MORPHOLOGIES OF ~190,000 GALAXIES AT z = 0–10 REVEALED WITH HST LEGACY DATA. I. SIZE EVOLUTION

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ABSTRACT

We present the redshift evolution of the galaxy effective radius re obtained from the Hubble Space Telescope (HST) samples of ~190,000 galaxies at z = 0–10. Our HST samples consist of 176,152 photo-z galaxies at z = 0–6 from the 3D-HST+CANDELS catalog and 10,454 Lyman break galaxies (LBGs) at z = 4–10 identified in the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS), HUDF 09/12, and HFF parallel fields, providing the largest data set to date for galaxy size evolution studies. We derive re with the same technique over the wide redshift range of z = 0–10, evaluating the optical-to-UV morphological K correction and the selection bias of photo-z galaxies+LBGs as well as the cosmological surface-brightness dimming effect. We find that re values at a given luminosity significantly decrease toward high z, regardless of statistics choices (e.g., re ∝ (1 + z)^{-1.0}±0.06 for median). For star-forming galaxies, there is no evolution of the power-law slope of the size–luminosity relation and the median Sérsic index (n ∼ 1.5). Moreover, the re distribution is well represented by log-normal functions whose standard deviation σr_e does not show significant evolution within the range of σr_e ∼ 0.45–0.75. We calculate the stellar-to-halo size ratio from our re measurements and the dark-matter halo masses estimated from the abundance-matching study, and we obtain a nearly constant value of re/r_{vir} = 1.0%−3.5% at z = 0–8. The combination of the re distribution shape+standard deviation, the constant re/r_{vir}, and n ∼ 1.5 suggests a picture in which typical high-z star-forming galaxies have disk-like stellar components in a sense of dynamics and morphology over cosmic time of z ∼ 0–6. If high-z star-forming galaxies are truly dominated by disks, the re/r_{vir} value and the disk-formation model indicate that the specific angular momentum of the disk normalized by the host halo is J_e/m_a ∼ 0.5–1. These are statistical results for major stellar components of galaxies, and the detailed study of clumpy subcomponents is presented in the paper II.

Key words: early universe – galaxies: formation – galaxies: high-redshift

Supporting material: machine-readable tables

1. INTRODUCTION

Galaxy sizes offer a variety of invaluable insights into galaxy formation and evolution. The slope of a size–stellar mass (or luminosity) relation, the size growth rate, and the size distribution are key quantities for understanding the development of galaxy morphology and the properties of host dark-matter (DM) halos.

Studies of high-z galaxy sizes show substantial progress with observations from the Hubble Space Telescope (HST), which is capable of imaging with high spatial resolution. Galaxy sizes defined by the effective radius, re, have been extensively measured with the Advanced Camera for Surveys (ACS) and the Wide Field Camera 3/IR channel on board HST for massive galaxies at 0 < z < 3 (e.g., van der Wel et al. 2014) and z > 3–4 Lyman break galaxies (LBGs) selected in the dropout technique (Steidel et al. 1999) (e.g., Trujillo et al. 2006; Dahlen et al. 2007; Toft et al. 2007, 2009; Grazian et al. 2012; Huang et al. 2013; McLure et al. 2013). However, these studies, particularly at high z, do not reach an agreement on the size growth rate. Oesch et al. (2010) have reported that the average size evolves roughly according to re ∝ (1 + z)^{-1} based on a z ∼ 7 LBG sample in the early-epoch data of their HST survey (see also, e.g., Bouwens et al. 2004; Holwerda et al. 2014). On the other hand, Hathi et al. (2008b) have argued that the average size scales as re ∝ (1 + z)^{-1.5} using LBGs at z ∼ 2–6 (see also, e.g., Ferguson et al. 2004). Some studies have provided results of a growth rate falling between these two growth rates (e.g., Mosleh et al. 2012, 2013; Ono et al. 2013). Moreover, Curtis-Lake et al. (2014) have suggested that there is no significant evolution of typical galaxy sizes if one uses not average but modal values of the size distribution for representative radii at a given redshift. These discrepancies in the evolutionary trend would be attributed to small HST samples at z > 3–4 and or potential biases caused by heterogenous samples and measurements taken from the literature.

The two size growth rates of re ∝ (1 + z)^{-1.5} and re ∝ (1 + z)^{-1} correspond to the cases of a fixed virial mass and a circular velocity of DM halos, respectively, if the stellar-to-halo size ratio (SHSR) is constant over the redshift range. Assuming the constant SHSR, a number of studies discuss the evolution of host DM halos with the size growth rates (e.g., Ferguson et al. 2004; Hathi et al. 2008a). However, the evolution of SHSR is not well understood. Recently, SHSRs have been estimated observationally with the results of abundance-matching techniques (e.g., Behroozi et al. 2010, 2013) for galaxies at z ∼ 0 (Kravtsov 2013) and at z ∼ 2–10 (Kawamata et al. 2014). Kawamata et al. (2014) conclude that there is a virtually constant value of SHSR, 3.3 ± 0.1%, over the wide redshift range. Galaxy disk-formation models of, for example, Fall (1983, 2002), Barnes & Efstathiou (1987), and
Mo et al. (1998) predict that galaxy disks acquire an angular momentum from its host DM halo through tidal torques during the formation of these systems, leading to the proportionality between the two sizes. The SHSR values provide us with information about the DM spin parameter and the fraction of specific angular momentum transferred from DM halos to the central galaxy disks (e.g., Mo et al. 1998).

Additionally, the size–stellar mass relation and the scatter of the size distribution present independent evidence for the picture of galaxy disk formation (e.g., Fall 1983, 2002, Bullock et al. 2001, Shen et al. 2003). van der Wel et al. (2014) have revealed that the slope of the size–stellar mass relation and the scatter do not significantly evolve at $0 \lesssim z \lesssim 3$ in a systematic structural analysis for large samples of star-forming galaxies (SFGs) and quiescent galaxies (QGs) with a photometric redshift (photo-$z$). The constant values of these quantities strongly suggest that the sizes of SFGs are determined by their host DM halos. However, the controversial results of the slope and scatter evolution are obtained at $z \gtrsim 3$–4 (e.g., Huang et al. 2013; Curtis-Lake et al. 2014), probably due to large statistical uncertainties given by the small galaxy samples. An analysis with a large LBG sample would reveal the galaxy structure evolution up to $z \sim 10$ with no significant statistical uncertainties and allow us to understand disk-formation mechanisms, internal star formation, and morphological evolution over cosmic time.

In this paper, we systematically investigate the redshift evolution of galaxy sizes with an unprecedentedly large sample of 186,603 galaxies at $z = 0$–10 made from the HST deep data of extragalactic legacy surveys. We assess the effects of morphological $K$ correction, statistics choice, and sample selection bias for galaxies at $z \lesssim 4$, and we then extend our systematic morphological measurements to $z \gtrsim 4$. This paper has the following structure. In Section 2, we describe the details of our HST galaxy samples. Section 3 presents methods for estimating galaxy sizes. In Section 4, we evaluate the morphological $K$ corrections, statistics-choice dependences, and selection biases. We show the redshift evolution of size-relevant physical quantities in Section 5. Section 6 discusses the implications for galaxy formation and evolution with the results of our structural analyses. We summarize our findings in Section 7.

Throughout this paper, we adopt the concordance cosmology with $(\Omega_m, \Omega_{\Lambda}, h) = (0.3, 0.7, 0.7)$ (Komatsu et al. 2011). All magnitudes are given in the AB system (Oke & Gunn 1983). We refer to the HST F606W, F775W, F814W, F850LP, F098M, F105W, F125W, F140W, and F160W filters as $V_{606}$, $i_{775}$, $I_{114}$, $z_{850}$, $Y_{998}$, $Y_{105}$, $J_{125}$, $H_{140}$, and $H_{160}$, respectively.

2. DATA AND SAMPLES

We make use of the following two galaxy samples constructed from the deep optical and near-infrared imaging data taken by HST deep extragalactic legacy surveys whose limiting magnitudes and point-spread function (PSF) FWHM sizes are summarized in Table 1. In the last subsection, we explain the stellar masses of the sample galaxies.

2.1. Sample of Photo-$z$ Galaxies at $z = 0$–6 in 3D-HST+CANDELS

The first sample is made of 176, 152 HST/WFC3-IR-detected galaxies with photometric redshifts (hereafter photo-$z$ galaxies) at $z = 0$–6 taken from Skelton et al. (2014). These galaxies are identified in five Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS) fields (Grogin et al. 2011; Koekemoer et al. 2011) and detected in stacked images of the $J_{125}$, $H_{140}$, and $H_{160}$ bands of WFC3/IR, which yields roughly a stellar-mass-limited sample. The photometric properties and the results of spectral energy distribution (SED) fitting for all of the sources are summarized in Skelton et al. (2014). The HST images and catalogs are publicly released at the 3D-HST website. The catalogs include the spectroscopic redshifts on the basis of the HST/WFC3 G141 grism observation (Brammer et al. 2012). We use galaxies whose physical quantities and photometric redshifts are well derived from SED fitting (specifically, sources with use Phot = 1 in the public catalogs). Table 2 summarizes the number of galaxies at each redshift in the photo-$z$ galaxy sample that we use. In this paper, we assume the Salpeter (1955) initial mass function (IMF). To obtain the Salpeter IMF values of stellar masses ($M_*$) and star-formation rates (SFRs), we multiply the Chabrier (2003) IMF values from the Skelton et al. (2014) catalog by a factor of 1.8.

We divide the sample of photo-$z$ galaxies at $z = 0$–4 into two subsamples of star-forming galaxies (SFGs) and QGs by the rest-frame $UVJ$ color criteria of Muzzin et al. (2013). Because the $UVJ$ color criteria are not tested for $z > 4$ sources, we do not apply these color criteria to the photo-$z$ galaxies at $z > 4$. Muzzin et al. (2013) find that the QG fraction is small, 10%, at $z \sim 3.5$, and it is likely that a QG fraction at the early cosmic epoch of $z > 4$ is negligibly small, perhaps <10%. We thus regard all of the $z > 4$ photo-$z$ galaxies as SFGs. The total numbers of SFGs and QGs are 165,517 and 10,631, respectively. The $H_{160}$ magnitude at the 50% completeness is ~26.5 mag for the photo-$z$ galaxies in the deep CANDELS fields. The details of the completeness estimates and values are presented in Skelton et al. (2014).

2.2. Sample of LBGs at $z = 4$–10 in CANDELS,
H UDF 09/12, and HFF

The second sample consists of 10,454 LBGs at $z = 4$–10 made by Y. Harikane et al. (2015, in preparation) in the CANDELS, the Hubble Ultra Deep Field 09+12 (UDF 09+12; Beckwith et al. 2006; Bouwens et al. 2011; Illingworth et al. 2013; Ellis et al. 2013) fields, and the parallel fields of Abell 2744 and MACS 0416 in the Hubble Frontier Fields (e.g., Coe et al. 2014; Ishigaki et al. 2014; Oesch et al. 2014; Atek et al. 2015). The numbers of our LBGs are summarized in Table 3. These LBGs are selected with the color criteria similar to those of Bouwens et al. (2014b). We perform source detections by SExtractor (Bertin & Arnouts 1996) in coadded images constructed from bands of $Y_{998}$, $J_{125}$, $H_{140}$, $I_{135}$, $J_{125}H_{140}$, and $H_{160}$ for the $z \sim 4$–7, 8, and 10 LBGs, respectively. The $J_{140}$ band is included in the coadded image for the $z \sim 7$–8 LBGs in the HUFD 09+12 field. The flux measurements are carried out in Kron (1980)-type apertures with a Kron parameter of 1.6 whose diameter is determined in the $H_{160}$ band. In two-color diagrams, we select objects with a Lyman break, no extreme-red stellar continuum, and no detection in passbands bluer than the spectral drop. See Y. Harikane et al. (2015, in preparation) for more details of the source detections and LBG selections.

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5 http://3dhst-research.yale.edu/3dhst.html
6 http://archive.stsci.edu/prepds/xdf/
The \( H_{160} \) magnitude at 50\% completeness is \( \sim 28 \) mag for the LBGs in the deep CANDELS fields (Bouwens et al. 2014b). The details of the completeness estimates and values are presented in Y. Harikane et al. (2015, in preparation).

Several previous studies on galaxy size have included a galaxy at \( z \sim 12 \) selected in the photo-z technique (Ellis et al. 2013). In this study, we do not use the galaxy at \( z \sim 12 \) because the redshift of the source is under debate (e.g., Bouwens et al. 2013; Brammer et al. 2013; Capak et al. 2013; Ellis et al. 2013; Pirzkal et al. 2013).

2.3. Stellar Masses of Photo-z Galaxies and LBGs

Some analyses and discussions in this work require the \( M_* \) of the photo-z galaxies and the LBGs. For the photo-z galaxies, we take \( M_* \) values from Skelton et al. (2014). For the LBGs, we derive stellar masses, adopting an empirical relation between UV magnitude \( M_{UV} \) and \( M_* \). First, we calculate \( M_{UV} \) from the total magnitudes in the LBG detection images (Section 3), assuming that the typical redshifts are \((z) \sim 3.8, 4.9, 5.9, 6.8, 7.9, \) and 10.4. The stellar masses are obtained by converting their \( M_{UV} \) through the empirical relation from González et al. (see also the updated result of González et al. 2014):

\[
\log M_* = -39.6 + 1.7 \times \log L_{1500},
\]

where \( L_{1500} \) is the luminosity at the rest-frame 1500 Å. This empirical relation is derived under assumptions similar to ours (the Salpeter IMF and no nebular emission lines included in the SED).

To test whether this empirical relation (Equation (1)) of \( L_{UV} - M_* \) is reliable and consistent with the \( M_* \) estimates of the photo-z galaxy sample, we compare this empirical relation with the \( M_{UV} - M_* \) relations derived from the photo-z galaxies.

We estimate \( M_{UV} \) from the absolute UV magnitudes at a wavelength of 2800 Å from the photo-z catalog, assuming that the majority of star-forming galaxies have a flat UV spectrum of \( f_{UV} \) constant. We present the \( M_{UV} - M_* \) relations of the photo-z galaxies in Figure 1. The UV magnitude correlates well with \( M_* \), suggesting the existence of the “star-formation main sequence” (e.g., Daddi et al. 2007; Lee et al. 2012; Whitaker et al. 2012; Steinhardt et al. 2014).

Figure 1 shows that the slopes of the relations appear to be flatter at a bright range of \( M_{UV} \approx -22 \) than at a faint \( M_{UV} \) range. Similar flat slopes are reported by a large survey area of the CANDELS fields (Stark et al. 2009; Lee et al. 2011; Salmon et al. 2015). Because our LBGs used in this analysis have magnitudes of \( M_{UV} \geq -22 \), we fit \( \log M_* = a + b M_{UV} \) to the \( M_{UV} - M_* \) relation at \( M_{UV} \geq -22 \), where \( a \) and \( b \) are free parameters. The best-fit functions for the photo-z galaxies are

\[
\log M_*[M_\odot] = 1.46 - 0.43 \times M_{UV}(z = 0 - 1),
= 0.82 - 0.45 \times M_{UV}(z = 1 - 2),
= 1.12 - 0.43 \times M_{UV}(z = 2 - 3),
= -0.22 - 0.49 \times M_{UV}(z = 3 - 4),
= -2.10 - 0.58 \times M_{UV}(z = 4 - 5),
= -2.45 - 0.59 \times M_{UV}(z = 5 - 6).
\]

If we assume that the magnitudes of 1500–1700 Å are the same for typical LBGs with \( f_{UV} \) constant, the slopes \( b \) of \(-0.58 \pm 0.02 \) and \(-0.59 \pm 0.03 \) at \( z \approx 4 - 6 \) roughly agree with that of Equation (1) (i.e., \( b = -0.68 \pm 0.08 \)). We thus conclude that the empirical relation (Equation (1)) is reliable and consistent with the \( M_* \) estimates of the photo-z galaxy sample. Moreover, no strong evolution in the \( M_{UV} - M_* \) relation is found at \( z \gtrsim 4 \) in Equation (2) and Figure 1. We use Equation (1) to estimate the \( M_* \) of our \( z \gtrsim 4 \) LBGs.
Table 2  
Number of Photo-\(z\) Galaxies for Our Size Measurements

| Field        | \(z = 0–1\) | \(z = 1–2\) \(^b\) | \(z = 2–3\) \(^b\) | \(z = 3–4\) | \(z = 4–5\) | \(z = 5–6\) |
|--------------|-------------|---------------------|---------------------|-------------|-------------|-------------|
| HUDF 09+12   | 294 (397)   | 368 (611)           | 8 (157)             | ...         | ...         | ...         |
| HUDF 09-P    | 2168 (3467)| 2024 (4707)         | 66 (1451)           | ...         | ...         | ...         |
| GOODS-S Deep | 1753 (2793)| 1402 (3847)         | 37 (1296)           | ...         | ...         | ...         |
| GOODS-S Wide | 2790 (4724)| 2267 (6313)         | 66 (2518)           | ...         | ...         | ...         |
| GOODS-N Deep | 3270 (5106)| 1778 (5168)         | 71 (2094)           | ...         | ...         | ...         |
| GOODS-N Wide | 3903 (5939)| 2731 (6611)         | 139 (2477)          | ...         | ...         | ...         |
| UDS          | 5157 (9175)| 5433 (15771)        | 209 (6094)          | ...         | ...         | ...         |
| AEGIS        | 6441 (11074)| 5833 (13943)        | 278 (6418)          | ...         | ...         | ...         |
| COSMOS       | 6856 (11385)| 3594 (9754)         | 179 (3915)          | ...         | ...         | ...         |

\(N_{\text{total}} (z)\)

| Field        | \(z = 0–1\) | \(z = 1–2\) \(^b\) | \(z = 2–3\) \(^b\) | \(z = 3–4\) | \(z = 4–5\) | \(z = 5–6\) |
|--------------|-------------|---------------------|---------------------|-------------|-------------|-------------|
| HUDF 09+12   | 294 (397)   | 368 (611)           | 8 (157)             | ...         | ...         | ...         |
| HUDF 09-P    | 2168 (3467)| 2024 (4707)         | 66 (1451)           | ...         | ...         | ...         |
| GOODS-S Deep | 1753 (2793)| 1402 (3847)         | 37 (1296)           | ...         | ...         | ...         |
| GOODS-S Wide | 2790 (4724)| 2267 (6313)         | 66 (2518)           | ...         | ...         | ...         |
| GOODS-N Deep | 3270 (5106)| 1778 (5168)         | 71 (2094)           | ...         | ...         | ...         |
| GOODS-N Wide | 3903 (5939)| 2731 (6611)         | 139 (2477)          | ...         | ...         | ...         |
| UDS          | 5157 (9175)| 5433 (15771)        | 209 (6094)          | ...         | ...         | ...         |
| AEGIS        | 6441 (11074)| 5833 (13943)        | 278 (6418)          | ...         | ...         | ...         |
| COSMOS       | 6856 (11385)| 3594 (9754)         | 179 (3915)          | ...         | ...         | ...         |

\(N_{\text{total}} (z)\)

**Notes.** Columns: (1) Field. (2)–(7) Number of photo-\(z\) galaxies that have S/N \(\geq 15\) and reliable GALFIT outputs in each redshift range. The value in parentheses is the number of photo-\(z\) galaxies in the parent sample.

* Total number of objects in the HUDF 09-P1 and HUDF 09-P2 fields.

\(^b\) The actual redshift range is \(2 \leq z < 2.1\) (\(1.2 \leq z \leq 2\)) for the \(\lambda_{\text{opt}}^\text{UV}\) measurement.

\(^c\) The numbers of QGs with \(\lambda_{\text{opt}}^\text{UV}\) are not shown here because of the rarity at \(z \geq 2–3\) and the UV faintness.

3. SIZE MEASUREMENT

In this section, we describe methods to measure galaxy sizes by using the high spatial resolution images of HST. To minimize the effect of morphological K correction, we use images of four bands, \(V_{606}\) and \(I_{814}\) on ACS\(^3\) and \(J_{125}\) and \(H_{160}\) on WFC3/IR. We select one of these bands whose entire passband is covered by the wavelength range of \(\lambda_{\text{opt}}^\text{UV} = 1500–3000\) Å or \(\lambda_{\text{opt}}^\text{IR} = 4500–8000\) Å of each object. If two or more filter passbands meet this criterion, we choose a band that observes the shortest wavelength. Prior to the size measurements, we extract \(18'' \times 18''\) cutout images from the \(V_{606}, I_{814}, J_{125}, H_{160}\) data at the position of each photo-\(z\) galaxy and LBG. The size of the cutout images is sufficiently

\(^3\) We make use of \(z_{814}\) for GOODS-North that has not been taken with the \(I_{814}\) band.
large to investigate entire galaxy structures, even for extended objects at $z \sim 0\!–\!1$. We use the coadded images of $Y_098$, $Y_095$, $J_{125}$, $H_{606}$, and $H_{560}$ constructed in Section 2.2 for the $z \sim 4\!–\!7$, 8, and 10 LBGs, respectively. The limiting magnitudes of these coadded images are summarized in Table 1.

We measure the galaxy size basically in the same manner as previous studies for high-$z$ LBGs (e.g., Ono et al. 2013) based on the two-dimensional (2D) surface-brightness (SB) profile fitting with the GALFIT software (Peng et al. 2002, 2010). We fit a single Sérsic profile (Sérsic 1963, 1968) to the 2D SB distribution of each galaxy to obtain the half-light radius along the semimajor axis, $r_{e,\text{major}}$. The $r_{e,\text{major}}$ is converted to the “circularized” radius, $r_{c}$, through $r_c = a\sqrt{b/\pi} = r_{e,\text{major}}\sqrt{q}$, where $a$, $b$, and $q$ are the major and minor axes and axis ratio, respectively. Several authors studying $z \sim 0\!–\!3$ galaxies claim that $r_{e,\text{major}}$ should be used because $r_{e,\text{major}}$ does not depend strongly on the galaxy inclination (e.g., van der Wel et al. 2014). However, the circularized radius $r_{c}$ has been widely used in size measurements for faint and small high-$z$ sources (e.g., Mosleh et al. 2012; Ono et al. 2013; Holwerda et al. 2014). We here use the circularized radius $r_{c}$ in order to perform self-consistent size measurements and fair comparisons from $z \sim 0$ to $z \sim 10$.

We create sigma and mask images to estimate the fitting weight of individual pixels and mask neighboring objects of the main galaxy components, respectively. The sigma images are generated from the drizzle weight maps produced by the HST data reduction (Koekemoer et al. 2003). We also include the Poisson noise from the galaxy light to the sigma image (e.g., Hathi et al. 2009; van der Wel et al. 2012). The mask images are constructed from segmentation maps produced by SExtractor. We identify neighboring objects with the SExtractor detection parameters of DETECT_MINAREA = 5 pixel, DETECT_THRESH = 2$\sigma$, DETECT_NTHRESH = 16, and DEBLEND_MINCONT = 0.0001.

We input initial parameters taken from the 3D-HST $+$CANDELS photometric catalog (Skelton et al. 2014) for the photo-$z$ galaxies. Specifically, the total magnitude $m$, axis ratio $q$, position angle P.A., and half-light radius $r_{e}$ of each galaxy are initial parameters that are written in the GALFIT configuration file. The Sérsic index $n$ is set to $n = 1.5$ as an initial value for the photo-$z$ galaxies, whereas the initial $n$ does not strongly affect the fitting results (Yuma et al. 2011, 2012).
In fact, we change the initial parameters of the Sérsic index to \( n = 1 \) and 3, but we still obtain similar best-fit \( n \) values even with these different initial parameters. For the LBG sample, the initial parameters are taken from the results of SExtractor photometry (Y. Harikane et al., in preparation). The Sérsic index for LBGs is fixed to 1.5 for reliable fitting for faint and small high-z sources. This fixed Sérsic index is justified by the evolution of \( n \) in SFGs, as demonstrated in Section 5.1. To obtain \( r_e \), \( n \), and \( q \), we allow the parameters to vary in the ranges \( \Delta m < 3 \) mag, \( 0.3 < r_e < 400 \) pixels, \( 0.2 < n < 8 \), and \( 0.0001 < q < 1 \), \( \Delta x < 2 \) pixel, and \( \Delta y < 2 \) pixel, which are quite similar to those of van der Wel et al. (2012). We discard objects whose one or more fitting parameters reach the limit of the parameter ranges (e.g., \( r_e = 400 \)). The PSF models of the HST images are provided by the 3D-HST project (Skelton et al. 2014).

We have analyzed the photo-z galaxies and LBGs shown in Sections 2.1 and 2.2. As we discuss below, the sizes of faint galaxies are poorly determined. We thus choose photo-z galaxies and LBGs whose sources have a signal-to-noise ratio (S/N) greater than 15. This S/N threshold is determined by Monte Carlo simulations for faint and small high-z sources (e.g., van der Wel et al. 2012; Ono et al. 2013). Tables 2 and 3 summarize the number of photo-z galaxies and LBGs, respectively, that are analyzed in our study. The object numbers in our size analysis are 142,273 (9767) in \( V_{606} \), 136,493 (10,118) in \( I_{814} \), 139,308 (10,845) in \( J_{125} \), and 147,204 (11,297) in \( H_{160} \) for the SFGs (QGs) of the photo-z sample, and 7233 for the LBGs. The total numbers of SFGs (QGs) that are well fit in the optical and UV stellar continuum emission are 59,115 (4234) at \( z \sim 0 \)–0.3 and 30,765 (799) at \( z \sim 1 \)–6, respectively, while the sizes of 4993 LBGs are securely measured. Tables 4 and 5 show the size measurements given by our structural analysis for the photo-z galaxies and the LBGs, respectively. Figure 2 presents example images of the fitting results, demonstrating that our size measurements are well performed.

Note that clumpy structures are masked in the fitting, as indicated in the mask panels of Figure 2. This masking procedure is included in our analyses because a single Sérsic profile fitting is not reliable for galaxies with clumpy structures. Moreover, the number of well-fit galaxies decreases if no masking is applied. Nevertheless, we examine whether the masking procedures change our conclusions, and we find that the \( r_e \) measurements are statistically comparable in galaxies with and without masking. The fraction of galaxies with clumpy structures ranges from \( \sim 30\% \) at \( z \sim 1\% \) to \( \sim 50\% \) at \( z \sim 2 \). This study only addresses the major stellar components of galaxies. The detailed analyses and the results of clumpy stellar subcomponents are presented in paper II.

van der Wel et al. (2012, 2014) obtain their \( r_e \) values in the \( J_{125}, H_{140}, \) and \( H_{160} \) bands for all of the 3D-HST+CANDLES galaxies using the GALAPAGOS software (Barden et al. 2012), which is a wrapper of SExtractor and GALFIT for morphological analyses. Several morphological studies have utilized GALAPAGOS, allowing for the simultaneous determination of both the structural parameters and the background flux level for multiobjects. In Figure 3, we compare our \( r_e \) measurements with those of van der Wel et al. (2014) estimated with GALAPAGOS. We find that our \( r_e \) values are in good agreement with those obtained by van der Wel et al.
We also find that faint galaxies with S/N < 15 are significantly scattered in Figure 3. This confirms that the threshold of S/N ≥ 15 is important for secure size measurements.

4. K CORRECTION, STATISTICAL CHOICE, AND SELECTION BIAS

4.1. Effect of Morphological K Correction

We investigate the effects of morphological K correction in our size measurements, comparing our $r_e$ at different wavelengths. Because the HST imaging data cover up to the H160 band, we can study the rest-frame UV morphology for galaxies at $z \gtrsim 3$. Understanding the effects of morphological K correction is considerably important in evaluating the size evolution of star-forming galaxies over a wide redshift range of 0 ≤ $z$ ≤ 10. The sizes in the rest-frame UV and optical stellar continuum emission, $r_e^{\text{UV}}$ and $r_e^{\text{Opt}}$, tracing different stellar populations, would yield a large difference in $r_e$. Here we make a comparison between $r_e^{\text{UV}}$ and $r_e^{\text{Opt}}$ of the SFGs at 1.2 ≤ $z$ ≤ 2.1 where both radii can be measured with the HST data.

Figure 4 shows the differences between $r_e^{\text{UV}}$ and $r_e^{\text{Opt}}$ for the SFGs at 1.2 ≤ $z$ ≤ 2.1 (gray dots) as a function of stellar mass. The gray circles represent the median values of $(r_e^{\text{UV}} - r_e^{\text{Opt}})/r_e^{\text{Opt}}$ in different stellar mass bins. The right panel shows histograms for the number of SFGs.
20% in all stellar mass bins. This indicates that the differences in statistical $r_e$ measurements are small for star-forming galaxies with $\log M_*=9-11$ M$_\odot$ at $z \sim 1-2$.

Similarly, van der Wel et al. (2014) have found that $r_e_{\text{major}}$ is typically smaller in redder bands for SFGs at $z \sim 0-2$ (see also, e.g., Szomoru et al. 2011; Wuyts et al. 2012). This trend is more significant in more massive SFGs. The smaller size in redder bands could be interpreted as heavier dust attenuation in the galactic central regions in bluer bands (e.g., Kelvin et al. 2012) and or inside-out disk formation (e.g., Bezanson et al. 2009; Brooks et al. 2009; Naab et al. 2009; Nelson et al. 2012; Patel et al. 2013). We confirm the wavelength dependence even in our $r_e$ in the most massive $M_*$ bin, as shown in Figure 4. van der Wel et al. (2014) have parameterized the wavelength dependence of $r_e_{\text{major}}$ as a function of redshift and stellar mass. Following the formula, the size difference fraction $(r_e^{15} - r_e^{Opt})/r_e^{Opt}$ is calculated to be $\sim 30\%$ for $z \sim 2$ galaxies with $\log M_*=11$ M$_\odot$.

Note that the difference of stellar population becomes smaller at $z > 2$ than at $z \sim 1-2$, which is because the short cosmic age of $z > 2$ provides a smaller stellar-age difference and less metal enrichment than that of $z \sim 1-2$. This agreement of $r_e^{15}$ and $r_e^{Opt}$ suggests that the statistical $r_e^{15}$ values represent the typical sizes of stellar-component distribution for star-forming galaxies of SFGs and LBGs at $z \geq 3$ with a small systematic uncertainty of $\leq 30\%$.8

We examine the effect of morphological $K$ correction in more detail by investigating the evolutionary trends of $r_e$ and size-relevant quantities in the rest-frame optical and UV emission for the photo-$z$ galaxies at $z \sim 0-6$. Figure 5 presents the redshift evolution of $r_e$, $n$, and the star-formation rate surface density (SFR SD), $\Sigma_{\text{SFR}}$. The SFR SD is derived in the effective radius and calculated by

$$\Sigma_{\text{SFR}}[M_\odot \text{yr}^{-1} \text{kpc}^{-2}] = \frac{\text{SFR}/2}{\pi r_e^2},$$

where a factor of 1/2 corrects for the SFR value, which is derived from the total magnitudes. For the photo-$z$ galaxies, we use SFRs taken from the catalog of Skelton et al. (2014). For LBGs, we compute SFRs from $L_{UV}$ using the relation of Kennicutt (1998a):

$$\text{SFR}[M_\odot \text{yr}^{-1}] = 1.4 \times 10^{-23} L_{UV} \text{[erg s}^{-1} \text{Hz}^{-1}].$$

van der Wel et al. (2014) have already examined the $r_e$ evolution at 5000 Å in the rest frame for galaxies at $0 \lesssim z \lesssim 3$ in the 3D-HST+CANDELS sample. In our study, we extend this analysis of $0 \lesssim z \lesssim 3$ to $z \gtrsim 4$, using the photo-$z$ galaxies and the LBGs.

In Figure 5, the median values of these quantities are in good agreement between the measurements in the rest-frame optical and UV emission of the SFGs at $2 \lesssim z \lesssim 3$. Additionally, the evolutionary tracks at $z \lesssim 3$ smoothly connect with those at $z \gtrsim 3$. We also find no strong dependence of these evolutionary trends on stellar mass. These agreements confirm a small effect of morphological $K$ correction on the median $r_e$ values.

8 In Figure 4, we find that the scatters of $(r_e^{15} - r_e^{Opt})/r_e^{Opt}$ are comparably large in high-mass and low-mass galaxies. Because the scatters originating from statistical errors should be smaller in the high-mass galaxies than in the low-mass galaxies, the scatters of the high-mass galaxies are probably dominated not by statistical errors but by intrinsic $r_e$ differences.

4.2. Statistical Difference and Selection Bias

We examine the redshift evolution of median, average, and modal $r_e$ of our galaxies to evaluate statistical differences and selection biases. We define four $L_{UV}$ bins for these analyses. The $L_{UV}$ bins are $1-10$, $0.3-1$, $0.12-0.3$, and $0.048-0.12$ L$_{UV}/L_{*_{z=3}}$, where $L_{*_{z=3}}$ is the characteristic UV luminosity of LBGs at $z \sim 3$ ($M_{UV}=-21$, Steidel et al. 1999).9 To investigate the $r_e$ distribution shape, in Figure 6 we plot the $r_e$ distribution of SFGs and LBGs at $z \sim 1-6$ in the bin of $L_{UV}=0.3-1$ L$_{UV}/L_{*_{z=3}}$ that has good $r_e$ measurement accuracies whose typical reduced $\chi^2$ values are the smallest among the $L_{UV}$ bins of the $r_e$ measurements. We fit the $r_e$ with the log-normal distribution

$$p(r_e) = \frac{1}{r_e \sigma_{r_e} \sqrt{2\pi}} \exp \left[ - \frac{\ln^2(r_e/r_{e,\text{avg}})}{2\sigma_{r_e}^2} \right],$$

where $r_{e,\text{avg}}$ and $\sigma_{r_e}$ are the peak of $r_e$ and the standard deviation of $\ln r_e$, respectively. We fit the log-normal functions to the $r_e$ distribution data with the two free parameters of $r_{e,\text{avg}}$ and $\sigma_{r_e}$, and we present the best-fit log-normal functions in Figure 6 for the data of good statistics, the SFGs at $z \sim 1-3$, and the LBGs at $z \sim 4-6$ in the $L_{UV}=0.3-1.0 L_{UV}$ bin. The $r_e$ distributions of the high-$z$ star-forming galaxies are well represented by the log-normal distribution. The reduced $\chi^2$ values are 0.006, 0.003, 0.004, 0.005, and 0.011 for the SFGs at $z = 1-2$ and 2-3 and the LBGs at $z \sim 4, 5,$ and 6, respectively. Figure 7 is the same as Figure 6, but for all of our galaxies. Figure 7 indicates that the $r_e$ distributions are well fitted by the log-normal functions in the wide range of redshift, $z \sim 0-6$, and the UV luminosity, $\sim 0.12-10 L_{UV}$. Note that log-normal functions cannot be fitted to the data of the $z \gtrsim 7$ galaxies and some low-$z$ galaxies in Figure 7 because of the small statistics. Moreover, the fitting result of $z \sim 0-1$ is only obtained for the $r_e^{Opt}$ distribution in the luminosity bin of $0.12-0.1 L_{UV}$ because of the poor statistics of the other luminosity bin data.

Because the $r_e$ distributions follow the log-normal functions, the average, median, and modal values of $\ln r_e$ should be the same. However, in previous studies, the size evolution is discussed with the average, median, and modal values of $r_e$ in the linear space (e.g., Bouwens et al. 2004; Oesch et al. 2010; Grazian et al. 2012; Ono et al. 2013; Holwerda et al. 2014). Here we obtain $r_e$ measurements with different statistics choices in the linear space, following the previous studies, and evaluate the differences in the size evolution results. We derive size growth rates based on average, median, and modal $r_e$ in a bin of $0.3-1 L_{UV}/L_{*_{z=3}}$ estimating the modal $r_e$ by fitting the size distributions with a log-normal function. In Figure 8, we compare our $r_e$ measurements with those of the previous studies that apply the different statistics.10 We confirm that our results are consistent with those of the previous studies. Moreover, Figure 8 indicates that galaxy sizes decrease from

9 The $L_{UV}$ bins are the same as in previous studies (e.g., Oesch et al. 2010). The LBGs in the faintest $L_{UV}$ bin are only used for the stacking analysis (Section 5.2).

10 Because there are only three LBGs at $z \sim 10$, the weighted average $r_e$ is only derived for our $z \sim 10$ LBGs. Note that the $z \sim 10$ data are presented in Figure 8, but that the data are not used to derive the size evolution function below.
We fit $r_e = B_z (1 + z)^{\beta_z}$ for the average, median, and modal $r_e$ values given by our and previous studies, where $B_z$ and $\beta_z$ are free parameters. The fitting is performed for the combination of $r_e^{\text{Opt}}$ and $r_e^{\text{UV}}$ as well as for $r_e^{\text{UV}}$ only. Table 6 summarizes the best-fit $B_z$ and $\beta_z$ values. Table 7 is a summary of the samples and $\beta_z$ values from our and previous studies for LBGs with $z \gtrsim 4$. Our average, median, and modal $r_e$ values scale as $\propto (1 + z)^{-2.5}$, indicating that, again, the choices of statistics in $r_e$ measurements has no significant effect on size growth rates. This conclusion is consistent with the result that $\sigma_{\text{ln} \ r_e}$ shows no significant evolution, as discussed in Section 6.1.1.

Most previous studies have employed average values for representative $r_e$. However, Figure 7 indicates that the median measurements trace the typical galaxy sizes parameterized by $\Sigma_{\text{SFR}}$ better than the average values do. Because the small samples of $z \gtrsim 7$ galaxies do not allow us to estimate modal $r_e$ values, we use median values for our main analyses, unless otherwise specified.

Figure 8 compares the $r_e$ values of SFGs and LBGs at $z \sim 4$–6 with a bright UV luminosity. In any statistics choice, we find that the $r_e$ values of SFGs and LBGs are comparable within a scatter of $\lesssim 30\%$. These results indicate that star-forming galaxies selected by photo-$z$ and dropout techniques statistically give similar $r_e$ values and that the bias from the different selection techniques is as small as $\lesssim 30\%$ in the $r_e$ determination.

5. RESULTS

5.1. Sérsic Index

The Sérsic index represents the SB profiles of galaxies. A high $n$ means a cusplier SB distribution, indicating the existence of a central bulge. On the other hand, a lower $n$ suggests a disk-like structure.
like light profile with a flatter SB distribution at the central galactic region. The Sérsic index depends on observed wave bands and stellar populations (e.g., color), which have been revealed by detailed structural analyses with multiple passbands for local galaxies (e.g., Häußler et al. 2013; Vika et al. 2013, 2014). Vulcani et al. (2014) have reported that \( n \) tends to be larger in redder bands for blue galaxies because of a bulge component with old stellar ages and/or dust attenuation at the central region.

Our results confirm that \( n \) values of QGs are significantly higher than those of SFGs at \( z \lesssim 2 \) in the Redshift-Sersic index right panel of Figure 5. For massive SFGs with \( \log M_\odot = 10-11 \), \( n \) values monotonically increase from \( n \sim 1-1.5 \) at \( z \sim 1 \) to \( n \sim 2-3 \) at \( z \sim 0 \). The evolutionary trend of \( n \) for the massive SFGs is similar to that of the QGs at \( z \sim 0-2 \), which is consistent with previous results (see the discussions in van Dokkum et al. 2010; Naab et al. 2009; Pastrav et al. 2013).

At \( 2 \lesssim z \lesssim 3 \), the \( n \) values of the SFGs at the rest-frame optical wavelengths are slightly smaller than those at the rest-frame UV wavelengths by \( \Delta n \lesssim 0.5 \), which is similar to the results of Vulcani et al. (2014) for local objects.

Interestingly, in Figure 5, we find that typical SFGs have a value of \( n \sim 1-1.5 \) at the wide redshift range of \( z \sim 1-6 \), albeit with the large scatter of individual galaxies. A similar claim is made by, for example, Morishita et al. (2014), but only

### Figure 6

Distribution of \( r_e^{UV} \) for the SFGs and the LBGs at \( z \sim 1-6 \) in the bin of \( L_{UV} = 0.3-1 L_{UV, z=3} \). The histograms and the curves show the \( r_e^{UV} \) distributions and the best-fit log-normal functions, respectively, for the SFGs at \( z = 1-2 \) (green) and \( 2-3 \) (light green) and the LBGs at \( z \sim 4 \) (blue), 5 (light blue), and 6 (cyan). The y axis is arbitrary. The histograms and curves are slightly shifted along the x and y axes for clarity. The shifted values are \( \Delta r_e = -0.25, -0.12, -0.09, -0.04, \) and 0 kpc for \( z = 1-2 \) and \( z = 2-3 \) star-forming galaxies and \( z \sim 4, \sim 5, \) and \( z \sim 6 \) LBGs, respectively. Although these choices of shifts moderately cancel out the trend of the \( r_e \) evolution, the \( r_e \) decrease toward high \( z \) is still clearly found.

### Figure 7

Distribution of \( r_e \) in different \( L_{UV} \) bins, \( 0.12-0.3 \) (left), \( 0.3-1 \) (middle), and \( 1-10 \) (right) \( L_{UV}/L_{UV, z=3} \). Each row displays galaxies from \( z = 0-1 \) (bottom) to \( z \sim 8 \) (top). The red, green, and blue histograms indicate the distribution of \( r_e \) for the star-forming galaxies and \( r_e^{UV} \) for the LBGs, respectively. The solid curves denote the best-fit log-normal functions for these histograms. The solid and dashed arrows present the median and average values of \( r_e \) with the color coding same as the curves. The y axis is arbitrary.

for \( z \sim 1-3 \) star-forming galaxies (Figure 5). Our results newly suggest that the typical Sérsic indices of star-forming galaxies are \( n \sim 1-1.5 \) at \( z \sim 3-6 \).

This constant \( n \) guarantees that we use a fixed \( n \) value of 1.5 in the size measurements for LBGs (Section 3).

### 5.2. Size–Luminosity Relation

We investigate the size–luminosity \( r_e-L_{UV} \) relation and its dependence on redshift. Figure 9 and Table 8 represent the size–luminosity relation at \( z = 0-8 \) for the SFGs and LBGs, where \( L_{UV} \) is presented with \( M_{UV} \). We cannot examine the size–luminosity relation at \( z \sim 10 \) because the number of \( z \sim 10 \) LBGs is only three. A large area of \( \sim 910 \) arcmin\(^2\) in the HST fields allows us to derive the \( r_e-L_{UV} \) relation in a wide range of magnitude, \( -23 \lesssim M_{UV} \lesssim -17 \) mag, even for \( z \sim 4 \) LBGs. Figure 9 shows that \( r_e \) has a negative correlation with \( M_{UV} \) at \( 0 \lesssim z \lesssim 8 \).
The evolution of $r_0$ is similar to those of the median $r_e$ values that are presented in Figure 8. Here we plot $r_e$ as a function of redshift in Figure 11, which is the same as Figure 8, but for the median $r_e$ values of three different UV luminosity samples. We fit the functions and find that the best-fit $\beta$ are $-1.22 \pm 0.05$, $-1.10 \pm 0.06$, and $-0.84 \pm 0.11$ in $L_{UV}/L_{z=0} = 0.12-0.3, 0.3-1$, and $1-10$, respectively (Table 6). The best-fit $\beta$ values are comparable to the one of $r_0$.

In contrast to the $r_e$ evolution, there is no significant evolution of $\alpha$ (Equation (6)) at $z = 0-8$ found in the right panel of Figure 10. We calculate the weighted-average value of $\alpha$ with our data points over $z = 0-8$ and obtain $\alpha = 0.27 \pm 0.01$. Figure 10 compares the $\alpha$ estimates of $z = 0-8$ obtained in the previous studies. The $\alpha$ measurements of local spiral and or disk galaxies are comparable to $\alpha \sim 0.27$ (de Jong & Lacey 2000; Shen et al. 2003; Courteau et al. 2007). At $z = 0-3$, van der Wel et al. (2014) have revealed that the slopes of the size–stellar mass relations do not evolve. Adopting Equation (2) to calculate $L_{UV}$ from the stellar masses, we obtain the $r_e$–$L_{UV}$ relation and evolution similar to our results. At $z > 4$, there are several $\alpha$ measurements reported by Curtis-Lake et al. (2014), Huang et al. (2013), Jiang et al. (2013), and Grazian et al. (2012). However, these data points of $\alpha$ are largely scattered (the right panel of Figure 10). Nevertheless, our $\alpha$ values fall within the scatter of the previous measurements.

Our results of the $r_e$ (or $r_0$) evolution and the constant $\alpha$ suggest that the $r_e$–$L_{UV}$ relation of star-forming galaxies is unchanged but with a decreasing offset of $r_e$ from $z = 0$ to 8. Because the morphological evolution trend of star-forming galaxies is simple, our results are a benefit to studies using Monte Carlo simulations for luminosity function determinations that require an assumption of high-$z$ galaxy sizes (e.g., Ishigaki et al. 2014; Oesch et al. 2014). Moreover, these morphological evolution trends are important constraints on the parameters of galaxy-formation models.

Note that there is a possible source of systematics given by the cosmological SB dimming effect by which we would underestimate $r_e$ (Section 3). To estimate the effect of the cosmological SB dimming, we measure the $r_e$ of $z \sim 4-8$ LBGs with stacked images that accomplish the detection limit deeper than the individual images by a factor of $\sim 20-30$. The $r_e$ values measured in the stacked images roughly reproduce the size–luminosity relation of Figure 9, suggesting that there are no signatures of systematics in the $r_e$ values measured by our GALFIT profile fitting technique. There is another possibility of the cosmological SB dimming effect. If a large population of diffuse high-$z$ galaxies exists that are not identified in our HST images, we would underestimate the $r_e$ values. However, it is unlikely that such a diffuse high-$z$ population exists. This is because the luminosity functions of $z \sim 4-6$ LBGs derived with HST data agree with those obtained by ground-based observations (Beckwith et al. 2006), whose PSF FWHM is $\sim 1''$, corresponding to 3–4 kpc in radius at $z \sim 4-6$. In other words, at these redshifts, there is no diffuse population with a radius up to $\sim 3-4$ kpc that is significantly larger than our size measurements of $r_e \lesssim 1$ kpc (see, e.g., Figure 6). We therefore conclude that our results of size measurements are not significantly changed by the cosmological SB dimming effect.

The $r_e$–$L_{UV}$ relation is fitted by

$$r_e = r_0 \left( \frac{L_{UV}}{L_0} \right)^{\alpha},$$

(6)

where $r_0$ and $\alpha$ are free parameters. The $r_0$ value represents the effective radius at a luminosity of $L_0$, which is similar to the parameter $\gamma$ used in, for example, Newman et al. (2012). The $\alpha$ value is the slope of the $r_e$–$L_{UV}$ relation. We select $L_0$ to the best-fit Schechter parameter $M^*$ at $z \sim 3$ that corresponds to $M_{UV} = -21.0$, following the arguments of Huang et al. (2013).

The left panel of Figure 10 shows the redshift evolution of $r_0$ and $\alpha$. We parameterize the size growth rate by fitting $r_0$ with a function of $B_\alpha(1+z)^{\beta_\alpha}$. The best-fit function is 6.9$(1+z)^{-1.20\pm0.04}$ kpc, which does not significantly change even with and without the $r_0^{\text{Opt}}$ results. We also carry out fitting with a function of $B_\beta h(z)\gamma$, where $B_\beta$ and $\beta_\beta$ are free parameters and $h(z) \equiv H/H_0 = \sqrt{\Omega_m(1+z)^3 + \Omega_k}$. Here the fitting of the $h(z)$-form functions are conducted because these $h(z)$-form functions could be a more realistic physical treatment, as claimed by, for example, van der Wel et al. (2014). The fitting results yield the best-fit function of 5.3$h(z)^{-0.97\pm0.04}$ kpc that is plotted in the left panel of Figure 10. Although we do not use the $r_e$ estimate of $z \sim 10$ for the fitting, the $z \sim 10$ data point is placed on the extrapolation of the best-fit function.

![Figure 8](image-url)
Table 6
Summary of the Best-fit Size Growth Rates

| Data points | Sample          | $L_{UV}/L_{*3}$ | $B_1$ (kpc) | $\beta_1$  | $B_H$ (kpc) | $\beta_H$  |
|-------------|-----------------|-----------------|--------------|------------|-------------|------------|
| Median      | All             | 1–10            | 4.78 ± 0.68  | -0.84 ± 0.11 | 3.80 ± 0.40 | -0.62 ± 0.08 |
|             | w/o $i^\text{Opt}$ | 0.3–1          | 5.45 ± 0.31  | -1.10 ± 0.06 | 4.33 ± 0.17 | -0.86 ± 0.04 |
|             |                 | 0.12–0.3        | 4.44 ± 0.19  | -1.22 ± 0.05 | 3.46 ± 0.13 | -0.97 ± 0.05 |
|             |                 | 0.3–1           | 5.21 ± 0.28  | -1.15 ± 0.07 | 3.54 ± 0.29 | -0.80 ± 0.05 |
|             |                 | 0.12–0.3        | 3.54 ± 0.58  | -1.11 ± 0.11 | 2.45 ± 0.32 | -0.78 ± 0.08 |
| Average     | All             | 1–10            | 5.80 ± 0.65  | -0.79 ± 0.10 | 4.91 ± 0.42 | -0.61 ± 0.07 |
|             | w/o $i^\text{Opt}$ | 0.3–1          | 5.85 ± 0.33  | -0.95 ± 0.07 | 4.83 ± 0.20 | -0.74 ± 0.04 |
|             |                 | 0.12–0.3        | 5.52 ± 0.43  | -1.17 ± 0.07 | 4.29 ± 0.27 | -0.87 ± 0.05 |
|             |                 | 0.3–1           | 11.4 ± 4.44  | -1.22 ± 0.25 | 7.48 ± 2.37 | -0.85 ± 0.18 |
|             |                 | 0.12–0.3        | 10.9 ± 2.94  | -1.36 ± 0.18 | 6.90 ± 1.50 | -0.95 ± 0.13 |
|             |                 | 0.3–1           | 6.82 ± 2.25  | -1.31 ± 0.20 | 4.37 ± 1.18 | -0.91 ± 0.14 |
| Mode        | All             | 1–10            | 4.00 ± 0.49  | -0.78 ± 0.08 | 3.07 ± 0.30 | -0.55 ± 0.57 |
|             | w/o $i^\text{Opt}$ | 0.3–1          | 4.45 ± 0.89  | -1.26 ± 0.17 | 2.97 ± 0.45 | -0.89 ± 0.12 |
|             |                 | 0.12–0.3        | 3.28 ± 0.18  | -1.23 ± 0.07 | 2.56 ± 0.11 | -1.00 ± 0.05 |
|             |                 | 0.3–1           | 10.9 ± 3.94  | -1.14 ± 0.25 | 7.45 ± 2.14 | -0.80 ± 0.17 |
|             |                 | 0.12–0.3        | 3.00 ± 0.19  | -1.01 ± 0.05 | 2.15 ± 0.10 | -0.71 ± 0.03 |

Notes. Columns: (1) Statistics of $r_c$. (2) Sample used in the fits for the size evolution. “All” denotes the use of all samples in an $L_{UV}$ bin, and “w/o $i^\text{Opt}$” represents the exclusion of the data points of $i^\text{Opt}$. (3) Bins of $L_{UV}$ in units of $L_{*3}$. (4) $B_1$ of $B_1/(1+z)^{6}$. (5) $\beta_1$ of $B_1/(1+z)^{6}$. (6) $B_H$ of $B_H/(1+z)^{6}$. (7) $\beta_H$ of $B_H/(1+z)^{6}$. $h(z) = H(z)/H_0 = \sqrt{\Omega_M(1+z)^3 + \Omega_L}$. $\beta_H$ of $B_H/(1+z)^{6}$.

Table 7
Summary of the LBG Size Growth Rates from Previous Studies

| References       | Number      | Redshift Range | $\beta_1/(1+z)^{6}$ | Statistics | Size Measurements |
|------------------|-------------|----------------|----------------------|------------|-------------------|
| Bouwens et al. (2004) | (2929)     | 2–6            | -1.05 ± 0.21         | Average    | SExtractor        |
| Ferguson et al. (2004) | (773)      | 2–5            | -1.15               | Average    | SExtractor        |
| Ravindranath et al. (2006) | 1333 (4694) | 3–5            | ~-1.5               | ...        | GALFIT            |
| Hathi et al. (2008a) | (61)       | 3–6            | -1.5                | Average    | SExtractor        |
| Conselice & Arnold (2009) | 583 (583)  | 4–6            | ~-1.5               | ...        | SExtractor        |
| Oesch et al. (2010) | (21)       | 7–8            | -1.12 ± 0.17         | Average    | SExtractor, GALFIT |
| Grazian et al. (2012) | (153)      | 7              | ~-1                | Median     | GALFIT            |
| Mosleh et al. (2012) | (218)      | 4–7            | -1.20 ± 0.11         | Median     | GALFIT            |
| Huang et al. (2013) | 1012 (1356) | 4–5            | ~-1                 | Mode       | SExtractor, GALFIT |
| Ono et al. (2013) | 15 (81)    | 7–10           | -1.30 ± 0.14         | Average    | GALFIT            |
| Curtis-Lake et al. (2014) | 1318 (3738) | 4–9            | -0.31 ± 0.26         | Mode       | SExtractor        |
| Holwerda et al. (2014) | 8 (8)       | 9–10           | -1.0 ± 0.1           | Average    | GALFIT            |
| Kawamata et al. (2014) a | 39 (39)    | 6–8            | -1.24 ± 0.1          | Average    | galfit            |
| This work        | 4993 (10454)| 4–10           | -1.10 ± 0.06         | Median     | GALFIT            |
| incl. Photo-$z$ SFGs | 89880 (312722)b | 0–6          | ...                 | ...        | ...               |

Notes. Columns: (1) Reference. (2) Number of galaxies whose size is measured in the reference. The values in parentheses are the number of galaxies in the parent sample. (3) Redshift range for size measurements of LBGs. (4) Best-fit $\beta_1$ of $(1+z)^{6}$ for a bright ($L_{UV} \sim 0.3–1 L_{*3}$) galaxy sample. (5) Statistics for deriving a representative $r_c$ at a redshift. “Mode” corresponds to the peak of the size distribution derived by fitting with a log-normal function (Equation (5)). (6) Method or software used to measure galaxy sizes.

a Sample galaxies are selected in a field of a galaxy cluster. This study corrects for the gravitational lensing effects of magnification and shear with their mass model.

b The value is the total number of SFGs whose sizes are well measured in $i^\text{Opt}$ and $i^{UV}$. See Table 2.
5.3. SFR Surface Density

We examine the redshift evolution of SFR SD $\Sigma_{\text{SFR}}$.

Figure 12 shows $\Sigma_{\text{SFR}}$ as a function of redshift. Figure 12 is the same as Figure 5, but for all of our galaxies up to $z = 8$ with the binning of $L_{\text{UV}}$ values. Figure 12 shows that $\Sigma_{\text{SFR}}$ gradually increases by redshift from $z \sim 0$ to 8. This evolutional trend and the $\Sigma_{\text{SFR}}$ values are consistent with those of $z \sim 4–8$ previously reported by, for example, Oesch et al. (2010) and Ono et al. (2013). Our results of the $\Sigma_{\text{SFR}}$ evolution suggest that the $\Sigma_{\text{SFR}}$ of typical high-$z$ galaxies continuously increases from $z \sim 0$ to 8.

In Figure 12, we also find that the increase rate per redshift becomes small at $z \gtrsim 4$ in the regime of log $\Sigma_{\text{SFR}} \sim 0.5–1 \ M_\odot$ yr$^{-1}$ kpc$^{-2}$. We obtain the $\Sigma_{\text{SFR}}$ evolution curve using Equation (3) with the inputs of the best-fit function $n_0 = 6.9(1 + z)^{-1.20\pm0.04}$ (Section 5.2) and the SFR estimated from the $L_{\text{UV}}$ value via Equation (4). Figure 12 presents the $\Sigma_{\text{SFR}}$ evolution curve. As expected, the $\Sigma_{\text{SFR}}$ evolution curve follows the $\Sigma_{\text{SFR}}$ data points. In other words, the slow $\Sigma_{\text{SFR}}$ evolution at $z \gtrsim 4$ is explained by the simple power-law galaxy size evolution of $n_0 = 6.9(1 + z)^{-1.20\pm0.04}$.

In Figure 13, we examine the dependence of $\Sigma_{\text{SFR}}$ on SFR and $M_*$.

The left and right panels of Figure 13 show $\Sigma_{\text{SFR}}$ as functions of SFR and $M_*$, respectively. For comparison, we also plot SDSS galaxies with an exponential SB profile in Lackner & Gunn (2012) and the Milky Way (Kennicutt & Evans 2012). These local galaxies are placed in the regime of low $\Sigma_{\text{SFR}}$ values. Obviously, Figure 13 reproduces the result of Figure 12 that $\Sigma_{\text{SFR}}$ is typically higher for high-$z$ galaxies than for low-$z$ galaxies. In the $\Sigma_{\text{SFR}}$–SFR diagram of Figure 13, $\Sigma_{\text{SFR}}$ positively correlates with SFR. This is because the $\Sigma_{\text{SFR}}$ and SFR values are related by Equation (3). The slopes of the $\Sigma_{\text{SFR}}$–SFR relation appear similar at $z \sim 2–8$. On the other hand, we find that the $\Sigma_{\text{SFR}}$–$M_*$ diagram of Figure 13 shows no strong dependence of $\Sigma_{\text{SFR}}$ on $M_*$ (see also, e.g., Wuyts et al. 2011). These two diagrams suggest that $\Sigma_{\text{SFR}}$ increases toward high $z$, keeping the similar $\Sigma_{\text{SFR}}$–SFR and $\Sigma_{\text{SFR}}$–$M_*$ relations over $z \sim 2–8$.

5.4. Size–UV Slope $\beta$ Relation

We derive the $r_e$–UV slope $\beta$ relation to investigate the dependence of galaxy sizes on stellar population. The $\beta$ parameter is defined by $f_\beta \propto \lambda^\beta$, where $f_\beta$ is a galaxy spectrum at $\sim 1500–3000 \, \AA$, which is a coarse indicator of the stellar population and extinction of galaxies. A small $\beta$ means a blue spectral shape, suggesting young stellar ages, low metallicity, and dust extinction.

For the SFGs, we calculate $\beta$ via

$$\beta = - \frac{m_{1700} - m_{2800}}{2.5 \log 1700/2800} - 2,$$

where $m_{1700}$ and $m_{2800}$ are the total magnitudes at wavelengths of 1700 and 2800 Å in the rest frame, respectively. These magnitudes are taken from the catalog of Skelton et al. (2014). For the $z \sim 4, 5,$ and 6 LBGs, we derive $\beta$, fitting the function of $f_\beta \propto \lambda^\beta$ to the magnitude sets of $i_{775}z_{850}Y_{105}J_{125}, \ z_{850}Y_{105}J_{125}H_{60},$ and $Y_{105}J_{125}H_{60}$, respectively, in the same manner as Bouwens et al. (2014a). For the $z \sim 7$ and 8 LBGs, we estimate $\beta$ using

$$\beta = -2.0 + 4.59(J_{125} - H_{60})(\text{for } z \sim 7),$$
Figure 14 represents the $r_e$–$\beta$ relation in the bin of $L_{UV}/L_{z=3}^\ast = 0.3–1$. We find that the $L_{UV}$–beta relation is poorly determined for the $z \sim 8$ LBGs, due to the small statistics, and the $z \sim 8$ result is not presented. In Figure 14, we identify clear trends that smaller galaxies have a bluer UV spectral shape at $0 \lesssim z \lesssim 7$. This is consistent with the results of $z \sim 6–8$ LBGs reported by Kawamata et al. (2014). This $r_e$–$\beta$ correlation indicates that young and forming galaxies typically have a small size. We find a negative correlation between $r_e$ and $\beta$ for the $z = 5–6$ SFGs. The negative correlation trend appears to be simply due to the small sample, which is not statistically significant.

\[ \beta = -2.0 + 8.68 (JH_{140} - H_{160}) \text{ (for } z \sim 8) \]. 

6. DISCUSSION

6.1. The $r_e$ Distribution and SHSR: Implications for Host DM Halos and Disks

Here we investigate the properties of the $r_e$ distributions in Section 6.1.1 and estimate SHSRs in Section 6.1.2. Combining these results and theoretical models, we discuss the host DM halos and the stellar dynamics in Section 6.1.3.

6.1.1. Log-normal Distribution of $r_e$

In Section 4.2, we find that the $r_e$ distributions of our galaxies are well fitted by the log-normal functions in the wide range of redshift, $z \sim 0–6$, and luminosity.
Figure 15 shows the best-fit $\sigma_{\text{in}, r_e}$ values as a function of redshift. Size measurement uncertainties $\sigma_{\text{in}, r_e, \text{err}}$ would broaden the width of the $r_e$ distribution. We estimate typical $\sigma_{\text{in}, r_e, \text{err}}$ in each $z$ and $L_{\text{UV}}$ bin. We correct $\sigma_{\text{in}, r_e}$ for the size measurement uncertainties through $\sigma_{\text{in}, r_e} = (\sigma_{\text{in}, r_e, \text{obs}}^2 + \sigma_{\text{in}, r_e, \text{err}}^2)^{0.5}$, where $\sigma_{\text{in}, r_e, \text{obs}}$ is the observed width of the $r_e$ distribution. We find that $\sigma_{\text{in}, r_e}$ values fall in the range of $0.45$–$0.75$ with no clear evolutional trend at $z \sim 0$–$6$. Our $\sigma_{\text{in}, r_e}$ values are slightly larger than the estimates for local disks in de Jong & Lacey (2000), Shen et al. (2003), and Courteau et al. (2007) and for late-type galaxies at $z \sim 0$–$3$ in van der Wel et al. (2014). These differences would be explained by the choices of the wavelengths for the galaxy size measurements because these previous studies measure galaxy sizes in the rest-frame optical wavelength. In fact, if we choose from the rest-frame UV luminosity to optical wavelength sizes for the size distribution, we obtain moderately small $\sigma_{\text{in}, r_e}$ values. However, differences of $\sim 20$–$30\%$ still remain beyond the error bars in Figure 15. These $\sim 20$–$30\%$ differences are probably explained by the sample and measurement technique differences. We also compare the $\sigma_{\text{in}, r_e}$ estimates of $z \sim 4$–$5$ LBGs given by Huang et al. (2013) and find a moderately large difference by a factor of $1.5$. However, the scatters of our measurements and the statistical uncertainties in the estimates of Huang et al. (2013) are too large to conclude on the differences.

6.1.2. SHSR

We estimate the SHSRs that are defined with the ratio of $r_e/r_{\text{vir}}$, where $r_{\text{vir}}$ is the virial radius of a host DM halo. The $r_{\text{vir}}$ value is calculated by

$$r_{\text{vir}} = \left( \frac{2GM_{\text{vir}}}{\Delta_{\text{vir}} \Omega_m(z) H(z)^2} \right)^{1/3},$$

where $\Delta_{\text{vir}} = 18\pi^2 + 82\pi - 39\pi^2$ and $x = \Omega_m(z) - 1$ (Bryan & Norman 1998). We obtain the virial mass of a DM halo, $M_{\text{vir}}$, from the stellar mass, $M_s$, of individual galaxies by using the relation determined by the abundance-matching analyses (Behroozi et al. 2010, 2013). Figure 16 shows $r_e/r_{\text{vir}}$ as a function of redshift and its dependence on $L_{\text{UV}}$ at $z \sim 0$–$8$. The $z$ ~ 10 data point is omitted because of the small statistics. In Figure 16, we find that $r_e/r_{\text{vir}}$ is $\sim 2\%$ for the star-forming galaxies and $\sim 0.5\%$ for the QGs. Interestingly, the $r_e/r_{\text{vir}}$ of the

### Table 8

Size–Luminosity Relation at $z = 0$–$8$

| $L_{\text{UV}}$ (mag) | $r_e^{\text{opt}}$ (kpc) | $M_{\text{UV}}$ | $r_e^{\text{UV}}$ (kpc) | $M_{\text{UV}}$ | $r_e^{\text{UV}}$ (kpc) |
|----------------------|----------------------|----------------|----------------------|----------------|----------------------|
| $z = 0$–$1$ SFGs     | $z = 1$–$2$ SFGs     | $z = 4$ LBGs   |
| $-21.0$              | $-21.0$              | $-19.0$        | $-18.0$              | $-17.0$        | $-15.0$              |
| $-20.0$              | $-20.0$              | $-19.0$        | $-18.0$              | $-17.0$        | $-15.0$              |
| $-19.0$              | $-19.0$              | $-18.0$        | $-17.0$              | $-16.0$        | $-15.0$              |
| $-18.0$              | $-18.0$              | $-17.0$        | $-16.0$              | $-15.0$        | $-14.0$              |
| $-17.0$              | $-17.0$              | $-16.0$        | $-15.0$              | $-14.0$        | $-13.0$              |
| $-16.0$              | $-16.0$              | $-15.0$        | $-14.0$              | $-13.0$        | $-12.0$              |

Note. Columns: (1), (3), (5) UV magnitude, (2), (4), (6) Median effective radius at the rest-frame optical or UV wavelength. The lower and upper limits indicate the 16th and 84th percentiles of the $r_e$ distribution, respectively.
star-forming galaxies is almost constant with redshift, albeit with large uncertainties at \( z \gtrsim 5 \). The no significant evolution of \( r_e/R_{\text{vir}} \) is reported by Kawamata et al. (2014) based on a compilation of data from the literature for star-forming galaxies at \( z \gtrsim 2 \). Our systematic structural analyses seamlessly confirm the report of no large evolution from \( z \approx 0 \) with the homogenous data sets and the same analysis technique over the wide redshift range. Figure 16 also indicates that there is no strong dependence of \( r_e/R_{\text{vir}} \) in the wide luminosity range of \( L_{\text{UV}} \sim 0.12 - 10L_{\odot} \). The SFR for the LBGs is corrected for dust extinction with the two relations of \( M_{\text{UV}} - \beta \) (Bouwens et al. 2014a) and IRX – \( 
abla \) (Meurer et al. 1999). The square represents the Milky Way (Kennicutt & Evans 2012). The gray dots indicate SDSS galaxies with an exponential SB distribution from a catalog of Lackner & Gunn (2012), whose \( \Sigma_{\text{SFR}} \) is calculated from the SFR and \( r_e \) values based on \( u \)-band magnitudes and single Sérsic profile fits, respectively. The stellar mass of the SDSS galaxies is taken from Kauffmann et al. (2003), Brinchmann et al. (2004), and Salim et al. (2007). The dashed lines correspond to constant effective radii of \( r_e = 0.1, 1, 10 \) kpc, from top to bottom. The horizontal lines are the weighted-average values of \( \Sigma_{\text{SFR}} \) in each redshift bin. The error bars denote the 16th and 84th percentiles of the distribution.

### Figure 13. SFR SD \( \Sigma_{\text{SFR}} \) as functions of SFR (left) and stellar mass (right). The small magenta and cyan circles indicate median \( \Sigma_{\text{SFR}} \) values at a given SFR or \( M_* \) for the LBGs at \( z \sim 2 \) and \( z \sim 4 \), respectively, based on \( r_e^{1/2} \). The large circles represent the LBGs at \( z \sim 4 \) (cyan), \( z \sim 6 \) (green), and \( z \sim 8 \) (dark blue). The black points denote individual LBGs at \( z \approx 7 - 8 \). The SFR for the LBGs is corrected for dust extinction with the two relations of \( M_{\text{UV}} - \beta \) (Bouwens et al. 2014a) and IRX – \( 
abla \) (Meurer et al. 1999). The square represents the Milky Way (Kennicutt & Evans 2012). The gray dots indicate SDSS galaxies with an exponential SB distribution from a catalog of Lackner & Gunn (2012), whose \( \Sigma_{\text{SFR}} \) is calculated from the SFR and \( r_e \) values based on \( u \)-band magnitudes and single Sérsic profile fits, respectively. The stellar mass of the SDSS galaxies is taken from Kauffmann et al. (2003), Brinchmann et al. (2004), and Salim et al. (2007). The dashed lines correspond to constant effective radii of \( r_e = 0.1, 1, 10 \) kpc, from top to bottom. The horizontal lines are the weighted-average values of \( \Sigma_{\text{SFR}} \) in each redshift bin. The error bars denote the 16th and 84th percentiles of the distribution.

Summarizing our observational findings for star-forming galaxies in Sections 6.1.1 and 6.1.2, we identify, over cosmic time of \( z \sim 0 - 6 \), that the \( r_e \) distribution is well represented by log-normal distributions, that the standard deviation is \( \sigma_{\text{ln}r_e} \gtrsim 0.45 - 0.75 \), and that the SHSR is almost constant, \( \sim 2\% \). It is interesting to compare these observational results with the theoretical predictions of the spin parameter \( \lambda \) distribution of host dark halos. DM \( N \)-body simulations suggest that \( \lambda \) follows a log-normal distribution with the standard deviation of \( \sigma_{\text{ln}\lambda} \sim 0.5 - 0.6 \) (e.g., Barnes & Efstathiou 1987; Warren et al. 1992; Bullock et al. 2001). The shape and the standard deviation of the \( \lambda \) distributions are very similar to those of \( r_e \). These similarities support an idea that galaxy sizes of stellar components would be related to the host DM halo kinematics. Our study has obtained this hint of a \( r_e - \lambda \) relation at a wide range of redshift, \( z \sim 0 - 6 \), that complements the previous similar claim made for \( z \lesssim 3 \) galaxies (van der Wel et al. 2014).

If \( r_e \) values are really determined by \( \lambda \) as indicated by the \( r_e \) distribution properties, stellar components of the high-\( z \) star-forming galaxies have dominant rotational motions that form stellar disks. In fact, according to disk-formation models (e.g., Fall & Efstathiou 1980; Fall 1983, 2002; Mo et al. 1998), gas receives the specific angular momentum from host DM halos through tidal interactions that make a constant SHSR similar to the one found in Section 6.1.2.

Moreover, in Section 5.1, we find that typical high-\( z \) star-forming galaxies have a low Sérsic index of \( n \sim 1.5 \) at \( z \sim 0 - 6 \). The combination of the log-normal \( r_e \) distribution, the \( r_e - \lambda \) standard deviation similarity, and the low Sérsic index suggests a picture in which typical high-\( z \) star-forming galaxies have stellar components similar to disks in stellar dynamics and morphology over cosmic time of \( z \sim 0 - 6 \).
6.2. Specific Disk Angular Momentum Inferred from the Observations and Models

As we discuss in Section 6, a number of observational results suggest that typical high-
\textit{z} star-forming galaxies have disk-like stellar components in dynamics and morphology at $z \sim 0–6$.

$$r_{\text{e}} = 1.678 \left( \frac{j_{\text{d}}}{m_{\text{d}}} \right) \frac{J_r}{\sqrt{m_{\text{d}} \lambda \left( c_{\text{vir}}, m_{\text{d}}, J_{\text{d}} \right)}} \left( \frac{r_{\text{d}}}{c_{\text{vir}}} \right),$$

where 1.678 is a coefficient for converting the scale length of the exponential disk $R_d$ to $r_{\text{e}}$. The $j_{\text{d}} (m_{\text{d}})$ value is an angular
Figure 17. Comparison between our SHSR, $r_{e,\text{vir}}$, and those of previous studies in a bin of $z \sim 0.3-1$. The symbols and lines are the same as those in Figure 8, and we include a measurement for local galaxies with the black filled circle (Kravtsov 2013). The $r_{e,\text{vir}}$ values of the gray symbols are taken from Kawamata et al. (2014), who compiled the results of the literature. The horizontal dashed, solid, and dot-dashed lines indicate weighted means of $\langle r_{e,\text{vir}} \rangle$ of average, median, and modal values, respectively. The red, green, and blue shaded areas illustrate the regions of $j_{\lambda}/m_{\lambda} = 1.5$, 1.0, and 0.5, respectively (see Section 6.2 for details). A typical error bar in our $r_{e,\text{vir}}$ estimates is shown at $z \sim 0.5$.

momentum (mass) ratio of a central disk to a host DM halo. The $f_{r_{e}}(c_{\text{vir}})$ and $f_{\lambda}(\lambda, c_{\text{vir}}, m_{d}, j_{\lambda})$ are functions related to halo and baryon concentrations, respectively. The $c_{\text{vir}}$ is the halo concentration factor. The full functional forms of $f_{r_{e}}(c_{\text{vir}})$ and $f_{\lambda}(\lambda, c_{\text{vir}}, m_{d}, j_{\lambda})$ are found in Mo et al. (1998). The SHSR $r_{e,\text{vir}}$ with a fixed $j_{\lambda}/m_{\lambda}$ shows little or no dependence on $m_{d}$ and $j_{\lambda}$. If we use $\lambda$ and $c_{\text{vir}}$ values well constrained by numerical simulations (e.g., Vitvitska et al. 2002; Davis & Natarajan 2009; Prada et al. 2012), we can constrain $j_{\lambda}/m_{\lambda}$.

Figure 17 presents $r_{e,\text{vir}}$ regions corresponding to $j_{\lambda}/m_{\lambda} = 0.5$, 1.0, and 1.5. To determine these regions, we randomly change the $\lambda$ and $c_{\text{vir}}$ values within the $\lambda = 0.058-0.045$ (Vitvitska et al. 2002; Davis & Natarajan 2009) and $c_{\text{vir}}$ ranges at log $M_{\text{vir}} = 11-13$ (M$_{\odot}$) in Figure 12 of Prada et al. (2012), respectively. We also assume the conservative range of $0.05 \leq m_{d} \leq 0.1$ (e.g., Mo et al. 1998). Substituting these numbers and our results of $r_{e,\text{vir}}$ (Section 6.1.2) into Equation (11), we obtain $j_{\lambda}/m_{\lambda} = 0.7-0.8$. Note that our estimates of $r_{e,\text{vir}}$ fall in $j_{\lambda}/m_{\lambda} \sim 0.5-1$ at $z \sim 0.5-8$, regardless of the statistical choices (Figure 17).

This result of $j_{\lambda}/m_{\lambda} \sim 0.5-1$ indicates that a central galaxy acquires more than half of the specific angular momentum from a host DM halo. Our $j_{\lambda}/m_{\lambda}$ values are comparable to the estimates with kinematical data for nearby disks ($j_{\lambda}/m_{\lambda} \sim 0.8$; Romanowsky & Fall 2012; Fall & Romanowsky 2013). Moreover, Genel et al. (2015) predict $j_{\lambda}/m_{\lambda} \sim 1$ for $z \sim 0$ late-type galaxies with the Illustris simulations (Genel et al. 2014; Vogelsberger et al. 2014a, 2014b). These independent studies for $z \sim 0$ galaxies confirm that our estimate of $j_{\lambda}/m_{\lambda} \sim 0.5-1$ is correct at $z \sim 0$ and suggest that the conclusion of no significant evolution of $j_{\lambda}/m_{\lambda}$ over $z \sim 0-8$ would be reliable. Genel et al. (2015) have revealed that galactic winds with high mass-loading factors (active galactic nucleus feedback) enhance (suppress) $j_{\lambda}/m_{\lambda}$. This suggests that the no significant evolution of $j_{\lambda}/m_{\lambda}$ at $0 \lesssim z \lesssim 8$ would place important constraints on parameters of galaxy feedback models.

In Section 6.1.2, we obtain that the SHSR of QGs is $\sim 0.5\%$, which is about four times smaller than that of star-forming galaxies. If we naively assume that QGs follow Equation (11) with one-fourth of the specific angular momentum of the star-forming galaxies, we obtain $j_{\lambda}/m_{\lambda} \sim 0.1-0.25$. This value is comparable to $j_{\lambda}/m_{\lambda} \sim 0.1$ for nearby ellipticals in Fall & Romanowsky (2013) and $j_{\lambda}/m_{\lambda} \sim 0.3$ for $z \sim 0$ early-type galaxies predicted in Genel et al. (2015). This small specific angular momentum of QGs would be explained by the loss of angular momentum via dynamical friction during merger events and or weak feedback (e.g., Scannapieco et al. 2008; Zavala et al. 2008).

6.3. Clumpy Structures of High-$z$ Star-forming Galaxies

Our study has shown a wide variety of morphological measurement results, supplemented by the theoretical models. It should be noted that these results are based on the structural analyses for major stellar components of the galaxies because we mask substructures such as star-forming clumps (e.g., Guo et al. 2014; Murata et al. 2014; Tadaki et al. 2014) in our analyses. The signatures of the morphological variety could emerge in dispersions of internal colors and SB profiles in recent structural analyses at $z \sim 2-3$ (e.g., Boada et al. 2015; Morishita et al. 2015). Moreover, we find that the SFR SD, $\Sigma_{SFR}$, increases toward high $z$ in Figures 12 and 13. This fact suggests that star-forming galaxies at high $z$ would tend to have a high gas mass density if we assume the Kennicutt–Schmidt law (Kennicutt 1998b). The gas-rich disks may enhance the formation of star-forming clumps through the process of disk instabilities (e.g., Genzel et al. 2011). The detailed analyses and results for the clumpy stellar subcomponents are presented in paper II (T. Shibuya et al. 2015, in preparation).

7. SUMMARY AND CONCLUSIONS

We study redshift evolution of $r_{e}$ and the size-relevant physical quantities such as Sérsic index $n$, $r_{e}$ distribution, $r_{e,\text{vir}}$, and the $r_{e}-L_{UV}$ relation using the galaxy samples at $z = 0-10$ made with the deep extragalactic legacy data of HST. The HST samples consist of 176,152 galaxies with a photo-$z$ at $z = 0-6$ from the 3D-HST+CANDELS catalog and 10,454 LBGs at $z = 4-10$ selected in CANDELS, HUDF 09/12, and parallel fields of HFF, which are the largest samples ever used for studies of galaxy size evolution in the wide redshift range of $z = 0-10$. Our systematic size analyses with the large samples allow us to measure galaxy sizes by the same technique and to evaluate the biases of morphological $K$ correction, statistics choices, and galaxy selection as well as the cosmic SB dimming. Using our galaxies at $z \sim 2-3$, we confirm that these biases are small, $\lesssim 30\%$, in the statistical sense for star-forming galaxies at high $z$, and do not change our conclusions on size evolution.

Our findings in this study are as follows.

1. The best-fit Sérsic index shows a low value of $n \sim 1.5$ for the star-forming galaxies at $z \sim 0-6$. The low $n$ values indicate that a typical star-forming galaxy has a disk-like SB profile.
2. We derive the $r_e-L_{\text{UV}}$ relation for star-forming galaxies over the wide redshift range of $z = 0$–8. The power-law fitting of $r_e = n_0 (L_{\text{UV}}/L_0)^\gamma$ reveals that $r_e$ values significantly decrease toward high $z$. Similar to the evolution of $r_h$, the average, median, and modal $r_e$ values in the linear space clearly decrease from $z \sim 0$ to $z \sim 6$. The $r_e$ values in any statistics evolve with $r_e \propto (1 + z)^{-1.0 \pm 1.3}$. The slope $\alpha$ of the relation has a constant value of $\alpha = -0.27 \pm 0.01$ at $0 \lesssim z \lesssim 8$, providing an important constraint for galaxy evolution models.

3. The SFR SD, $\Sigma_{\text{SFR}}$, increases from $z \sim 0$ to $z \sim 8$, whereas we find no stellar-mass dependence of $\Sigma_{\text{SFR}}$ in this redshift range. The increase of $\Sigma_{\text{SFR}}$ suggests that high-$z$ star-forming galaxies would have a gas mass density higher than low-$z$ star-forming galaxies on average, if one assumes that the Kennicutt–Schmidt law does not evolve significantly by redshift.

4. We identify a clear positive correlation between $r_e$ and $\beta$ for star-forming galaxies at $z \sim 0$–7 in the luminosity range of $0.3$–$1.0 L_{\odot}$, This is explained by a simple picture in which galaxies with young stellar ages and low metal-dust contents typically have a small size.

5. The $r_e$ distribution of UV-bright star-forming galaxies is well represented by log-normal functions. The standard deviation of the log-normal $r_e$ distribution $\sigma_{\text{r}_e}$ is $\sim 0.45$–0.75, and $\sigma_{\text{r}_e}$ does not significantly change at $z \sim 0$–6. Note that the structure formation models predict that the distribution of a DM spin parameter $\lambda$ follows a log-normal distribution with the $\lambda$-distribution’s standard deviation of $\sigma_{\lambda} \sim 0.5$–0.6. The distribution shapes and standard deviations of $r_e$ and $\lambda$ are similar, supporting an idea that galaxy sizes of stellar components could be related to the host DM halo kinematics.

6. Combining our stellar $r_e$ measurements with host DM halo radii, $r_{\text{vir}}$, estimated from the abundance-matching study of Behroozi et al., we obtain a nearly constant value of $r_e/r_{\text{vir}} = 1.0\%$–3.5\% at $0 \lesssim z \lesssim 6$ in any of the statistical choices of average, median, and mode.

7. The combination of the log-normal $r_e$ distribution with $\sigma_{\text{r}_e} \approx 0.45$–0.75 and the low Sérsic index suggests a picture in which the typical high-$z$ star-forming galaxies have stellar components similar to disks in stellar dynamics and morphology over cosmic time of $z \sim 0$–6. If we assume the disk-formation model of Mo et al. (1998), our $r_e/r_{\text{vir}}$ estimates indicate that a central galaxy acquires more than half of its specific angular momentum from its host DM halo, $j_0/m_0 \approx 0.5$–1.

These results are based on the major stellar components of galaxies because we mask galaxy substructures such as star-forming clumps in our analyses. The detailed analyses and results for the clumpy stellar subcomponents are presented in paper II (T. Shibuya 2015, in preparation). We expect that future facilities such as the James-Webb Space Telescope, the Wide-Field Infrared Survey Telescope, the Wide-field Imaging Surveyor for High-redshift telescope, and 30 m telescopes will obtain deep near-infrared images with a high spatial resolution, a PSF FHWM of $\lesssim 0'1$ – $0'2$, for a large number of galaxies at $z \sim 10$ and beyond. Surveys with these facilities will reveal when the size–luminosity relation emerges and whether the first galaxies fall within the extrapolation of the $r_e$ evolution and the nearly constant relation of $r_e/r_{\text{vir}} = 1.0\%$–3.5\% at $z \sim 0$–8 and 0–6, respectively, that we find in this study.

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