PHYSICAL PROPERTIES OF SPECTROSCOPICALLY CONFIRMED GALAXIES AT $z \geq 6$. II. MORPHOLOGY OF THE REST-FRAME UV CONTINUUM AND Lyα EMISSION*

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ABSTRACT

We present a detailed structural and morphological study of a large sample of spectroscopically confirmed galaxies at $z \geq 6$ using deep Hubble Space Telescope (HST) near-IR broad-band images and Subaru Telescope optical narrow-band images. The galaxy sample consists of 51 Lyα emitters (LAEs) at $z \approx 5.7$, 6.5, and 7.0, and 16 Lyman break galaxies (LBGs) at 5.9 $\leq z \leq 6.5$. These galaxies exhibit a wide range of rest-frame UV continuum morphology in the HST images, from compact features to multiple component systems. The fraction of merging/interacting galaxies reaches 40%-50% at the brightest end of $M_{1500} \leq -20.5$ mag. The intrinsic half-light radii after correcting for point-spread function (PSF) broadening, are roughly between $r_{hl,in} \approx 0.05$ (0.3 kpc) and $0.3$ (1.7 kpc) at $M_{1500} \leq -19.5$ mag. The median $r_{hl,in}$ value is 0.16 (0.9 kpc). This is consistent with the sizes of bright LAEs and LBGs at $z \geq 6$ found in previous studies. In addition, more luminous galaxies tend to be larger and exhibit a weak size–luminosity relation, $r_{hl,in} \propto L^{0.14}$ at $M_{1500} \leq -19.5$ mag. The slope of 0.14 is significantly flatter than those in fainter LBG samples. We discuss the morphology of $z \geq 6$ galaxies with nonparametric methods, including the concentration, asymmetry, and smoothness system and the Gini and $M_{20}$ parameters, and demonstrate their validity through simulations. We search for extended Lyα emission halos around LAEs at $z \approx 5.7$ and 6.5 by stacking a number of narrow-band images. We do not find evidence of extended Lyα halos predicted by cosmological simulations. Such halos, if they exist, could be weaker than predicted. Finally, we investigate positional misalignment between the UV continuum and Lyα emissions in LAEs. While the two positions are generally consistent, several merging galaxies show significant positional differences. This is likely caused by a disturbed interstellar medium distribution due to merging activity.

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

Online-only material: color figures

1. INTRODUCTION

Structural and morphological studies of galaxies provide basic, apparent information. Nearby galaxies are generally classified into three broad categories: spiral, elliptical, and irregular. The majority of luminous nearby galaxies ($z \leq 0.1$) are spirals and ellipticals (Abraham & van den Bergh 2001). At higher redshifts, galaxies are not as well developed, and the fraction of irregular galaxies steadily increases (e.g., Driver et al. 1995, 1998). Galaxy morphology and structure have also been well researched in the redshift range of $0.1 \leq z \leq 1$ (e.g., Brinchmann et al. 1998; Lilly et al. 1998; Schade et al. 1999; Carlberg et al. 2000; Le Fèvre et al. 2000; van den Bergh et al. 2000 and references therein). These galaxies show more disturbed structures than nearby galaxies do in the rest-frame UV and optical (e.g., Abraham & van den Bergh 2001; Windhorst et al. 2002; Taylor-Mager et al. 2007; Blanton & Moustakas 2009; Shi et al. 2009). The fraction of irregular galaxies increases from less than 10% at $z \leq 0.5$ to ~30% at $z \approx 1$ (e.g., Brinchmann et al. 1998; van den Bergh et al. 2000). In addition, more galaxies were identified as merging systems, reflecting the hierarchical build-up of galaxies and mass assembly in the cold dark matter (CDM) scenario (White & Rees 1978; Cole et al. 2000). For example, nearly 20% of $z \approx 1$ galaxies in the Le Fèvre et al. (2000) sample are in close pairs.

For galaxies at $z \geq 2$–3, morphological classification is challenging, as most galaxies appear peculiar. They are also smaller toward higher redshifts (Ferguson et al. 2004). In addition, galaxies appear much fainter due to cosmological $(1 + z)^2$ surface brightness (SB) dimming. Traditional classifications, including Hubble’s tuning-fork system, are no longer practical at these higher redshifts. Therefore, nonparametric methods such as the concentration, asymmetry, and smoothness (CAS) system (Conselice 2003) and the Gini and $M_{20}$ parameters (Lotz et al. 2004) play an important role. Most morphological and structural...
analyses in this redshift range were done in the GOODS fields (Giavalisco et al. 2004) because of the high-quality *Hubble Space Telescope (HST)* data (e.g., Lowenthal et al. 1997; Ravindranath et al. 2006; Law et al. 2007; Cassata et al. 2010). In the rest-frame UV, $z \geq 3$ galaxies are usually compact (from one to several kiloparsecs), but many of them display extended features or multiple clumps in deep *HST* images (e.g., Giavalisco et al. 1996; Venemans et al. 2005; Ravindranath et al. 2006; Pirzkal et al. 2007; Conselice & Arnold 2009; Cooke et al. 2010; Gronwall et al. 2011; Law et al. 2012). For example, the Ravindranath et al. (2006) sample contains thousands of photometrically selected LBGs at $z \geq 2.5$, and about 30% of them have multiple cores. In Law et al. (2012), a sample of spectroscopically confirmed galaxies in a similar redshift range also showed a high fraction of interacting systems.

In the highest redshift range $z \geq 6$, morphological studies become even more difficult. Galaxies appear very faint, and their rest-frame UV light moves to the near-IR wavelength range, where telescope resolution is poorer. A typical galaxy occupies only a few pixels even in *HST* near-IR images, so size is usually the only physical parameter that can be reliably measured in the literature. Studies based on photometrically selected galaxies have shown that $z \geq 6$ galaxies are generally very compact, and most of them are barely spatially resolved. For example, Oesch et al. (2010) reported the sizes of 16 LBGs at $z \geq 7$ in the Hubble Ultra-Deep Field (HUDF) and they found that only two of the galaxies in their sample showed extended features, and the rest were very compact ($\lesssim 1$ kpc). This sample is very faint. However, observations of a handful brighter galaxies with spectroscopic redshifts also suggest compact morphology, with a typical size of $\lesssim 1$ kpc (e.g., Stanway et al. 2004; Dow-Hygeldun et al. 2007; Cowie et al. 2011). Note that at low redshifts galaxy size is correlated with physical properties such as mass and luminosity. Such relations may still exist in high-redshift galaxies, but could have evolved over time (e.g., Grazian et al. 2012; Mosleh et al. 2012).

In this paper, we will carry out a structural and morphological study of a sample of 67 galaxies at $z \geq 6$. The sample is the largest collection of spectroscopically confirmed galaxies in this redshift range, including 51 Lyα emitters (LAEs) and 16 Lyman break galaxies (LBGs). This paper is the second in a series presenting the physical properties of these galaxies. In the first paper (Jiang et al. 2013, hereafter Paper I), we presented deep Subaru optical and *HST* near-IR data. We also derived various rest-frame UV continuum and Lyα emission properties, including UV-continuum slope $\beta$, the Lyα rest-frame equivalent width (EW), and star formation rates (SFRs). These galaxies have steep UV continuum slopes, roughly between $\beta \approx -1.5$ and $-3.5$, with a mean value of $\beta \sim -2.3$, and a range of Lyα EWs from $\sim 10$ to $\sim 200$ Å. Their SFRs are moderate, from a few to a few tens of solar masses per year. In this paper, we will study the structure and morphology of their rest-frame UV continuum emission based on our *HST* images, and of their Lyα emission based on our ground-based narrow-band images.

The layout of the paper is as follows. In Section 2 we briefly review our galaxy sample and the optical and near-IR data that will be used for the paper. We measure the structure and morphology of the UV continuum emission in Section 3, and of the Lyα emission in Section 4. We then discuss our results and summarize the paper in Section 5. Throughout the paper we use a $\Lambda$-dominated flat cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ (Komatsu et al. 2011). All magnitudes are on the AB system (Oke & Gunn 1983).

### 2. GALAXY SAMPLE AND DATA

In Section 2 of Paper I, we provided a detailed description of our galaxy sample and the multi-wavelength data that we studied. Here we summarize that information. There are a total of 67 spectroscopically confirmed galaxies in our sample: 62 are from the Subaru Deep Field (SDF; Kashikawa et al. 2004), and the remaining 5 are from the Subaru *XMM-Newton* Deep Survey field (SXDS; Furusawa et al. 2008). They represent the most luminous galaxies in terms of Lyα luminosity (for LAEs) or UV continuum luminosity (for LBGs) in this redshift range. The SDF galaxy sample contains 22 LAEs at $z \sim 5.7$ (Shimasaku et al. 2006; Kashikawa et al. 2011), 25 LAEs at $z \sim 6.5$ (Taniguchi et al. 2005; Kashikawa et al. 2006, 2011), and 1 LAE at $z = 6.96$ (Iye et al. 2006). The LAEs at $z \sim 5.7$ and 6.5 have a relatively uniform magnitude limit of 26 mag in the narrow bands NB816 and NB921 and thus make a well-defined sample. The SDF sample also contains 14 LBGs at 5.9 $\leq z \leq$ 6.5 (Nagao et al. 2004, 2005, 2007; Ota et al. 2008; Jiang et al. 2011; Toshikawa et al. 2012). The LBG candidates in these studies were selected using different criteria, and have a rather inhomogeneous depth. The SXDS sample consists of five galaxies, including two LBGs at $z \sim 6$ (Curtis-Lake et al. 2012) and three LAEs at $z \sim 6.5$ (Ouchi et al. 2010). All these galaxies are listed in Table 1 of Paper I.

The SDF and SXDS were observed with the Subaru Suprime-Cam (Kashikawa et al. 2004; Furusawa et al. 2008). They have extremely deep optical images in a series of broad and narrow bands. Public stacked images are available for the two fields, but the public data do not include the images taken recently. In Paper I, we produced our own stacked images in six broad bands ($BVRI^*z'y$) and three narrow bands (NB816, NB921, and NB973) by including all available data in the archive. Our stacked images have great depth with excellent PSF FHWMs of 0.5–0.7. The near-IR imaging data for the SDF galaxies are from three *HST* GO programs 11149 (PI: E. Egami), 12329, and 12616 (PI: L. Jiang). The *HST* observations were made with a mix of instruments and depths. The majority of the galaxies were observed with WFC3 in the F125W (hereafter $J_{125}$) and F160W (hereafter $H$ or $H_{160}$) bands. The typical integration time was two *HST* orbits (roughly 5400 s) per band. This provides a depth of $\sim 27.5$ mag (5σ detection) in the $J_{125}$ band, and $\sim 27.1$ mag in the $H_{160}$ band (see also Windhorst et al. 2011). The pixel size in the final reduced WFC3 images is 0.06′. Several SDF galaxies were observed with NICMOS in the F110W (hereafter $J_{110}$) and $H_{160}$ bands. The typical integration time was also two *HST* orbits. The depths in the two bands are $\sim 26.4$ mag and $\sim 26.1$ mag, respectively. The pixel size in the final reduced NICMOS images is 0.1. The five SXDS galaxies were covered by the UKIDSS Ultra-Deep Survey (UDS). Their *HST* WFC3 near-IR data were obtained from CANDELS (Grogin et al. 2011; Koekemoer et al. 2011). The exposure depth of the CANDELS UDS data is 1900 s in the $J_{125}$ band and 3300 s in the $H_{160}$ band.

The majority of the galaxies in our sample were detected with high significance in the near-IR images. Only 15 of them—which were among the faintest in the optical—have weak detections ($<5\sigma$) in the $J$ band ($J_{125}$ or $J_{110}$). See Table 1 of Paper I, for the optical and near-IR photometry of the galaxies and Table 2 of Paper I for the basic physical properties, including the rest-frame UV continuum luminosity, slope $\beta$, the Lyα luminosity and EW, and SFR. The thumbnail images of all the galaxies are provided in Appendix A of Paper I.
Figure 1. Thumbnail images of the 44 (out of 67) galaxies that have more than 10σ detections in the stacked HST images, shown in order of increasing redshift. The numbers of the galaxies plotted in this figure correspond to the galaxy numbers given in Table 1 of Paper I. The size of the first 43 images is 25 pixel², which corresponds to 2.5′′ × 2.5′′ in NICMOS images (no. 25, 30, and 31), or 1.5′′ × 1.5′′ in WFC3 images (the rest). The size of no. 67 is 45 × 25 pixels (or 2.7′′ × 1.5′′).

3. UV CONTINUUM MORPHOLOGY

In this section, we will derive structural and morphological parameters for the galaxies in our sample. Although our galaxies represent the most luminous ones at z ≥ 6, they appear faint and small compared to lower-redshift galaxies. The majority of them are point-like sources in the Subaru optical images. Even in the HST WFC3 images they usually occupy a very limited number of pixels. Hence, the study of these distant galaxies is challenging. In previous literature, galaxy size was often the only parameter that could be reliably measured for z ≥ 6 galaxies. Classifications for nearby galaxies, such as the classical Hubble’s tuning-fork system, cannot be applied to these objects. In this section, we will measure the sizes of our galaxies and try to characterize their morphology using nonparametric methods, such as the CAS system (Conselice 2003), and the Gini and M₂₀ parameters (Lotz et al. 2004). These methods are primarily used for low-redshift galaxies, though they have already been used for galaxies at z = 4 ~ 6 (e.g., Pirzkal et al. 2007; Conselice & Arnold 2009). We will also study interacting/merging systems in our sample.

In order to calculate the above parameters, we took advantage of all our HST images. For each galaxy in our sample, we combined (the weighted average) its J- and H-band images and made a stacked HST image to improve the signal-to-noise ratio (S/N). By doing this, we assume that the effect of the morphological k-correction—the dependence of galaxy structure on wavelength—is negligible in the wavelength range considered. This is because the J and H bands cover a similar rest-frame UV wavelength range (~1780 Å versus ~2200 Å) for z ≃ 6 galaxies. Our further analyses were then based on the stacked images. The J and H bands do not cover Lyα emission for our galaxies, so the morphology in the stacked images is purely from their UV continuum emission (other nebular lines can generally be safely ignored; see also Cai et al. 2011 and Kashikawa et al. 2012). In Figure 1, we show the thumbnail images of 44 out of 67 galaxies that have more than 10σ detections of their total fluxes in the stacked images. We will focus on these 44 galaxies in this section. Note that we excluded object no. 12, since it overlaps with a bright foreground star, as explained in Paper I.

In Figure 1, we do not show the galaxies with less than 10σ detections as most of them are very faint. Others have shallower images (e.g., one-orbit depth). We would not have obtained reliable morphological information for these individual faint galaxies so we combined their images and made a single stacked
shows the weak relation between systematic uncertainties. The dashed line (best log-linear fit to all data points) with simulations in Section 3.1. The error bars include both measurement and illustrates the weak relation between the PSF size in our HST image has a much higher S that the galaxies all have the same magnitude. The final stacked image. The individual images were scaled before stacking so that the galaxies all have the same magnitude. The final stacked image has a much higher S/N.

3.1. Size

We use the half-light radius $r_{hl}$ to describe the size of a galaxy. The half-light radius $r_{hl}$ is the radius that encloses half of the total light. In Figure 2, the upper panel shows the measured $r_{hl}$ as the function of $M_{1500}$, the absolute AB magnitude of the continuum at rest-frame 1500 Å. The measured $r_{hl}$ were calculated from elliptical apertures using SEXtractor (Bertin & Arnouts 1996). Physical quantities such as $M_{1500}$ were derived in Paper I. The blue and red circles in Figure 2 represent the LAEs at $z \approx 5.7$ and 6.5 (including $z \approx 7$), respectively, and the green circles represent the LBGs at $z \approx 6$. We do not include object no. 67 since it has three well-separated components and its $r_{hl}$ is most likely meaningless. The black star indicates the stacked image of the faint galaxies described above. The measurement uncertainties in the upper panel were derived from the simulations described below. These galaxies roughly span a luminosity range of $-22 \leq M_{1500} \leq -19.5$, and a radius range of $0.1 \leq r_{hl} \leq 0.3$ (or 0.6–1.7 kpc) without correcting for PSF broadening. The median $r_{hl}$ value is 0.19 (≈1.1 kpc). Note that the sample in Figure 2 is dominated by the galaxies at $M_{1500} \leq -20$ mag. The stacked image of the faint galaxies has a relatively smaller radius $r_{hl} \approx 0.14$ (≈0.8 kpc). The median $r_{hl}$ value for the whole sample of 67 galaxies is 0.16 (≈0.9 kpc), if we assume that the faint galaxies in this sample with $M_{1500} \geq -19.5$ mag have $r_{hl}$ smaller than this median value.

We estimated measurement uncertainties for $r_{hl}$ from simulations. For each galaxy, we made a mock galaxy by fitting a Sérsic function to the galaxy. This was done with the two-dimensional fitting algorithm GALFIT (Peng et al. 2002). This noiseless mock galaxy was put in 300–400 random positions, one at a time, in the blank regions of the same science image. We then measured $r_{hl}$ for the mock galaxy using the same method as we used our real $z \geq 6$ galaxies. We denoted the standard deviation of the measured $r_{hl}$ as the measurement uncertainty of $r_{hl}$ for this galaxy. The measurement uncertainties of $r_{hl}$ in our sample (shown as the error bars in the upper panel of Figure 2) have a median value of 10%.

We estimated the intrinsic half-light radius $r_{hl,in}$ and systematic uncertainties from simulations as well. Because of the PSF broadening and lower SB at larger sizes, the observed (or measured) $r_{hl}$ is a complex function of galaxy size, brightness, and intrinsic profile. Simulations have been widely used to investigate these systematic effects (e.g., Driver et al. 2005; Häussler et al. 2007; Cibinel et al. 2012; Grazian et al. 2012; van der Wel et al. 2012). We started with the GALFIT parameters obtained above, and considered four parameters: the Sérsic index $n$, the axis ratio $b/a$, brightness, and $r_{hl,in}$. Based on these parameters, we produced a large set of mock galaxies in a grid of $n$, $b/a$, $M_{1500}$, and $r_{hl,in}$. The values of $n$ were chosen to be 1, 1.5, and 2 times the measured $n$ from our galaxies, and the values of $b/a$ were chosen to be 1, 2/3, and 1/3 times the measured $b/a$ from our galaxies. This is because the PSF broadening could largely decrease $n$ and increase $b/a$ in low-resolution images. The luminosity coverage ($-22.4 \leq M_{1500} \leq -19.4$) and $r_{hl,in}$ coverage ($0.03 \leq r_{hl,in} \leq 0.4$) that we chose are roughly consistent with the actual coverage of our galaxy sample. The mock galaxies were oversampled so that their $r_{hl,in}$ sizes were at least 20 pixels. Then they were convolved with PSF images and rebinned to match the pixel scales of our HST images. Finally, each of the rebinned mock galaxies was placed in over 300 random positions in the blank regions of our science images. The $r_{hl}$ of this mock galaxy is the median $r_{hl}$ value measured at these random positions.

Figure 3 shows part of our simulation results. It illustrates the measured $r_{hl}$ as a function of $r_{hl,in}$ at four different magnitudes. It clearly shows that at small sizes, $r_{hl}$ is significantly larger than $r_{hl,in}$ due to the PSF broadening. At large sizes, however, $r_{hl}$ starts to fall short of $r_{hl,in}$ because we start to lose low SB pixels. This also happens at smaller sizes for fainter galaxies. At the faintest magnitude $M_{1500} = -19.5$ mag, $r_{hl}$ will never exceed 0.3 in our images, regardless of $r_{hl,in}$. On the other hand, if faint galaxies are always small, as seen in deeper HST images (e.g., Windhorst et al. 2008; Oesch et al. 2010; Grazian et al. 2012), their $r_{hl}$ should not be significantly smaller than $r_{hl,in}$ (see Figure 3).
we assume that the faint galaxies at $M_r \sim -22.3$, similar to the $r_h$ range in our sample. Previous studies have shown that the galaxy size roughly scales with redshift as $(1 + z)^m$, with $m$ close to 1–1.2 (e.g., Ferguson et al. 2004; Bouwens et al. 2006; Oesch et al. 2010; Mosleh et al. 2012), so the size of galaxies evolves slowly at high redshift. This is why high-redshift galaxies have a similar size range. Malhotra et al. (2012) found, however, that LAEs have a relatively constant size in the redshift range of $2.25 < z < 6$, and do not show a size-redshift relation. While our sample does not have a large redshift coverage, our galaxy sizes are quite consistent with those in their sample.

3.1.1. Size–Luminosity Relation

Figure 2 shows that fainter objects appear to have larger $r_{hl}$, meaning that more luminous galaxies tend to have larger physical sizes. This size–luminosity relation has been reported for both low- and high-redshift star-forming galaxies (e.g., Taniguchi et al. 2009; Oesch et al. 2010; Grazian et al. 2012; Ono et al. 2012). For example, with a large sample of photometrically selected LBGs at $z \sim 7$ in the CANDELS fields, Grazian et al. (2012) found a strong relation $r_h \propto L^{α}$, with slope $α \approx 1/2$. In Figure 2, we illustrate the size–luminosity relation by displaying the best log-linear fits (dashed lines). The best fitting results in the two panels are $r_h \propto L^{0.11\pm0.02}$ and $r_{hl, in} \propto L^{0.14\pm0.03}$, respectively. Our slopes are much flatter than those in Grazian et al. (2012) and those in other fainter LBG samples. This is because our galaxy sample is much brighter than theirs. Our relation is derived from galaxies in the luminosity range of $M_{1500} \leq -19.5$ mag, while the Grazian et al. (2012) sample covers a range of $M_{UV} \leq -18$ mag. Their relation largely depends on galaxies fainter than $-19.5$ mag, as seen in Figure 9 of their paper. In the brighter galaxies, their $r_h$ (or $r_{hl, in}$) shows less of a trend with luminosity, also noted by Grazian et al. (2012). In fact, our best fit to the galaxies with $M_{1500} \leq -20$ mag (dash-dotted line in Figure 2) gives a nearly flat slope of $α = 0.06 \pm 0.03$, suggesting little correlation between size and luminosity in the most luminous galaxies.

It should be pointed out that the relation between the measured size and luminosity could be affected by systematic effects shown in Figure 3. Figure 4 illustrates how such effects shape the $r_{hl, in}$–$M_{1500}$ relation for mock galaxies from the simulations above (see also e.g., Cibinel et al. 2012). The open circles indicate the intrinsic sizes $r_{hl, in}$, and the filled circles are the measured sizes $r_{hl}$ at different luminosities. The colors red and blue indicate the two different HST images in which the mock galaxies are placed. The two panels are for two sets of Sérsic index $n$: 1 and 2 times the measured $n$ from our $z \geq 6$ galaxies. Figure 4 shows that fainter galaxies (with the same intrinsic size) appear to be smaller, as already shown in Figure 3. For the same reason, larger galaxies (with the same intrinsic luminosity) appear to be slightly fainter. We have taken these effects into account in Figure 2. They do not have a significant impact on the size–luminosity relation in Figure 2: the corrected relation does not become flatter because it also depends on other factors such as the source distribution.

Finally, we point out that the size–luminosity relation in our sample is not affected by a possible selection effect, i.e., that we may have missed some faint galaxies with large sizes during the galaxy candidate selection. This is because these galaxies were selected in optical images. They are bright and point-like sources in the optical broad bands (for LBGs) or narrow bands (for LAEs). Also note that the exclusion of faint galaxies in our

![Figure 3.](image-url) Measured half-light radius $r_h$ as a function of intrinsic half-light radius $r_{hl, in}$ at four different magnitudes, derived from our simulations in Section 3.1. The red dotted lines indicate the equality relation. At small sizes, $r_{hl, in}$ is significantly larger than $r_{hl, in}$ due to PSF broadening. At large sizes ($r_{hl, in} \geq 0.2–0.3$), $r_h$ starts to fall short of $r_{hl, in}$. This happens at smaller sizes for fainter galaxies. We illustrate this trend by displaying the best second-order polynomial fit to the data points (blue dashed lines). The green dashed lines show the relation of $r_{hl, in}^2 = r_h^2 - r_{PSF}^2$, which is a good approximation at small sizes and/or high luminosities, but underestimates $r_{hl, in}$ elsewhere.

(A color version of this figure is available in the online journal.)

A simple way to correct for PSF broadening is to estimate $r_{hl, in}$ in quadrature, i.e., $r_{hl, in}^2 = r_h^2 - r_{PSF}^2$, where $r_{PSF}$ is the PSF radius. Figure 3 shows that this equation is a good approximation at small sizes and/or high luminosities (green dashed lines), but it underestimates $r_{hl, in}$ elsewhere.

We used the relations in Figure 3 to estimate intrinsic sizes and associated systematic uncertainties for our galaxies. The results are shown in the lower panel of Figure 2. The error bars include both measurement and systematic uncertainties, with systematic uncertainties being the dominant factors for most galaxies. With this correction, the values of $r_{hl, in}$ for our galaxies at $M_{1500} \leq -19.5$ mag range from $0.05 \pm 0.3$ kpc) to $0.17 \pm 0.9$ kpc. The $r_{hl, in}$ for the stacked object is about $0.09$. The median $r_{hl, in}$ value for the whole sample of 67 galaxies is $0.13 \pm 0.7$ kpc), if we assume that the faint galaxies at $M_{1500} \geq -19.5$ mag in this sample have $r_{hl, in}$ smaller than this median value.

The galaxy sizes in our sample roughly agree with those of high-redshift LAEs and LBGs with similar luminosities from previous studies. For example, Pirzkal et al. (2007) found that the average $r_h$ for a sample of luminous LAEs at $z = 5$ is $0.17$. Taniguchi et al. (2009) found a median $r_h$ of $0.15$ for LAEs at $z = 5.7$. In the Hathi et al. (2008) and Conselice & Arnold (2009) LBG samples of $z = 4 \sim 6$ galaxies, the $r_h$ ranges are $0.1–0.3$, similar to the $r_h$ range in our sample. Previous studies have shown that the galaxy size roughly scales with redshift as $(1 + z)^m$, with $m$ close to 1–1.2 (e.g., Ferguson et al. 2004; Bouwens et al. 2006; Oesch et al. 2010; Mosleh et al. 2012), so the size of galaxies evolves slowly at high redshift. This is why high-redshift galaxies have a similar size range. Malhotra et al. (2012) found, however, that LAEs have a relatively constant size in the redshift range of $2.25 < z < 6$, and do not show a size-redshift relation. While our sample does not have a large redshift coverage, our galaxy sizes are quite consistent with those in their sample.
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3.2. Nonparametric Measurements of Morphology

In this subsection, we will characterize galaxy structure and morphology using nonparametric methods, including the CAS (Conselice 2003), the Gini coefficient \( C \), and the \( M_{20} \) parameters (Lotz et al. 2004). These methods have been widely used for low-redshift galaxies. They usually provide a reliable description of galaxy structure, and are able to distinguish different types of galaxies from one another. To obtain accurate measurements of these quantities, two criteria are often required: high S/Ns and large object sizes compared to the PSF size. For low-redshift galaxies, especially those in \( HST\) images, the sizes of galaxies are many times larger than their PSFs, so the two criteria are naturally met in deep \( HST\) images. At higher redshifts, galaxies are fainter and smaller, so it is difficult to meet the two criteria, and these parameters become less reliable. We investigate the reliability of these measurements for our sample in detail below.

3.2.1. CAS, Gini, and \( M_{20} \) Parameters

Concentration (C) measures how compact the galaxy light profile is. We adopted the commonly used definition \( C = 5 \log (r_{80}/r_{20}) \) (e.g., Bershady et al. 2000; Conselice 2003), where \( r_{80} \) and \( r_{20} \) are the radii that contain 80% and 20% of the total galaxy flux, respectively. Asymmetry (A) measures how rotationally symmetric a galaxy is (Abraham et al. 1996; Conselice 2003). It is calculated by subtracting the image rotated by 180° from the original galaxy image. Smoothness (S), or clumpiness, measures how clumpy a galaxy is (Conselice 2003). Conselice & Arnold (2009) found that \( S \) fails to accurately describe clumpiness for \( z = 4 \sim 6 \) galaxies, so we did not calculate \( S \) in this paper. The \( M_{20} \) parameter, or the second-order moment of the brightest 20% of the galaxy, is similar to the concentration \( C \), and measures how the galaxy light is concentrated (Lotz et al. 2004). The Gini coefficient \( G \) describes how even the galaxy light distribution is (Abraham et al. 2003; Lotz et al. 2004). We computed \( G \) and \( M_{20} \) as described by Lotz et al. (2004).

The measurements of these parameters are shown in Figure 5. The measurement uncertainties were estimated from simulations using the same method we employed for the uncertainties of \( r_{80} \). We took the model galaxies obtained in Section 3.1 and put them in many random positions in the blank regions of our \( HST\) images. We then measured \( CAGM_{20} \) at each position, and calculated the standard deviations of these parameters. The standard deviations, or measurement uncertainties, are shown as the error bars in Figure 5. These uncertainties include the effects of S/N in the images, but do not account for systematic uncertainties associated with sparse spatial sampling of distant small and faint sources, which we investigate in Section 3.2.2.

Compared to low-redshift galaxies, our galaxies are located in a much narrower range in the parameter space (Figure 5; see also Figures 6 and 7). They appear to be less concentrated and more asymmetric, and their light distribution is more even. This is most likely because the measured quantities have been substantially affected by the low resolution of our images. For example, \( C \) has a narrow range between \( \sim 2 \) and \( \sim 3 \), and there is

![Figure 4](image-url)

**Figure 4.** Measured half-light radius \( r_{hl} \) as a function of \( M_{1500} \) for simulated galaxies. The open circles indicate the input intrinsic sizes \( r_{hl,in} \) of the galaxies in our simulations. The filled circles are the measured sizes \( r_{hl} \) at different luminosities. The red and blue colors indicate two different \( HST\) images that the mock galaxies are placed in. The dotted lines are used to guide the eye. The two panels are for two sets of Sérsic index \( n \): 1 and 2 times the measured \( n \) from our \( z \geq 6 \) galaxies. They show that fainter galaxies (with the same intrinsic size) appear to be smaller, as also shown in Figure 3. For the same reason, larger galaxies (with the same intrinsic luminosity) appear to be slightly fainter (see discussion in Section 3.1).

(A color version of this figure is available in the online journal.)

![Figure 5](image-url)

**Figure 5.** Morphological parameters \( CAGM_{20} \) for the galaxies in our sample. The measurement uncertainties were estimated from simulations in Section 3.2.1. Compared to low-redshift galaxies, our galaxies occupy a much narrower range in the parameter space due to the low resolution of the images. Nevertheless, each parameter is correlated with one or more of the other parameters. The red dashed lines are the best linear fits to the relations. (A color version of this figure is available in the online journal.)
a lack of highly concentrated values of C. Due to the low spatial resolution, the measurements of $r_{50}$ and $r_{20}$ are not robust. In particular, for highly concentrated galaxies, the inner radius $r_{20}$ is smaller than one pixel and is likely to be significantly overestimated, so $C$ is then underestimated. We will discuss these systematic effects using simulations below.

3.2.2. Systematic Effects from Simulations

In order to address how the low spatial resolution of the images affects the measurements of the parameters $CAGM_{20}$, or how reliable these parameters are (for $z \geq 6$ galaxies), we ran a series of simulations slightly different from those in Section 3.1. Here we started with low-redshift real galaxies instead of model galaxies, because model galaxies are smooth, and do not cover a large range of the parameter space. For example, $A$ is zero for a noiseless, single-component model galaxy. We chose to use the galaxy images in the library of galSVM (Huertas-Company et al. 2008, 2011). These low-redshift galaxies are large and bright, and their images have high $S/N$s. We randomly selected 1/10 of the galaxies from this library. Then we visually inspected these galaxies and removed those with possible foreground stars. Our final sample consists of 740 galaxies. Their morphological parameters are shown in Figure 6 (the scale in this figure is very different from that in Figure 5). These galaxies cover a large range of the parameter space of $CAGM_{20}$.

By rescaling these real galaxies in size and flux, we produced a large set of mock galaxies with a high spatial resolution at $z \geq 6$, in the grid of magnitude ($-22 < M_{1500} < -19$) and size ($0.05 < r_{nl,in} < 0.4$). The mock galaxies were then convolved with the PSF images and rebinned to match the pixel scales of our HST images. Finally, the rebinned mock galaxies were placed in many random positions in the blank regions of the HST images, and their morphological parameters were measured.

Figure 6. Morphological parameters $CAGM_{20}$ for 740 low-redshift bright galaxies selected from the library of galSVM (Huertas-Company et al. 2008, 2011). These galaxies cover a large range of the parameter space. The blue dashed lines are the best linear fits to the data points, showing the correlations among these parameters. Note that the scale in this figure is very different from that in Figure 5.

(A color version of this figure is available in the online journal.)

Figure 7 shows an example of our simulation results (black dots). In this example, we preserved the relative magnitudes and sizes of the galaxies, and scaled the sample as a whole so that the scaled sample covers a similar range of magnitude and size as our $z \geq 6$ galaxies do. This is the best way to preserve the scatter of source distributions in the parameter space. The comparison between Figure 6 and Figure 7 shows that the parameters of these mock galaxies measured in our low-resolution images are quite different from the intrinsic values because they occupy a smaller range of the parameter space. For example, the mock galaxies are significantly less concentrated in our images ($2 < C < 3$ in Figure 7 versus $2 < C < 5$ in Figure 6). As we already mentioned, $C$ is significantly underestimated for highly concentrated galaxies because $r_{20}$ is much smaller than one pixel in our HST images. Since $M_{20}$ also describes galaxy concentration, it is underestimated as well (less negative here). This was also noted by Lotz et al. (2006). Due to the low spatial resolution, our images cannot resolve subtle structures, so the mock galaxies show lower $G$ coefficients, or more evenly distributed light. The limitation of $G$ has been reported (e.g., Lisker 2008). Because of the low resolution, the $A$ values of the mock galaxies are also much larger.

In Figure 7 we also plot our $z \geq 6$ galaxies (red circles). Their morphological measurements are taken directly from Figure 5. Their positions in the parameter space are quite consistent with those of the mock galaxies. This suggests that the $z \geq 6$ galaxies are possibly not intrinsically less concentrated, more asymmetric, or less even in light distribution. This is simply
because our images do not meet one critical requirement for using these methods, i.e., large galaxy sizes compared to the PSF size, so our measurements have been systematically biased by the low-resolution images. On the other hand, these parameters are probably still meaningful for galaxies at similar redshifts if they are measured in HST images of the same depth and pixel size. For example, the intrinsically more concentrated galaxies are still more concentrated in our HST images as measured by C. We demonstrate this using the simulations of the 740 mock galaxies shown in Figure 7. We first chose the galaxy pairs whose difference of the measured C (or any of CASM\textsubscript{20}) was larger than 2\(\sigma\) (\(\sigma\) is the measurement uncertainty). Among these galaxy pairs, we then selected those in which the galaxy with a larger intrinsic C still had a larger measured C in the low-resolution images. The fraction of such pairs for C is 93%. The fractions for ASM\textsubscript{20} are 70%, 98%, and 92%, respectively. If we increase 2\(\sigma\) to 3\(\sigma\) above, the fractions for CASM\textsubscript{20} increase to 97%, 78%, 100%, and 95%, respectively. This suggests that for the vast majority of galaxies, the low resolution of our HST images does not change their relative values of these morphological parameters. We emphasize that the absolute measured values of these parameters for \(z \geq 6\) galaxies in HST images are not to be compared to the absolute measured parameters of lower-redshift galaxies.

### 3.2.3. Relations among the Morphological Parameters

The morphological parameters correlate with each other. We have seen such correlations in low-redshift galaxies (e.g., Lotz et al. 2004, 2006; Conselice & Arnold 2009). In Figure 6, the dashed lines are the best linear fits to the 740 low-redshift galaxies, and show the relations among CAGM\textsubscript{20}. As expected, these parameters are correlated. The moment \(M_{20}\) correlates well with C, A, and G. Both \(M_{20}\) and C describe how the galaxy light is concentrated, and they are strongly correlated by definition. The relations between \(M_{20}\) and A & G reflect that more concentrated galaxies have more rotationally symmetric profiles and more unevenly distributed light. The Gini coefficient G is correlated with C and A in addition to \(M_{20}\). Its relations with C and A indicate that galaxies with more concentrated or more rotationally symmetric profiles tend to have more unevenly distributed light. These relations still exist among the 740 mock galaxies in Figure 7 since the relative values of the parameters are preserved, as we discussed above. On the other hand, some relations become weaker with a larger scatter. For example, the relations between A and CAG are much flatter, mainly because the coverage of C has shifted from 2 \(\leq C \leq 5\) to 2 \(\leq C \leq 3\).

In Figure 5, the red dashed lines show the correlations of CAGM\textsubscript{20} for our \(z \geq 6\) galaxies. These correlations are consistent with those for the mock galaxies in Figure 7. In particular, the relations between \(M_{20}\) and CAG are still fairly well preserved, and the relations between C and A are as weak as those shown in Figure 7. We will see in the next subsection that these corrections for relatively bright galaxies in our sample are better with a smaller scatter (Figure 10). Therefore, although our measured CAGM\textsubscript{20} of the \(z \geq 6\) galaxies are systematically biased by the low-resolution images, these parameters, when interpreted carefully, are still somewhat meaningful for galaxies measured in the HST images of the same depth and pixel size.

### 3.3. Interacting Systems

It is interesting to study interacting/merging systems, which trace hierarchical mass assembly in the CDM scenario. A close visual inspection of Figure 1 shows that some galaxies are clearly extended with interacting or multi-component features. At lower redshifts, these systems can be identified by pair counts (e.g., Le Fèvre et al. 2000), the CAS system (e.g., Conselice 2003), or the G and \(M_{20}\) parameters (e.g., Lotz et al. 2008). Galaxies at \(z \geq 6\) are faint and small, so it is difficult to properly distinguish regular and interacting/merging systems. Although we have derived morphological parameters CAGM\textsubscript{20}, they were biased, and their ability to identify merging systems at \(z \geq 6\) has never been examined. Therefore, we identify interacting/merging systems by visual inspection. Visual classification was the easiest way to classify galaxies and in many cases it is still the best way to identify merging systems at high redshifts.

We considered the following two types of galaxies as candidate interacting/merging systems: (1) galaxies with two or more distinct cores and (2) galaxies with extended elongated features and/or long tails. We identified such systems in 24 relatively bright (\(M_{1500} \leq -20.5\) mag) galaxies. For fainter galaxies, our images are not deep enough to properly identify all of the faint components or extended features. Figures 8 and 9 show 12 galaxies that were identified as interacting systems with \(M_{1500} \leq -20.5\) mag. Figure 8 shows 11 galaxies in the stacked \((J + H)\) images, and Figure 9 shows the \(z = 6.96\) LAE (no. 62) in the two \(J\) bands. The red profiles are the SB contours of the rest-frame UV emission. Six of them clearly show double or multiple clumps, including no. 4, 24, 34, 49, 62, and 67.
usually have one bright core and one or more fainter clumps. No. 62 and 67 are particularly interesting. No. 62 in Figure 9 has almost two identical components, and no. 67 has three widely separated cores. This is discussed further in the next subsection. Three additional galaxies, no. 36, 58, and 61, do not clearly show multiple clumps, but have long tails like tidal tails seen in low-redshift merging galaxies. The rest of the 12 systems (no. 15, 44, and 47) do not show multiple components or tails, but they are rather extended and elongated. They could be in the end of the merging process.

We then estimate the fraction of mergers among galaxies with $M_{1500} \leq -20.5$ mag. The fraction is 50% (38% if we exclude the three galaxies that do not show multiple components or tails). The fraction is even higher in the galaxies with $M_{1500} \leq -21$ mag. We have 18 galaxies in this magnitude range, and 10 of them are mergers. The fraction of mergers is 56% (39% if we exclude the three galaxies mentioned above). This is consistent with the fractions in the brightest galaxies at low redshifts of $z \simeq 2–3$. For example, the fraction of mergers in the $M_B < -21$ mag galaxy sample of Conselice (2003) is 40%–50%. The typical fraction in the brightest galaxies in the Law et al. (2012) sample is also ~40%. The merger fraction in fainter galaxies is smaller because merger systems consist of multiple components, and usually have stronger SFRs and UV emission. For the galaxies fainter than $M_{1500} \simeq -20.5$ mag in our sample, our images are deep enough to identify double-core systems with comparable emission. We find that these systems are very rare at $M_{1500} \geq -20.5$ mag. Studies in deeper fields have indicated a lower merger fraction in low-luminosity galaxies. For example, Oesch et al. (2010) presented the morphology of 16 $z \geq 7$ LBGs in the HUDF, and only found two galaxies with extended features.

3.3.1. Notes on Individual Objects

Galaxy no. 62. No. 62 is a $z = 6.964$ LAE. It is the first spectroscopically confirmed LAE at $z \simeq 7$ (Iye et al. 2006). Figure 9 shows that it has two similar components in both $J$ bands. We used GALFIT to model the two components. Two Sérsic functions were simultaneously fitted to the two components (two left-hand images in Figure 9). The middle images in Figure 9 show the best model fits, and the residuals are on the right-hand side. The two components in both bands can be well described by the Sérsic function. The separation between the two cores is about $0.2~(\sim 1$ kpc; see also Cai et al. 2011).

Galaxy no. 67. No. 67 is a LAE at $z = 6.595$. It was discovered as a giant LAE by Ouchi et al. (2009). It is one of the brightest galaxies in terms of both Lyα luminosity and UV continuum luminosity. The most striking feature is the three well-separated cores which are all lined up. The central core is relatively weak. This galaxy is clearly resolved in our ground-based $z$- and $y$-band images. The separation between the two side cores reaches ~1″2, or 7 kpc. This is the largest separation we have seen at $z \geq 6$. This object also has strong emission in the IRAC bands, suggesting a large stellar mass of $\geq 10^{10} M_\odot$ (Ouchi et al. 2009).

3.3.2. Morphology of Interacting Systems

As we mentioned, the above interacting galaxies were identified with visual inspection. Morphological parameters were not used for selection because the criteria for interacting systems at $z \geq 6$ are unclear. We check our interacting systems in the parameter space in Figure 10. Figure 10 is similar to Figure 5, but it only plots the galaxies with $M_{1500} \leq -20.5$ mag in our sample. The red squares represent the interacting galaxies. Figure 10 shows that the interacting galaxies are almost indistinguishable from the rest in the parameter space. The asymmetry $A$ is widely accepted as an efficient parameter to identify mergers at low redshift (e.g., Conselice 2003; Conselice & Arnold 2009; Lotz et al. 2006, 2008; Law et al. 2012). In Figure 10, however, $A$ is no longer a good indicator of mergers, although the galaxies with the largest $A$ in our sample are mostly interacting systems.

An interesting feature of Figure 10 is the better correlation among the morphological parameters compared to Figure 5. The scatter in the relations is smaller for the brighter galaxies with...
existence of strong correlations among $CAGM_{20}$ for our $z \geq 6$ galaxies.

4. Lyα MORPHOLOGY

In this section we will study the Lyα morphology of LAEs using our ground-based narrow-band images. We will not measure the structure and morphology for individual galaxies since they are mostly point-like objects in the ground-based images. Although these images have excellent PSF sizes of $\sim 0.5\arcsec$–0.7", the PSF sizes are still much larger than those of the $HST$ images. Therefore, we will focus on Lyα halos around LAEs, which could extend many arcseconds from the objects. We will also compare the positions of Lyα emission with those of UV continuum emission, and find any possible positional difference between the two.

4.1. Lyα Halos

Because of the resonant scattering of Lyα photons by neutral hydrogen, Lyα emission could form large diffuse Lyα halos around high-redshift galaxies. Steidel et al. (2011) first found very extended Lyα halos in a sample of luminous galaxies at $2 < z < 3$. The galaxies were UV-continuum-selected, but more than a half of them showed net Lyα emission and $\sim 20\%$ have Lyα EW greater than 20 Å. They were able to find large Lyα emission halos ($\geq 80$ kpc) in the stacked images of all sub-samples of their galaxies. They further claimed that all LBGs would be classified as LAEs or Lyα blobs, if imaging data are deep enough to detect Lyα halos. Matsuda et al. (2012) confirmed the existence of extended Lyα halos around $z \simeq 3$ galaxies. They used more than 2000 LAEs at $z \simeq 3.1$, and grouped them into sub-samples based on luminosity and surface overdensity. They stacked narrow-band (Lyα) images for each sub-sample, and found that all of the stacked images showed extended ($\geq 60$ kpc) Lyα emission halos. Recently, Feldmeier et al. (2013) found that the existence of Lyα halos around LAEs is not convincing. They also used a large sample of a few hundred LAEs at $z \simeq 2.1$ and 3.1. They paid particular attention to the systematic effects from large-radius PSF and large-scale flat fielding. When these effects were taken into account, they did not find strong evidence of extended Lyα halos in the stacked narrow-band images at either redshift. They tried different ways to reconcile the discrepancy between their results and previous ones, but the reason for the discrepancy is still not clear.

Stacking narrow-band images has not been done for $z \geq 6$ galaxies. However, cosmological simulations have predicted the existence of extended Lyα emissions around $z \geq 6$ galaxies (e.g., Zheng et al. 2011; Dijkstra & Kramer 2012; Jeeson-Daniel et al. 2012). For example, by including the resonant scattering of Lyα photons in both circumgalactic media and the intergalactic medium (IGM), Zheng et al. (2011) showed that a Lyα-emitting halo in a high-redshift galaxy can extend up to 1 Mpc. They further pointed out that such halos could be detected by stacking 100 $z \simeq 5.7$ LAEs in 4 hr exposure narrow-band images in the SXDS. Here we combine the narrow-band (Lyα) images of LAEs at $z \simeq 5.7$ and 6.5.

In order to detect diffuse Lyα halos around LAEs, we made use of all known LAEs at $z \simeq 5.7$ and 6.5 in the SDF and SXDS fields from Kashikawa et al. (2011) and Ouchi et al. (2008, 2010). The narrow-band images were taken with the Subaru telescope. The total integration time in the NB816 and NB921 bands was 10 and 15 hr for the SDF (Kashikawa et al. 2004), and 4 hr and 10 hr for the SXDS (Ouchi et al. 2008, 2010). The data reduction of the SDF images were presented in Section 2 of Paper I. The reduction of the SXDS images was done in the same way. These narrow-band images have great depth with excellent PSF sizes of $0.5\arcsec$–0.7". We rejected a small number of galaxies that are either very faint or blended with nearby bright objects. The final sample contains 43 LAEs at $z \simeq 5.7$ and 40 LAEs at $z \simeq 6.5$.

To stack these images, we first cut image stamps for all individual objects. We then re-sampled the image stamps so that the objects are in the center of each image. After all other images in the images were masked out, we co-added (averaged) the images with sigma-clipping ($5\sigma$ rejection). In order to detect diffuse Lyα halos around LAEs, we made use of all known LAEs at $z \simeq 5.7$ and 6.5 in the SDF and SXDS fields from Kashikawa et al. (2011) and Ouchi et al. (2008, 2010). The narrow-band images were taken with the Subaru telescope. The total integration time in the NB816 and NB921 bands was 10 and 15 hr for the SDF (Kashikawa et al. 2004), and 4 hr and 10 hr for the SXDS (Ouchi et al. 2008, 2010). The data reduction of the SDF images were presented in Section 2 of Paper I. The reduction of the SXDS images was done in the same way. These narrow-band images have great depth with excellent PSF sizes of $0.5\arcsec$–0.7". We rejected a small number of galaxies that are either very faint or blended with nearby bright objects. The final sample contains 43 LAEs at $z \simeq 5.7$ and 40 LAEs at $z \simeq 6.5$.
Figure 12. Radial profiles of the stacked images in Figure 11. The units of SB are $10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. The solid profiles with 1σ error bars represent the stacked LAEs, and the dashed profiles represent the stacked stars. The insets show the radial profiles on a log scale. The LAE profiles are broader than the PSF sizes, and exhibit slightly longer tails than the PSF profiles do, meaning that the Lyα emission is resolved. This is because galaxies are not point sources, and exhibit a slightly more extended radius than its PSF profile. Given the 1σ limit of $1.2 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, its SB is still consistent with zero at $r \geq 2\arcsec$. Therefore, Figure 12 does not show convincing evidence of extended Lyα halos.

It is difficult to answer whether our stacked images are deep enough to detect Lyα halos, if they do exist at the two redshifts. Our images are certainly deep enough to detect the LBG halos at $z \approx 3$ reported by Steidel et al. (2011) and the LAE halos at $z \approx 3.1$ in Matsuda et al. (2012). The depth to detect $z \geq 6$ LAE halos is observationally unknown. From cosmological simulations, Zheng et al. (2011) predicted Lyα halo sizes in $z = 5.7$ LAEs. They found two characteristic scales for the halos. The inner, steeper one extends to $3\arcsec$–$4\arcsec$, and the outer, flatter one extends to a few tens of arcseconds. While our images are not deep enough to detect the outer halos, they are almost deep enough to detect the inner scale halos as seen in Figure 3 of Zheng et al. (2011), where the Lyα radial profiles are shown for LAEs in dark matter halos of $\sim 10^{11} M_\odot$. As pointed out by Zheng et al. (2011), the size of the diffuse Lyα emission also depends on the mass of dark matter halo. If the average mass of the dark matter halos in our LAEs is smaller than $10^{11} M_\odot$, our current data may not be able to detect the diffuse Lyα emission.

It is also likely that the Lyα halos (if they exist) have been diluted to a much lower level during the construction of the stacked images. The stacked images can properly recover Lyα halos only when they are smoothly and symmetrically distributed around galaxies. If halos are highly asymmetric and/or clumpy, the emission of halos will be significantly diluted in average stacked images, and could totally disappear in median stacked images. From the observations of $z \sim 6$ quasars or cosmological simulations, we know that the distribution of IGM at $z \sim 6$ is inhomogeneous (e.g., Fan et al. 2006; Mesinger 2010). If the distribution of IGM affects the shape of Lyα halos (via resonant scattering), the distribution of Lyα halos is also likely asymmetric and clumpy.

Finally, it is possible that these LAEs do not have extended Lyα halos, or that their halo emission is not as strong as predicted by Zheng et al. (2011), especially when dust is taken into account (e.g., Finkelstein et al. 2011). Zheng et al. (2011) did not consider dust in their simulations. We know that high-redshift LAEs are not free of dust. In particular, the brightest galaxies may exhibit significant dust extinction, as implied by their UV colors (see Paper I). When Lyα photons are resonantly scattered by dusty neutral hydrogen, the Lyα emission is substantially reduced (Yajima et al. 2012). The reduction is more severe at larger distances from the object because photons at larger distances need to pass through more dust before they escape. This process would significantly reduce the visibility of possible diffuse Lyα emission, and make it much more difficult to detect. A much larger sample of LAEs is needed to resolve this issue.

4.2. Lyα–Continuum Misalignment

The comparison between the positions of UV continuum and Lyα emission provides useful information on how Lyα
photons escape from a galaxy. Ly\(\alpha\) and UV continuum photons usually come from the same star-forming regions, although Ly\(\alpha\) photons are likely more sensitive to the regions with more recent star-forming activity. As we mentioned earlier, Ly\(\alpha\) emission is complicated by resonant scattering and IGM absorption so the observed position of Ly\(\alpha\) emission could be different from the position of UV continuum emission. For example, a large positional difference has been found in a \(z = 3.334\) galaxy (Rauch et al. 2011). Due to the small sizes of high-redshift galaxies, current ground-based observations are not able to detect these positional differences. We rely on the HST, which has observed a large number of high-redshift galaxies. HST observations were mostly made for rest-frame UV continuum emission, and there are usually no suitable HST narrow-band filters for Ly\(\alpha\) emission. One example of HST imaging of Ly\(\alpha\) emission is the work of Finkelstein et al. (2011), who observed the Ly\(\alpha\) emission of a small sample of \(\gtrsim 4.4\) LAEs with a narrow-band filter. They did not find strong evidence of positional misalignment between UV and Ly\(\alpha\) emission.

We used our large sample of LAEs to search for possible positional offsets between UV and Ly\(\alpha\) emission at \(z \approx 5.7\) and 6.5. We used our HST images as UV continuum images and Subaru narrow-band images as Ly\(\alpha\) images. As we mentioned above, the narrow-band images have excellent PSF FWHM sizes around 0.3–0.7\arcsec. During the construction of the HST images (Paper I), we matched the coordinates of the HST images to those of the optical images. To avoid any large-scale variation, we refine the coordinates of the HST images. For each LAE, we found 10–20 nearby objects that were relatively bright and round. We then matched the positions of the nearby objects in the two sets of images. The typical refinement was smaller than the size of one pixel (0.06\arcsec). The uncertainty in the object positions, derived from the distribution of the nearby objects, is about the size of 1–2 pixels. We plotted the Ly\(\alpha\) positions on top of the UV continuum positions. Figure 13 shows a few examples of bright galaxies. The red profiles are the contours of the UV emission SB, and the green crosses indicate the positions (and 1\(\sigma\) uncertainties) of the Ly\(\alpha\) emission.

For the majority of the LAEs in our sample, the positions of the UV continuum and Ly\(\alpha\) emission agree with each other. In particular, we do not find positional misalignment at a significance level of >2\(\sigma\) among almost all compact and round LAEs. Object no. 3 in Figure 13 is a typical example, in which the center of the Ly\(\alpha\) emission is close to the center of the continuum emission. For the merging/interacting systems, however, we see significant positional differences. Figure 13 shows examples of these systems. They exhibit a variety of Ly\(\alpha\) positions relative to the peak positions\(^{11}\) of the UV continuum emission: (1) Ly\(\alpha\) positions close to those of the brightest components in the UV images, including galaxies no. 15, 47, and 61; (2) Ly\(\alpha\) positions close to those of the fainter components or merger tails in the UV images, including no. 14, 44, and 58; and (3) Ly\(\alpha\) positions somewhere between the positions of the bright and faint components, but closer to the bright components, including no. 4 and 49. No. 62 and 67 are again interesting. The Ly\(\alpha\) position of no. 62 is roughly in the middle of the two similarly bright components. No. 67 does not show three distinct Ly\(\alpha\) emission clumps as its UV emission does.

\(^{11}\) For an interacting galaxy, the position of its peak emission (as seen from the SB contour) could be very different from the position of the overall galaxy emission measured, for example by fitting a Gaussian to the marginal x, y distributions (used by IRAF DAOPHOT). Here our positions refer to the positions of peak emission.

Figure 13. Positions of UV continuum and Ly\(\alpha\) emission for a sample of bright galaxies. The red contours and their scales are similar to those shown in Figure 8. They display the UV continuum emission seen in the HST images. The green crosses indicate the positions (and 1\(\sigma\) uncertainties) of the Ly\(\alpha\) emission from our ground-based narrow-band images. The first object no. 3 represents a typical compact galaxy, whose positions of UV continuum and Ly\(\alpha\) emission agree with each other. The rest of the objects are merging/interacting systems, which show a variety of Ly\(\alpha\) position offsets relative to the UV continuum positions, including significant positional misalignment.

(A color version of this figure is available in the online journal.)

Instead, it shows a single bright Ly\(\alpha\) emission core with some extended features. The Ly\(\alpha\) center is not in any of the three UV clumps. It is between the left and central clumps, slightly closer to the central one.

Our results suggest that in compact galaxies the observed location of Ly\(\alpha\) emission does not deviate from its original position, while in merging/interacting systems, the observed Ly\(\alpha\) location could be significantly different from its original position, without preferential positions of offsets. If the final location of Ly\(\alpha\) emission is determined by the process of resonant scattering, our results can be explained by the ISM distribution (e.g., Finkelstein et al. 2011). In a non-disturbed galaxy, the ISM distribution is relatively symmetric around the object (though not necessarily uniform, since it could be clumpy). The randomly scattered photons do not have preferred directions, so the observed location is still close to the original. In an interacting system, the ISM is re-distributed by merging activity. The distribution of the disturbed ISM is therefore not symmetric anymore. This results in an offset of the observed Ly\(\alpha\) position.

This result could have an impact on the spectroscopy of bright LBGs at \(z \gtrsim 6\) (e.g., Stark et al. 2011; Curtis-Lake et al. 2012). While most of the positional offsets in our sample are smaller than 0.2\arcsec, at least two are around 0.3–0.4\arcsec. If one uses \(\lesssim 1\)\arcsec\...
slit to identify their Lyα emission lines, based on the positions of continuum emission, one could miss them due to the large offsets. However, galaxies with such large offsets are very rare, so this result will not significantly reduce the success rate of identifying Lyα lines in LBGs.

5. DISCUSSION AND SUMMARY

The comparison in Section 3.1 shows that the sizes of our galaxies are consistent with those of bright z ≥ 6 LAEs and LBGs from previous studies. Our findings disagree with the claim made by Dow-Hygelund et al. (2007) that LAEs are more compact than LBGs. This is likely because the Dow-Hygelund et al. (2007) sample is very small, whereas LAEs have a large range of sizes. It is indeed difficult to make proper comparisons without a large sample as the galaxy size depends on redshift and luminosity. Most of our galaxies are LAEs. Another large LAE sample is the sample by Taniguchi et al. (2009), who observed a number of LAEs at z ∼ 5.7 with the HST ACS F814W filter. Although this filter includes Lyα emission, it is so wide that its emission is dominated by the UV continuum. They found that the average size of the sample is 0.05 ± 0.2, similar to ours. Among the photometrically selected LBG samples at z ≥ 6, a recent, large sample is that of Grazian et al. (2012). This sample contains a number of bright (as well as faint) LBGs at z ∼ 6–7 in the CANDELS field. The sizes of these galaxies are quite consistent with those of our galaxies at the same luminosities. Therefore, we conclude that LAEs and LBGs with similar luminosities have similar physical sizes.

In this paper (and in Paper I), galaxies found by the narrow-band technique are defined as LAEs and those found by the dropout technique are defined as LBGs. As we discussed in Paper I, this classification only reflects the methodology that we apply to select galaxies. It does not mean that the two types of galaxies are intrinsically different. In Section 5.3 of Paper I, when we derived the UV continuum luminosity function of LAEs, we used another popular definition of LAEs based on the Lyα emission, i.e., a galaxy is a LAE if its Lyα EW is greater than 20 Å. With this definition, almost all of the galaxies in our sample are LAEs. This definition is physically more meaningful, but observationally difficult, because one can easily obtain a flux-limited sample, not an EW-limited sample. We have 16 LBGs (former definition) in our sample, but these are not typical LBGs. They are spectroscopically confirmed, and thus only represent those with a strong Lyα emission. In Paper I we found that our LAEs and LBGs are indistinguishable in many aspects of the Lyα and UV continuum properties. In this paper, we also found that these LAEs and LBGs have similar physical sizes and morphological parameters. This confirms one of our conclusions in Paper I: that LAEs are a subset of LBGs with strong Lyα emission lines.

This paper is the second in a series presenting the physical properties of a large sample of spectroscopically confirmed galaxies at z ≥ 6. The sample consists of 51 LAEs and 16 LBGs, and represents the most luminous galaxies in terms of Lyα luminosity (for LAEs) or UV continuum luminosity (for LBGs) in this redshift range. In Paper I we derived various properties of rest-frame UV continuum and Lyα emission. In this paper we have conducted a detailed structural and morphological study of the galaxies using deep HST near-IR images and Subaru narrow-band images. In order to measure the morphology of the rest-frame UV continuum emission, we constructed a stacked HST image for each object by combining its J- and H-band images. UV morphology was then measured for those with >10σ detections (roughly corresponding to M_{1500} < −19.5 mag) in the stacked HST images.

We used the half-light radius to describe the sizes of galaxies. The intrinsic sizes r_{hl,in} (at M_{1500} < −19.5 mag) in our sample, after correcting for PSF broadening, are from ≤0.05 (≤0.3 kpc) to ∼0.3 (~1.7 kpc), with a median value of 0.16 (~0.9 kpc). These values are consistent with those of bright, photometrically selected LBGs at similar redshifts. Additionally, more luminous galaxies tend to have larger sizes, exhibiting a weak size–luminosity relation r_{hl,in} ∝ L^{0.14}. The slope 0.14 is significantly flatter than those in fainter LBG samples. Our objects show a wide range of morphology in the HST images, including compact galaxies and double/multiphase component systems. The brightest galaxies in the sample have a large fraction of merging/interacting systems. The fraction of mergers reaches 40%–50% at M_{1500} < −20.5 mag.

We have tried to describe the structure and morphology of our z ≥ 6 galaxies using nonparametric methods, including the CAS system, and the Gini and M_{20} parameters. Compared to low-redshift galaxies, these galaxies occupy a smaller range in the parameter space of CAGM_{20}. Our simulations show that the measurements of these parameters have been systematically biased due to the low resolution of the HST images. On the other hand, the relative values of these morphological parameters are likely preserved for the vast majority of galaxies. In addition, we found all expected correlations among CAGM_{20} for the z ≥ 6 galaxies. These correlations suggest that the parameters are probably still meaningful for galaxies at similar redshifts if they are measured in HST images of the same depth and pixel size.

For the first time, we searched for Lyα emission halos around z ≥ 6 galaxies in narrow-band images. We combined a large number of narrow-band images for LAEs at z ∼ 5.7 and 6.5, respectively. The stacked images reached a depth of ~1.2 × 10^{-19} erg s^{-1} cm^{-2} arcsec^{-2} (1σ). We did not find evidence of extended diffuse Lyα emission as predicted by cosmological simulations. It is possible that our images are still not deep enough to detect Lyα emission halos, or that the Lyα halo emission was diluted to a much lower level during the construction of the stacked images. It is also possible that the halo emission is not as strong as predicted. A much larger LAE sample is needed to solve this question. We also investigated positional differences between the rest-frame UV continuum emission and the Lyα emission in LAEs, using the HST images and optical narrow-band images. While in compact LAEs the two positions are quite consistent, some merging galaxies show significant positional differences with no preferred directions of offsets. This was explained by the distribution of the disturbed ISM.

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