipticity LBGs, unless the sample is severly biased against face-on disks close to the survey detection limit. Our simulations show that this is not the case for the bright LBGs used in the present analysis. Moreover, the ellipticity distribution in the presence of such a bias is expected to show a much faster fall-off (Elmegreen et al. 2005), than the gradual fall-off at low ellipticities observed for the LBGs. Without the kinematic information it remains unclear what fraction of the LBGs with elongated morphology are rotationally-supported disks. The rotation curves derived from spectroscopy of the optical emission lines for small samples of LBGs suggest that there may be rotating disks among them (Pettini et al. 2001; Moorwood et al. 2000). Recently, Erb et al. (2003) have obtained kinematic data for a sample of color-selected, star-forming galaxies at $z \sim 2$ which have extended, disk-like morphology in the GOODS ACS images. Although, the slits were aligned along the galaxy elongation in most cases, only two of the 13 galaxies in their $z = 2$ sample showed evidence for tilted emission lines that could be attributed to rotation. Thus, elongated morphology may not necessarily imply rotating disks. Interestingly, Erb et al. (2003) report a correlation between the velocity dispersions and morphologies, such that the more elongated galaxies have smaller velocity dispersions. If the same relation holds true for LBGs, then this implies that while some fraction of the LBGs may be rotating disks, it is likely that most are not. The available kinematic studies of high-z star-forming galaxies suggests that an alternate explanation, such as, filaments or bars with active star-formation may be required to account for the excess of elongated morphologies observed among the LBGs.

6.2.2. *Star-forming clumps along gas-rich filaments*

According to recent hydrodynamical simulations of galaxy formation (Keres et al. 2005; Birnboim & Dekel 2003; Dekel & Birnboim 2005), the gas within dark matter halos that have masses lower than a critical mass ($M_{halo} \sim 10^{11.4} M_{\odot}$) does not get heated close to the virial temperatures ($\sim 10^6$ K), and cool by radiative process to form galaxy disks as suggested by the standard disk formation models (White & Rees 1978; Fall & Efstathiou 1980). Instead, in these halos the gas may be accreted into disks through cold flows ($< 10^5$ K) along filamentary structures. The dominant mode of accretion at any redshift is determined by the critical halo mass which evolves with redshift. At high redshifts ($z > 3$), the cold mode of gas accretion which occurs along filamentary structures within the virial radius of the dark matter halos is found to be dominant (Keres et al. 2005). Both cold and hot accretion modes become important at intermediate redshifts, and the hot mode begins to dominate as the mass scale of galaxies increases at low redshifts ($z < 1$). While existing models make no specific predictions regarding morphology, one of the observational signatures of this transition is likely to be a change in the ellipticity distribution. If at $z > 3$, most of the mass assembly occurs through cold mode accretion along filaments down to individual galaxy scales, followed by star formation in massive clumps within the filaments, we would expect the galaxy to be elongated with the major axis directed along the filament. At lower redshifts $z \sim 1$, the galaxies may evolve towards a broader range in axial ratios with the lower ellipticities resulting from the hot mode accretion, mergers, and bulge formation. The observed peaked ellipticity distributions for LBGs at $z > 3$, and the evolution in the shapes of star-forming galaxies between $z > 3$ and $z \sim 1.2$ in our study, appear to be in concordance with this picture.

6.2.3. *Bars at redshifts* > 2.5

To further investigate the origin of the skewness in the ellipticity distribution we have visually examined galaxies with ellipticities between 0.6 and 0.9, the range where there is an excess compared to the present day distribution. Some fraction ($\sim 10\%$) are clearly mergers but a very qualitative examination of the images shows that roughly 20% of these objects have features typical of bar morphology. A further 30% could be consistent with a bar origin, or clumpy bars similar to those found at $z \sim 1$ in the ACS survey of the Tadpole galaxy field (Elmegreen, Elmegreen, & Hirst 2004). A few example cases of likely bars or bar–signatures among LBGs is presented in Figure 12. Unlike the classical bars seen locally, the light distribution in some cases do not appear symmetric due to on-going star formation. Some LBGs show enhancements of star formation at the bar ends and at the galaxy center, both classic bar signatures observed in low-z galaxies. The presence of a classic bar morphology in the UV comes as a surprise, because the bars observed in local galaxies usually have red optical colors. Although present-day barred galaxies show suppressed star formation in the bar, owing to gas shear, one expects a higher gas fraction at early times, which has the potential to promote star formation throughout the bar. Furthermore, as we mentioned previously, the much younger stellar populations at these redshifts means that there is no morphological *k*–correction, i.e. galaxy morphologies appear the same in the rest-frame optical and UV bands (Dickinson 2000, Papovich et al. 2003). The above bar fraction ($\sim 50\%$), combined with the significant but smaller fraction of mergers, chains, and edge-on galaxies, is sufficient to explain the observed excess of elongated systems.

In most cases the bar appears to contain all the stars in the galaxy and, hence, must be at least a few scale lengths in size. It remains unclear whether the surface brightness dimming might cause one to miss a larger scale low surface brightness disk within which the bar resides. In fact, in a few cases a very faint two armed spiral extends out from the ends of the bar. At least in these cases, the bar is smaller than the whole galaxy. The exponential fits to the bars yield a mean scale-lengths of $\sim 1.7-2.0$ kpc, which is small compared to local barred galaxies, but is comparable to the mean size of the LBGs with disk-like morphology. One might find the existence of large bars surprising given that most bars today are only about a scale length in size and never contain a majority of the stellar mass. The idea that bars are typically about a scale length in radius has been reinforced by numerical simulations of forming bars. Moreover, the ubiquity of bar *instability* in N-body simulations has led to the belief that such instabilities induced by noise fluctuations and environmental tidal triggering explains the prevalence of bars in nature. However, strong external perturbations, typical in forming galaxies owing to their more frequent massive satellites and mergers, can form a bar of larger size by temporarily overcoming the background potential to induce the formation of a large bar (Holley-Bockelmann et al. 2005). The bars are expected to be short-lived with lifetimes of about 1 Gyr, and as the bulge component grows the gas-rich disk is more stable to bar formation. Therefore, the bar fraction is expected to decrease at low redshifts, and the ellipticity distribution should evolve toward that observed for local galaxies. Recent observations have shown that the bar fraction is close to 25-30% (Jogee et al. 2004; Elmegreen et al. 2005) and remains almost constant at $z \leq 1$. We find that the peaked ellipticity distribution seen at $z > 2.5$ evolves towards the flat distribution seen for local galaxies, by redshift $z \sim 1.2$, consistent with what is expected if the fraction of gas-rich bars is higher ($\sim 50\%$) at high-z.

7. SUMMARY

We have used the GOODS images to analyse the rest-frame UV morphologies of about 1333 of the most luminous LBGs in order to quantify the morphological types among them, and to study the evolution of the morphology of actively star-forming galaxies from $z > 2.5$ to $z \sim 1.2$.

We find that about 40% of the LBGs have the exponential light profiles observed for local disk galaxies. Contrary to the results from previous studies, we find that spheroid-like morphology is not dominant, and only 30% of the LBGs have close to $r^{1/4}$ profiles expected for spheroids. About 30% of the LBGs have non-exponential, shallower ($n < 0.8$) profiles and visual examination shows that this class includes bulgeless disk galaxies with clumpy star formation, chain galaxies, and close pairs or mergers. The fraction of UV bright spheroids is found to be higher at high redshifts. The decrease in the fraction of spheroids from $z = 4$ to $z \sim 1.2$ is likely due to continued gas accretion and rebuilding of the disks which host most of the recent star formation.

LBGs have ellipticity distributions that do not resemble the distributions for local spheroids or disks. The ϵ distribution is skewed towards large ellipticities, and shows a peak at $\epsilon > 0.5$. The peak at high ellipticity effectively rules out the possibility that LBGs are drawn from a population of circular disks or a population of oblate spheroids. The high ellipticities suggest elongated morphologies are dominant, which may be prolate or triaxial. The peak of the distribution shifts from $\epsilon = 0.7$ at $z \sim 4$

to $\epsilon = 0.5$ at $z \sim 3$, and evolves to the relatively flat distribution observed for local galaxies by $z \sim 1.2$.

The skewed ellipticity distribution of LBGs, with a peak at high ellipticity suggests that the LBGs are not dominated by rotating disks, but are likely to have intrinsic elongated morphology, such as, filaments or bars. Recent simulations of galaxy formation in the cold dark matter cosmology suggest that galaxies at $z > 3$ are likely to have formed in filaments of cold gas accretion within dark halos. This may induce a directionality among the early galaxy population, such as the one we observe among our LBG sample, whereby the star formation occurs in bursts along the filaments. Another possibility which can explain the excess of elongated morphologies among LBGs is that we may be observing bars at very early epochs, and these are commonly found in the hydrodynamical simulations involving gas-rich galaxies at high-z. The high–z bars have large scale-length comparable to the size of the galaxy disks, unlike the bars seen in present-day disk galaxies.

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FIGURE CAPTIONS

Fig. 1. — A summary of the 2-D surface-brightness modeling using *Galfit* is shown for the B-dropouts or LBGs at $z \sim 3.8$. The original image (*panel 1*), the Sérsic model (*panel 2*), and the residual image (*panel 3*) are shown along with the one-dimensional surface brightness profiles (*panel 4*). The 1-D profiles were derived by doing ellipse fits on the original image (*crosses*), and on the best-fit model (*open circles*). A comparison of the two profiles shows that the model reproduces the smooth galaxy profile very well. Clumpiness generally tends make the profiles flatter than a pure exponential profile as seen in the lowest panel. The positive residuals appear white on the residual image. Each image is $2.''0 \times 2.''0$.

Fig. 2. — Montage of LBGs at $z \sim 3$ arranged in the order of decreasing central concentration or Sérsic index, *n*, reveals the diverse rest-frame UV (~ 1600Å)morphology. The number on the upper left in each panel is the ID from the GOODS v1.1 catalog, and the numbers on the lower right are the total UV magnitude in AB magnitudes, the effective radius (r_e) in arcseconds, and *n*. We distinguish the following morphological types among LBGs; $r^{1/4}$ bulge-like ($n > 2.5$), exponential disks ($2.5 > n > 0.8$), and multiple cores, chains, or mergers ($n < 0.8$). Each image is $2.''0 \times 2.''0$.

Fig. 3. — Same as Figure 2, but for the LBGs at $z \sim 4$.

Fig. 4. — Summary of the results from the Monte-Carlo simulations which show the recovered Sérsic index measurements as a function of the size, and magnitude. The results are shown for about 50,000 simulated galaxies which include almost equal numbers of $r^{1/4}$ profile (*black points*) and exponential profile (*red points*) types with random orientation. The spheroids clearly show larger spread in *n* at small sizes and faint magnitudes, but exponential profiles are fairly well recovered over the full range of sizes and magnitudes.

Fig. 5. — Summary of the results from the Monte-Carlo simulations which show the recovered ellipticity measurements as a function of the size, and magnitude. The results are shown for about 50000 simulated galaxies which include almost equal numbers of $r^{1/4}$ profile (*black points*) and exponential profile (*red points*) types with random orientation. The ellipticities for spheroids and exponential disks are well-recovered over a large range of magnitudes and sizes. The scatter becomes significant only at $m > 25.5$ with very little dependence on the profile type, and the input sizes.

Fig. 6. — Summary of the results from the Monte-Carlo simulations which show the comparison of ellipticity measurements from the 2-D analysis, and from SExtractor as a function of the input ellipticity, size, and magnitude. The input ϵ distribution in the simulations is close to uniform in the range 0 to 1. The left panel shows the results from 2-D Sérsic function fitting using *Galfit*, and the right panel shows the measurements given by *SExtractor*. Clearly, the measured ϵ tends to scatter towards large values at small input ϵ, half-light radius $r_e < 0.''2$, and at faint magnitudes (m$>$ 25.0). However, the 2-D fits have a much smaller bias since they account for the PSF convolution, and also sample the wings of the galaxy profile out to about five times r_e.

Fig. 7. — Comparison of the structural parameters for galaxies derived from GOODS and the deeper UDF data are shown versus the average S/N in the GOODS images. Measurements for all 760 galaxies (*black points*) that are common to the GOODS and UDF images for which we have done the morphological analysis are shown for the *z*–band. The comparison for LBGs at *z* = 3 (*blue triangles*), 4 (*green triangles*), and 5 (*red triangles*) are shown in the F606W, F775W, and F850LP bands which corresponds to $\approx$ rest-frame 1600Å wavelengths. The measured parameters are in good agreement between the two datasets. The scatter becomes significant only at $< S/N >$ less than 15, but most of our LBG candidates have higher $< S/N >$.

Fig. 8. — Simulated images generated by redshifting the rest-frame UV GALEX images of local galaxies from the Nearby Galaxies Survey (NGS) out to *z* = 3. The fluxes have been boosted to account for the observed ≈ 3 magnitude evolution in L^* from *z* = 0 to 3 (Wyder et al. 2005; Arnouts et al. 2005). The intrinsic sizes at high redshift is assumed to be about one-third of the present-day size (Ferguson et al. 2004). Without assuming the luminosity-size evolution, most of the star-forming galaxies would not even be visible in the redshifted images. The LBGs observed at *z* = 3 and 4 (***figures 2 and 3***) appear to have morphological analogues among the local galaxies, although the LBGs are much brighter and often have faint features that appear like tidal tails.

Fig. 9. —
The histograms show the observed distribution of Sérsic index, *n*, for the luminous LBGs ($L > 0.5L^*_{1600,z=3}$) at $z \sim 3, 4$ and 5, and for all galaxies and starbursts with spectroscopic redshifts $z \sim 1.2$. Also shown are the recovered *n* distribution (*dashed lines*) from Monte–Carlo simulations using artificial galaxies with *n* = 4 (*red*) and *n* = 1 (*blue*) profiles. Although the recovered *n* distribution shows a larger dispersion for the *n* = 4 models, the $n > 2.5$ criteria does help to distinguish the bulge-like galaxies from pure exponential disks.

Fig. 10. —
The histogram shows the observed distribution of ellipticities for the LBGs with ($L > 0.5L^*_{1600,z=3}$) at $z > 2.5$ in the GOODS data, and for the galaxies and starbursts at $z \sim 1.2$. The curves show the input (*dotted*) and output (*dashed*) ellipticity distribution for the simulated galaxies with pure *n* = 4 (*red*) and *n* = 1 (*blue*) profiles. The range of ellipticities are well-recovered for the typical S/N for

LBGs in the GOODS data. In all the panels, the *black dotted* curves show the sum of the ϵ distribution for the local ellipticals and spiral disks in the APM survey (taken from Lambas, Maddox, & Loveday 1992).

Fig. 11. —
The observed ϵ distribution for star-forming galaxies as a function of redshift, for the different profile types. LBGs with $n \geq 2.5$ (*left panel*) which are spheroid-like based on their brightness profiles, and with $n < 2.5$ (*right panel*) which include disk-like (*black*) and merger-like (*magenta*) are shown separately. The ϵ distribution for the local ellipticals (*red, dotted curve*) and spirals (*blue, dotted curve*) from the APM survey are shown for comparison. The ϵ distribution of LBGs is found to be skewed towards high ϵ implying that they are more elongated than the local galaxies, irrespective of profile type. The spheroid-like and disk-like galaxies at $z \sim 1.2$ show ϵ distribution very similar to that of their local counterparts.

Fig. 12. —
Examples of LBGs with high ellipticity ($\epsilon > 0.6$) which appear to have bar-like morphology and other bar signatures, such as spiral arms arising from the ends of a bar, or star formation at the bar ends.

TABLE 1: Restframe UV properties of local galaxies redshifted to $z = 1.2$ and 3

		Sérsic index, n		Ellipticity, ϵ	
Galaxy (1)	Hubble Type (2)	$z = 3.0$ (3)	$z = 1.2$ (4)	$z = 3.0$ (5)	$z = 1.2$ (6)
NGC 1399	E1pec	2.09	2.00	0.19	0.11
NGC 1316	(R)SAB(s)0	0.31	0.65	0.02	0.26
Cen A	S0pec	0.04	0.29	0.68	0.52
M81	SA(s)ab	0.28	0.05	0.57	0.43
NGC 1068	(R)SA(rs)b	1.79	1.73	0.24	0.25
M51	SAbc	0.25	0.21	0.29	0.27
M83	SAB(s)c	0.38	0.26	0.13	0.02
NGC 253	SAB(s)c	0.06	0.05	0.77	0.78
NGC 628	SA(s)c	0.36	0.18	0.06	0.02
M101	SAB(rs)cd	0.39	0.15	0.36	0.33
NGC 2403	SAB(s)cd	0.77	0.59	0.44	0.42
NGC 247	SAB(s)d	0.09	0.06	0.73	0.72
NGC 925	SAB(s)d	0.43	0.26	0.57	0.54
HCG 92	interacting	0.76	0.35	0.75	0.57

Note.— Summary of the surface brightness profile analysis from simulations using GALEX images of local galaxies redshifted to $z = 3.0$ and 1.2.(1) Galaxy name ; (2) Hubble Types from NASA's Extragalactic Database (NED); (3) & (4) measured Sérsic index at $z = 3$ and $z = 1.2$; (5) & (6) measured elliptcities at $z = 3$ and $z = 1.2$.

TABLE 2: Fraction of Morphological Types among Star-forming Galaxies at $z > 3$ and $z \sim 1.2$

				Sérsic index, n			
z (1)	N_{total} (2)	L > 0.5 L_* (3)	$N_{*,morph}$ (4)	$n > 4$ steep (5)	$4.0 \geq n \geq 2.5$ $r^{1/4}$-type (6)	$2.5 > n \geq 0.8$ exponential-type (7)	$n < 0.8$ multiple/mergers (8)
1.2 (all)	1025	425	378	0.08	0.08	0.26	0.58
1.2 (starbursts)	292	175	153	0.08	0.06	0.27	0.58
3.1	1409	735	662	0.15	0.12	0.42	0.31
3.8	2440	513	493	0.22	0.13	0.33	0.31
4.9	845	198	178	0.29	0.15	0.31	0.25

Note.— The fraction of morphological types among bright star-forming galaxies at $z \sim 1.2$ and LBGs for which structural parameters have been measured using the 2-D analysis. (1) Redshift ; (2) Number of LBGs selected by the "dropout" technique in the GOODS fields at $z > 2.5$, and star-forming galaxies at $z \sim 1.2$ selected by spectroscopic redshifts; (3) number of LBGs with L > 0.5 L_* where L_* is defined as in Steidel et al. (1999); since only few (< 20) $z \sim 1.2$ galaxies satisfy the luminosities defined for LBGs, we have not applied the same luminosity cut for galaxies at $z \sim 1.2$ and instead use the 0.5 L_* value at $z = 1$ from the literature (Wyder et al. 2005, Arnouts et al. 2005); (4) number of L > 0.5 L_* for which morphological parameters were measured with $\chi^2_\nu < 1.0$; (5)-(9) fraction of galaxies belonging to the various morphological class based on their n values.

TABLE 3: STATISTICAL COMPARISON OF STAR-FORMING GALAXIES AT $z \sim 1.2$ AND LBGS AT $z > 3$

	redshift, z		
	3.1	3.8	4.9
mean n	2.09±2.1	2.54±2.5	3.07±2.7
K-S test, P(n)	9E-07	3E-07	9E-10
mean ϵ	0.53±0.19	0.56± 0.19	0.59±0.20
K-S test, P(ϵ)	0.03	1E-4	6E-4

NOTE.— The mean n and ϵ for the $z = 1.2$ galaxy sample is 2.07 ± 2.4 and 0.50 ± 0.21, and for starbursts at $z = 1.2$, the values are 1.51 ± 1.8 and 0.51 ± 0.20. The K-S test for n and ϵ distribution gives the probablity (P(n) and P(ϵ)) that the null hypotheses that the $z \sim 1.2$ and $z > 3$ samples are drawn from the same parent population cannot be rejected. The low values for P(n) and P(ϵ) suggests that it is unlikely that the star-forming galaxies sample at $z \sim 1.2$ and $z > 3$ are drawn from the same distribution.

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