MORPHOLOGIES OF \( \sim 190,000 \) GALAXIES AT \( z = 0–10 \) REVEALED WITH HST LEGACY DATA. II.
EVOLUTION OF CLUMPY GALAXIES

TAKATOSHI SHIBUYA\(^1\), MASAMI OUCHI\(^1,2\), MARIKO KUBO\(^1\), AND YUICHI HARIKANE\(^1,3\)

\(^1\) Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwanoha, Chiba, Chiba 277-8582, Japan; shibuya\_at\_icrr.u-tokyo.ac.jp
\(^2\) Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), University of Tokyo, Kashiwa, Chiba 277-8583, Japan
\(^3\) Department of Physics, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo, 113-0033, Japan

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ABSTRACT

We investigate the evolution of clumpy galaxies with Hubble Space Telescope (HST) samples of \( \sim 17,000 \) photo-z and Lyman break galaxies at \( z \simeq 0–8 \). We detect clumpy galaxies with off-center clumps in a self-consistent algorithm that is well tested with previous study results, and we measure the number fraction of clumpy galaxies at the rest-frame UV, \( f_{\text{clumpy}}^\text{UV} \). We identify an evolutionary trend of \( f_{\text{clumpy}}^\text{UV} \) over \( z \simeq 0–8 \) for the first time: \( f_{\text{clumpy}}^\text{UV} \) increases from \( z \simeq 8 \) to \( z \simeq 1–3 \) and subsequently decreases from \( z \simeq 1 \) to \( z \simeq 0 \), which follows the trend of the Madau–Lilly plot. A low average Sérsic index of \( n \simeq 1 \) is found in the underlying components of our clumpy galaxies at \( z \simeq 0–2 \), indicating that typical clumpy galaxies have disk-like surface brightness profiles. Our \( f_{\text{clumpy}}^\text{UV} \) values correlate with physical quantities related to star formation activities for star-forming galaxies at \( z \simeq 0–7 \). We find that clump colors tend to be red at a small galactocentric distance for massive galaxies with \( \log M_*/M_\odot \gtrsim 11 \). All of these results are consistent with the picture that a majority of clumps form in the violent disk instability and migrate into the galactic centers.

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

1. INTRODUCTION

Galaxy morphology offers invaluable insights into galaxy formation and evolution. Nearby and low-\( z \) galaxies are categorized mainly into three morphological types, i.e., spirals, spheroids, and irregular systems (the Hubble sequence: Hubble 1926). In contrast to this low-\( z \) morphological classification, observations with Hubble Space Telescope (HST) have revealed that galaxies hosting several bright patchy structures, aka clumpy galaxies, are more abundant at \( z \simeq 1–3 \) than in the local universe (e.g., Cowie et al. 1995; Giavalisco et al. 1996; van den Bergh et al. 1996; Elmegreen et al. 2004, 2005, 2008, 2009a, 2009b, 2013; Elmegreen & Elmegreen 2005, 2006; Glazebrook 2013; Kubo et al. 2013, 2016; Murata et al. 2014; Tadaki et al. 2014; Garland et al. 2015; Guo et al. 2015; Huertas-Company et al. 2015; Bournaud 2016).

Physical properties of the clumps have been intensively investigated by imaging observations with the Advanced Camera for Surveys (ACS) and Wide Field Camera 3 (WFC3)/IR channel on board HST. Spectral energy distribution (SED) analyses with HST multiwavelength suggest that typical clumps have a stellar mass of \( \log M_*/M_\odot \simeq 8–9 \) and young stellar ages of \( \lesssim 0.5 \) Gyr (e.g., Guo et al. 2012; Wyут et al. 2012). Combined with gravitational lensing effects, the high spatial resolving power of HST reveals that the size of clumps ranges from \( \simeq 0.1 \) kpc to \( \simeq 1 \) kpc (e.g., Swinbank et al. 2009; Jones et al. 2010; Livermore et al. 2012, 2015; Wisnioski et al. 2012).

Even in substantial observational efforts, the clump formation mechanisms have not been fully understood. Two viable candidates have been proposed as a clump formation mechanism: (1) the violent disk instability (VDI; Dekel et al. 2009a, 2013) and (2) galaxy mergers (e.g., Di Matteo et al. 2008, although cf. Taniguchi & Shioya 2001). The former and the latter are the “in situ” and “ex situ” origins for clumps, respectively. In the case of VDI, clumps are predicted to form in unstable regions where the Toomre \( Q \) parameter (Toomre 1964) is below a critical value (an order of unity) in thick and gas-rich galaxy disks (e.g., Noguchi 1998; Immeli et al. 2004a, 2004b; Bournaud et al. 2007, 2009; Agertz et al. 2009, 2015; Dekel et al. 2009a; Ceverino et al. 2010; Romeo et al. 2010; Tacconi et al. 2010; Forbes et al. 2012; Hoffmann & Romeo 2012; Romeo & Agertz 2014). On the other hand, mergers of compact galaxies would also add clumpy components on galaxies, providing the similar clumpy morphology.

The fate of clumps has also been a matter of debate. Theoretical studies and numerical simulations have predicted that clumps at disk regions migrate into the galactic centers owing to dynamical frictions and/or clump–clump interactions (e.g., Immeli et al. 2004a, 2004b; Dekel et al. 2009a; Ceverino et al. 2012; Inoue & Saitoh 2012; Mandelker et al. 2014, 2015). The migrating clumps would subsequently contribute to the formation of a central proto-bulge. In contrast, several numerical simulations have suggested that clumps are destroyed by their own and/or galactic feedback before the clump migration (e.g., Genel et al. 2012; Hopkins et al. 2012; Moody et al. 2014). The disrupted clumps could become components of galaxy disks (e.g., Bournaud et al. 2014). These predictions indicate that clumps are important structures for characterizing the morphological evolution of galaxies.

A powerful observational technique is to construct spatial \( Q \) and velocity \( (v) \) maps on clumpy galaxies for distinguishing the two clump formation mechanisms. During the past decade, spatially resolved kinematic properties for clumpy galaxies have been examined by exploiting adaptive optics systems and integral field spectrographs (IFSs; e.g., Förster Schreiber et al. 2011; Genzel et al. 2011, 2014; Newman et al. 2012). According to these IFS studies, \( Q \) values on clump regions tend to be below unity. The low \( Q \) value is evidence that clumps are below unity. The low \( Q \) value is evidence that clumps are...
have the in situ origin and form through VDI. The velocity structure also provides important hints of whether clumps are dynamically bounded in host galaxies. The velocity of typical clumps follows global motions of host galaxy disks within $\Delta v \lesssim 200$ km s$^{-1}$, which suggests the in situ clump origin (e.g., Bournaud et al. 2008; Wisnioski et al. 2011, 2012, 2013; Sobral et al. 2013; Burkert et al. 2015; Tacchella et al. 2015d). In contrast, statistical studies with IFSs indicate that ex situ clumps appear to be rare among $z \approx 2$ star-forming galaxies (e.g., Shapiro et al. 2008; Bournaud 2016). In the case of the ex situ origin (i.e., mergers), clumps could show a large velocity offset ($\Delta v \gtrsim 300$ km s$^{-1}$) with respect to host galaxies (e.g., Menéndez-Delmestre et al. 2013).

These results support the picture that a majority of clumps have the in situ origin for $z \lesssim 2$ massive galaxies. As a next step, we examine the major mechanism of clump formation over cosmic time. However, these kinematic analyses are expensive owing to requirements of deep IFS spectroscopic observations. Recently, Guo et al. (2015) suggested that an abundance of clumpy galaxies is one of the useful probes for investigating clump formation mechanisms. Using $HST$ imaging data, Guo et al. (2015) systematically measured number fractions of clumpy galaxies in overall galaxy samples (the clumpy fraction; $f_{\text{clumpy}}$) at $z \approx 0$–3. Comparisons between $f_{\text{clumpy}}$ and theoretical predictions suggest that clumps are likely to form in VDI and galaxy mergers for galaxies with $\log M_*/M_\odot \gtrsim 11$ and $<10$, respectively. However, $f_{\text{clumpy}}$ has still not been unveiled beyond $z \approx 3$. Systematic $f_{\text{clumpy}}$ measurements over a wide redshift range would provide useful hints for understanding the major clump formation mechanism and properties of clumpy host galaxies.

In this paper, we investigate the redshift evolution of clumpy galaxies using $HST$ legacy data. We identify clumpy galaxies at $z \approx 0$–8 in a self-consistent clump detection algorithm using the large galaxy sample. This is the second paper in a series studying the galaxy morphology with the $HST$ samples. The organization of this paper is as follows. In Section 2, we describe the details of the $HST$ galaxy samples. Section 3 shows the $HST$ images and galaxies used for our clumpy structure analyses. We present methods to identify clumpy structures in Section 4. In Section 5, we perform Monte Carlo simulations to evaluate the intrinsic clump luminosity and clump detection completeness. We show the redshift evolution of $f_{\text{clumpy}}$, radial surface brightness (SB) profiles of clumpy galaxies, relations between clumps and physical quantities of host galaxies, and clump colors in Section 6. In Section 7, we discuss the implications for clump formation mechanisms. We summarize our findings in Section 8.

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, F909M, F105W, F125W, F140W, and F160W filters as $V_{606}$, $I_{775}$, $I_{814}$, $z_{850}$, $Y_{909}$, $Y_{105}$, $J_{125}$, $H_{140}$, and $H_{160}$, respectively.

2. DATA AND SAMPLES

We use the following two galaxy samples in this study. These galaxy samples are constructed from the deep optical and near-infrared imaging data taken by $HST$ deep extragalactic legacy surveys. Paper I summarizes the limiting magnitudes and point-spread function (PSF) sizes of the $HST$ images.

2.1. Sample of Photo-$z$ Galaxies in 3D-HST+CANDELS

The first sample is made up 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 WFC3-IR images. The stacked WFC3-IR images are created by combining three noise-equalized $HST$/WFC3-IR bands, $J_{125}$, $H_{140}$, and $H_{160}$ (see Skelton et al. 2014, for more details). The imaging of these IR bands yields roughly a stellar-mass-limited sample. The photometric properties and the results of SED fitting for all the sources are summarized in Skelton et al. (2014). The $HST$ images and catalogs are publicly released on the 3D-HST Web site.

We use galaxies whose physical quantities and photometric redshifts are well derived from SED fitting (specifically, sources with $\text{use
gal}$ = 1 in the public catalogs). In this paper, we assume a Salpeter (1955) initial mass function (IMF) for the fair comparison with previous studies. 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 into two subsamples of star-forming galaxies (SFGs) and quiescent galaxies (QGs) by specific SFR (sSFR) values. Galaxies with sSFR $>0.1$ and $<0.1$Gyr$^{-1}$ are classified as SFGs and QGs, respectively.

Structural parameters such as semimajor axes ($R_{\text{major}}$), position angle (P.A.), axial ratios ($q$), circularized effective radii ($r_e$), and Sérsic indices ($n$) have been obtained from our Sérsic profile fitting (Sérsic 1963, 1968) with GALFIT (Peng et al. 2002, 2010) (Paper I). In the GALFIT fitting, clumpy subcomponents of galaxies have been masked to acquire these structural parameters of major stellar components. By using SExtractor, we have generated mask images that define regions of neighboring objects and clumpy subcomponents around the main galaxies. We have conducted the GALFIT profile fitting with these mask images, omitting the masked regions (see Peng et al. 2002). The SFR surface density (SFR SD), $\Sigma_{\text{SFR}}$, was calculated by an equation of $\Sigma_{\text{SFR}} = \text{SFR}/(2\pi r_e^2)$. See Paper I for details.

2.2. Sample of LBGs in CANDELS, HUDF 09/12, and HFF

The second sample consists of 10,454 LBGs at $z \approx 4$–10 made by Harikane et al. (2015) in CANDELS, the Hubble Ultra Deep Field 09+12 (HDF 09/12; Beckwith et al. 2006; Bouwens et al. 2011; Ellis et al. 2013; Illingworth et al. 2013) fields, and the parallel fields of Abell 2744 and MACS0416 in the Hubble Frontier Fields (e.g., Atek et al. 2015; Coe et al. 2015; Ishigaki et al. 2015; Oesch et al. 2015). These LBGs are selected with color criteria similar to those of Bouwens et al. (2015). We perform source detections by SExtractor (Bertin & Arnouts 1996) in co-added images constructed from bands of $y_{090}$, $y_{105}$, $J_{125}$, $H_{140}$, and $H_{160}$ for the $z \approx 4$–7, 8, and 10 LBGs, respectively. The $J_{140}$ band is included in the co-added $y_{090}$.

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5. The first paper presents a study on galaxy sizes at $z \approx 0$–10 (Shibuya et al. 2015, hereafter Paper I).

6. http://3dhst.research.yale.edu/Home.html

7. http://archive.stsci.edu/prepds/xdf/
image for the $z \approx 7$–8 LBGs in the HUDF 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 Harikane et al. (2015) for more details of the source detections and LBG selections.

Similarly for the photo-{$z$} galaxies, we have obtained $R_{e,\text{major}}, q,$ and $r_e$ for the LBG sample. We note that the LBGs have no Sérsic index measurements as a result of fixing $n$ values in the GALFIT fitting. We have also derived $\Sigma_{\text{FIR}}$ and UV slope $\beta$ for the LBGs. The $\beta$ value is defined by $f_{\beta} \propto \lambda^{\beta}$, where $f_{\beta}$ is the galaxy spectrum at the rest-frame wavelengths of $\approx$1500–3000 Å. See Paper I for details.

### Table 1

| Population     | $z = 0$–1 | $z = 1$–2 | $z = 2$–3 | $z = 3$–4 | $z = 4$–5 | $z = 5$–6 | $N_{\text{gal}}$ ($N_{\text{clumpy}}$) | $N_{\text{gal}}$ ($N_{\text{clumpy}}$) |
|----------------|-----------|-----------|-----------|-----------|-----------|-----------|--------------------------------|--------------------------------|
| SFGs (UV)      | 2187 (859)| 3236 (1842)| 1429 (672)| 94 (44)   | 12 (6)    | 4 (2)     | 6962 (3425) | 4021 (595)                  |
| QGs (UV)       | 1079 (195)| 786 (346) | 144 (50)  | 11 (3)    | 1 (1)     | 0 (0)     | 2977 (1179) | 1102 (232)                  |
| SFGs (Opt)     | 1353 (645)| 1624 (534)| ...       | ...       | ...       | ...       | 2977 (1179) | 1102 (232)                  |
| QGs (Opt)      | 579 (137) | 523 (95)  | ...       | ...       | ...       | ...       | 2977 (1179) | 1102 (232)                  |

**Notes.** Columns: (1) Galaxy population. The rest-frame wavelength for clumpy structure analyses is given in parentheses. (2)–(7) Numbers of SFGs, QGs, and LBGs used for our clumpy structure analyses in each redshift bin. The values in parentheses indicate the total numbers of clumpy galaxies. The redshift range is confined to $z = 0.5$–1 because of the small galaxy number at $z \leq 0.5$.

* The LBGs at $z \approx 10$ are excluded in our clumpy structure analyses owing to the small sample size.

### 3. HST-BAND IMAGES AND GALAXIES FOR CLUMPY STRUCTURE ANALYSES

In this section, we describe HST-band images and galaxies used for our clumpy structure analyses.

#### 3.1. HST-band Images

To minimize the effect of morphological $K$-correction, we use images of HST multiwavebands. In this study, we investigate clumps at the rest-frame UV (1500–3000 Å) and optical (4500–8000 Å) wavelengths. These clumps are hereafter referred to as “UV clumps” and “optical clumps,” respectively. For UV clumps, we use $V_{606}$ for $z = 0$–2, $I_{604}$ for $z = 2$–3 photo-$z$ galaxies, and co-added images of $Y_{099}, J_{105}, H_{160}$ and $J_{125}/H_{160}$ for $z \geq 4$ LBGs. For optical clumps, we choose $J_{125}$ for $z = 0$–1 and $H_{160}$ for $z = 1$–2 photo-$z$ galaxies.

Guo et al. (2015) analyzed a larger number of ACS bands, $B_{355}V_{606}i_{775}z_{850}$, for UV clumps in the GOODS-S field compared to ours. Here we restrict our bands to $V_{606}$ and $I_{604}$ for a homogeneous analysis in all the CANDELS fields owing to the lack of $B_{355}$, $i_{775}$, and/or $z_{850}$ in AEGIS, COSMOS, and UDS. The difference of these HST-band choices has provided no significant impacts on results of clumpy structure analyses (Guo et al. 2015).

#### 3.2. Sample Galaxies

We select bright, large, and face-on galaxies from the two galaxy samples (Section 2) for secure identifications of clumpy structures. We analyze photo-$z$ galaxies with $\log(M_{\text{d}}/M_\odot) \geq 9$, $H_{160} < 24.5$ mag, an $H_{160}$-band semimajor axis of $R_{\text{major}} \geq 0^{\prime}2$, and $q \geq 0.5$ in the ACS-band images. These selection criteria are the same as those of Guo et al. (2015). We restrict analyses to galaxies with $R_{\text{major}} \geq 0^{\prime}4$ for the WFC3/IR-band images owing to a broader PSF size than that of ACS. In total, 6962 (2977) SFGs and 2021 (1102) QGs are selected for analyses of UV (optical) clumps.

For the LBGs, we apply only a magnitude cut of $m_{\text{UV}} < 27$ mag, where we securely compare results of automated clump identification methods and visual inspections in typical HST deep fields (e.g., Jiang et al. 2013). Moreover, with this $m_{\text{UV}}$ threshold, we obtain at least 10 sample galaxies at each redshift. This sample size enables us to perform statistical measurements of clumpy structures up to $z \approx 8$. The total number of LBGs at $z \approx 4$–8 is 3848 for the clumpy structure analyses. Here we exclude the LBGs at $z \approx 10$ owing to the small sample size. The effect of the selection criterion choices is discussed in Sections 6.1.4 and 6.1.5.

Table 1 summarizes the number of photo-$z$ galaxies and LBGs used for our clumpy structure analyses.

### 4. ANALYSIS

In this section, we describe methods to identify clumpy structures in the HST images. The clumpy structures of galaxies have been examined in several ways, e.g., by using SExtractor (e.g., Murata et al. 2014), CLUMPFIND (Williams et al. 1994), the nonparametric morphological indices (e.g., Conselice 2003), and based on the visual inspection (e.g., Elmegreen et al. 2007). Recently, Guo et al. (2015) developed a method to investigate clumpy galaxies at $z \approx 0$–3 and identified off-center UV clumps in large HST/ACS data. In our

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8 We make use of $\delta_{850}$ for GOODS-North, which has not been observed with the $I_{604}$ band.

9 Our visual inspections confirm that the LBGs at $z \approx 10$ show no clumpy structures (see also Holwerda et al. 2015).
study, we employ a method similar to that of Guo et al. (2015) to compare our measurements with those of Guo et al. We also newly apply this technique to both ACS and WFC3/IR images. The identification parameters for the WFC3/IR images are determined by our careful visual inspections.

1. **Object images.**—We extract 18″ × 18″ cutout images from the HST data at the position of each photo-z galaxy and LBG. The size of cutout images is sufficiently large to investigate entire galaxy structures even for extended objects at z ≃ 0–1.

2. **Segmentation maps.**—We also cut out SExtractor segmentation maps with the same size as for the object images to define areas searching for clumps. We use H160 segmentation maps that are generated by our SExtractor detections and publicly released on the 3D-HST Web site. SExtractor frequently outputs segmentation areas smaller than intrinsic galaxy sizes for faint sources. We enlarge individual segmentation areas (so-called dilation; see Galametz et al. 2013; Guo et al. 2013) with a task of GAUSS in IRAF according to isophotal areas of each galaxy. Our dilation technique is slightly different from, e.g., Galametz et al. (2013) with the TFIT software. We find that the difference of dilated areas provides negligible impacts on our results of our clumpy structure analyses.

3. **Detection of clumps.**—We detect clumpy objects within galaxies. We first smooth the object images through a boxcar filter with a side of 10 pixels (= 0″6). We find that the choice of the boxcar filter size does not significantly affect the results of clump identification (e.g., f_clump). Next, we subtract the smoothed images from the original ones to make clumpy objects stand out. These subtracted images are referred to as contrast images. To avoid detections of sky noise, we mask all pixels with a flux less than 2σ of sky background fluctuation. Sky background levels are measured in the contrast images after a 3σ flux clipping. Finally, we perform SExtractor detections within regions defined with the dilated segmentation maps. We require these clumpy objects to have an area larger than five (seven) contiguous pixels, DETECT_MINAREA = 5 (7), for the ACS (WFC3/IR) images. We define “clump candidates” as these detected objects.

4. **Photometry of clumps.**—We carry out photometry for the clump candidates. We measure an aperture flux, f_aper, within a radius of r_aper = 3 (6) pixels, corresponding to 0″18 (0″36) for clump candidates in the ACS (WFC3/IR) images. These photometric apertures would include background fluxes of host galaxies. We subtract the background fluxes of host galaxies from f_aper. The average SB in a circular ring at r = 4–10 (8–20) pixels is considered to be the background fluxes for clump candidates in the ACS (WFC3/IR) images. The background-subtracted f_aper is converted to a total flux, f_tot, by applying aperture corrections. The factors of aperture corrections range from ≃0.7 to ≃0.8. The aperture photometry with the aperture correction generally provides reliable measurements of the intrinsic clump magnitudes. This is because almost all of the clumps selected by our method have a point-source-like radial profile (see also Guo et al. 2015). We convert f_tot to a luminosity, L_cl, under the assumption that these clump candidates are physically associated with host galaxies.

Guo et al. (2015) find that L_cl at a small galactocentric distance, d_cl, tends to be overestimated owing to bright central structures (e.g., bulges). We evaluate these “luminosity overestimate ratios” in Monte Carlo simulations (Section 5) and correct for L_cl.

5. **Selection of clumps.**—We select off-center clumps among the clump candidates based on their luminosity and position. We employ the following criteria:

\[ \frac{L_{\text{cl}}}{L_{\text{gal}}} \geq 0.08 \text{ and } 0.5 \leq d_{\text{cl}}/r_e < 8, \]

where L_{gal} is the luminosity of a host galaxy. To measure d_{cl}, we use flux-weighted centers determined by the SExtractor detections of Skelton et al. (2014) and Harikane et al. (2015). The segmentation areas are typically more effective than the outer boundary of d_{cl}/r_e = 8. In this study, we define “clumpy galaxies” as objects with at least one off-center clump that meets Equation (1).

For the LBG sample, we do not use the d_{cl}/r_e criterion. This is because high-z LBGs are unlikely to have evolved bright cores at the centers. We define clumpy galaxies as objects with at least two clumps that meet only the L_{cl}/L_{gal} criterion in Equation (1).

Figure 1 shows examples of clumpy galaxies. The results of clump identification appear to be in good agreement with visual inspections.

5. **LUMINOSITY OVERESTIMATE RATIOS AND DETECTION COMPLETENESS**

We perform Monte Carlo simulations to evaluate luminosity overestimate ratios (ΔL/L_in) and detection completeness (F_c) in the same manner as the analysis in Guo et al. (2015). First, we create an artificial clump by using MKOBJECTS in the IRAF package. Second, the artificial clump is broadened to the PSF size of an HST image. Third, the artificial clump is added to a segmentation area of a real galaxy. Here we randomly change luminosity L_{cl}/L_{gal} and position d_{cl}/r_e of the artificial clump in ranges of −2.5 ≤ log(ΔL/L_{gal}) < 0 and 0.1 ≤ d_{cl}/r_e < 3, respectively. Finally, we detect the artificial clump and carry out photometry in the same manner as for the real galaxies (Section 4). This procedure is repeated 50 times for each galaxy at a given L_{cl}/L_{gal} and d_{cl}/r_e. We perform the simulation for 1000 galaxies in each HST band and field.

Panel (a) of Figure 2 shows the luminosity overestimate ratios, ΔL/L_in ≡ (L_{out} − L_{in})/L_{in}, as a function of d_{cl}/r_e, where L_{in} (L_{out}) is the input (output) clump luminosity in the Monte Carlo simulation. As shown in panel (a), ΔL/L_in gradually increases toward the galactic centers and reaches ΔL/L_in ≃ 0.3 at d_{cl}/r_e = 0.5 for the V_{606}k_{14} images. These trends are consistent with that of Guo et al. (2015). In contrast, we find that the J_{125}H_{160} images have a relatively high value of ΔL/L_in ≃ 1.5 at d_{cl}/r_e = 0.5. These high ΔL/L_in values would result from the broad PSF sizes of J_{125}H_{160} and/or a flux contribution of bright central bulge-like objects at the rest-frame optical wavelengths.

Panel (b) of Figure 2 represents F_c as a function of L_{cl}/L_{gal}. We find that clumps are well identified even for low-M* and high-z galaxies (i.e., F_c ≥ 0.5 at L_{cl}/L_{gal} ≥ 0.08). We correct for the detection incompleteness by using the following
Figure 1. Examples of clumpy galaxies identified in our selections. The left, middle, and right panel sets indicate SFGs, QGs, and LBGs, respectively. Each of the four-panel sets for the SFGs and the QGs presents the three-color composite, the rest-frame UV, the rest-frame optical images, and the clump position maps, from left to right. In the clump position maps, the black and blue circles denote UV clump candidates and selected UV clumps with $L_{\text{cl}}/L_{\text{gal}} \geq 0.08$, respectively. The thick and thin red squares indicate optical clumps with $L_{\text{cl}}/L_{\text{gal}} \geq 0.1$ and $L_{\text{cl}}/L_{\text{gal}} = 0.08-0.1$, respectively. Each row, from top to bottom, represents example clumpy galaxies from $z \simeq 0$ to $z \simeq 3$. Each of the two-panel sets for the LBGs exhibits the co-added images (left) and the clump position maps (right). Each row, from top to bottom, denotes clumpy LBGs from $z \simeq 4$ to $z \simeq 8$. The white tick indicates the size of 1″.

Figure 2. Results of the Monte Carlo simulations for the clump identifications. (a) Luminosity overestimate ratios, $\Delta L/L_{\text{in}}$, as a function of $d_{\text{cl}}/r_e$. The cyan solid, green solid, orange dashed, and magenta dot-dashed curves show $\Delta L/L_{\text{in}}$ for the $V_{606}$, $I_{814}$, $J_{125}$, and $H_{160}$ band images, respectively. The vertical dashed line denotes the inner $d_{\text{cl}}/r_e$ threshold ($d_{\text{cl}}/r_e = 0.5$; see Section 4 for details). The horizontal dashed line presents $\Delta L/L_{\text{in}} = 0$. (b) Detection completeness of clumps, $F_c$, as a function of $L_{\text{cl}}/L_{\text{gal}}$. The left and right panels indicate $F_c$ in the rest-frame UV and optical wavelengths, respectively. The cyan, green, and magenta curves denote $F_c$ at $z = 0$–1, 1–2, and 2–3, respectively. The short-dashed, long-dashed, and solid curves represent $\log M_*/M_{\odot} = 9$–10, 10–11, and 11–12, respectively. The horizontal dashed lines denote $F_c = 0.5$. The vertical dashed lines indicate the threshold of fractional luminosity, $L_{\text{cl}}/L_{\text{gal}} = 8\%$, for the clump identifications.
equation:

\[ f_{\text{clumpy,cor}} = f_{\text{clumpy}} + \frac{1}{n_e} \left( \frac{1}{F_e} - 1 \right) f_{\text{clumpy}} - \frac{1}{n_e} \left( \frac{1}{F_e} - 1 \right) \left( f_{\text{clumpy}} \right)^2, \]  

(2)

where \( f_{\text{clumpy,cor}} \) and \( n_e \) are an incompleteness-corrected clumpy fraction and the number of clumps in a host galaxy, respectively. We assume \( n_e = 2 \) for incompleteness correction, similarly to Guo et al. (2015). The correction with Equation (2) typically makes \( f_{\text{clumpy}} \) increase by a factor of \( \sim 1.1-1.2 \). We find that \( F_e \) is most sensitive to \( M_s \) (\( \sim M_{\text{gal}} \)) and \( z \) of host galaxies. For this reason, we correct for the detection incompleteness for the redshift evolution of \( f_{\text{clumpy}} \) (Section 6.1), but for analyses in a given \( M_s, L_{\text{gal}} \) and \( z \) bin (e.g., Section 6.3.1).

6. RESULTS

6.1. Evolution of Clumpy Fractions

We present our \( f_{\text{clumpy}} \) measurements for the photo-\( z \) galaxies and the LBGs in Section 6.1.1. We compare our \( f_{\text{clumpy}} \) values for the photo-\( z \) galaxies and the LBGs with results of previous studies in Sections 6.1.2 and 6.1.3, respectively. In Section 6.1.4, we show the redshift evolution of \( f_{\text{clumpy}} \) at \( z \approx 0-8 \) in a compilation of the photo-\( z \) galaxy and LBG samples. In Section 6.1.5, we check whether our results of \( f_{\text{clumpy}} \) at \( z \approx 0-8 \) are reliable.

6.1.1. Clumpy Fractions for the Photo-\( z \) Galaxies and the LBGs

We present \( f_{\text{clumpy}} \) for the photo-\( z \) galaxies at \( z \approx 0-3 \) and the LBGs at \( z \gtrsim 4 \). Figure 3 shows \( F_e \)-corrected clumpy fractions \( f_{\text{clumpy,cor}} \) for the SFGs and the QGs. We measure the number fraction of galaxies with UV clumps, \( f_{\text{UV,cor}} \), and optical ones, \( f_{\text{opt,cor}} \). In Figure 3, galaxies at \( z \gtrsim 3 \) are not shown owing to the small sample size (see Table 1).

For the SFGs, we find that \( f_{\text{UV,cor}} \) basically decreases from \( z \approx 3 \) to \( z \approx 0 \) in all the \( M_s \) bins. These \( f_{\text{UV,cor}} \) evolutions appear to slightly depend on \( M_s \) in the sense that \( f_{\text{UV,cor}} \) in a high-\( M_s \) bin drops toward low \( z \). In a high-\( M_s \) bin of log \( M_s/M_\odot = 11-12 \), \( f_{\text{UV,cor}} \) has \( \approx 70\% \) at \( z \gtrsim 2 \) and gradually decreases to \( \approx 20\% \) at \( z \approx 0 \). In an intermediate-\( M_s \) bin of log \( M_s/M_\odot = 10-11 \), \( f_{\text{UV,cor}} \) has \( \approx 50\% \) at \( z \approx 2-3 \) and then drops to \( \approx 40\% \) at \( z \approx 0 \). In a low-\( M_s \) bin of log \( M_s/M_\odot = 9-10 \), \( f_{\text{UV,cor}} \) has an approximately constant value of \( f_{\text{UV,cor}} \approx 50\%-60\% \) at \( z \approx 1-3 \) and slightly decreases to \( \approx 40\% \) at \( z \approx 0 \). In contrast, \( f_{\text{opt,cor}} \) shows small values, \( \approx 10\%-30\% \), at \( z \approx 0-3 \) compared to \( f_{\text{UV,cor}} \). There is no significant dependence of \( f_{\text{opt,cor}} \) on \( M_s \).

For the QGs, the evolutional \( f_{\text{UV,cor}} \) trends are similar to those of the SFGs. Even in the similarity of the \( f_{\text{UV,cor}} \) evolution, \( f_{\text{opt,cor}} \) for the QGs are typically smaller than those for the SFGs by a factor of \( \approx 1.4 \). The \( f_{\text{UV,cor}} \) values for the QGs gradually decrease from \( \approx 30\%-50\% \) at \( z \approx 3 \) to \( \approx 10\%-30\% \) at \( z \approx 0 \). The relatively high \( f_{\text{UV,cor}} \) values could be explained by a high sSFR for our QGs (see also Section 6.3). The average sSFR value is log sSFR \( \approx -1.8 \) for our QGs at \( z \approx 1-2 \). The high sSFR indicates that our QGs have not been completely quenched. In contrast, \( f_{\text{opt,cor}} \) for the QGs has small values of \( \approx 10\%-20\% \) at \( z \approx 0-2 \) in all the \( M_s \) bins. We find no significant dependence of both \( f_{\text{UV,cor}} \) and \( f_{\text{opt,cor}} \) on \( M_s \) for the QGs. Following the small sample size of the optical clumps, we mainly focus on UV clumps (e.g., \( f_{\text{UV,cor}} \)) in Sections 6.2–6.4.

Figure 4 shows \( f_{\text{UV,cor}} \) for the \( z \approx 4-8 \) LBGs with a UV luminosity of \( L_{\text{UV}} = 0.3-L_{\text{UV},*} \), where \( L_{\text{UV},*} \) is the characteristic UV luminosity of LBGs at \( z \approx 3 \). Our measurement is remarkably consistent with the lack of HST filters covering the rest-frame optical wavelengths at \( z \gtrsim 3 \). As shown in Figure 4, we find that \( f_{\text{UV,cor}} \) remains roughly constant around \( \approx 20\% \) for the LBGs at \( z \approx 4-8 \) albeit with the large error bars at \( z \gtrsim 6 \).

6.1.2. Comparisons of \( f_{\text{clumpy}} \) between our Photo-\( z \) Galaxies and Previous Studies

We compare our \( f_{\text{clumpy}} \) for the photo-\( z \) galaxies with those of previous studies at \( z \approx 0-3 \) in Figure 3. Table 2 summarizes previous studies on clumpy galaxies at \( z \approx 0-3 \). The \( f_{\text{clumpy}} \) data points and the error bars of these previous studies are taken from Guo et al. (2015). In most cases, our clump identification method is slightly different from those of these previous studies (see Table 2). We hereafter specify the methods in the following comparisons for several of these studies.

The clumpy structures have widely been investigated for star-forming galaxies at the rest-frame UV wavelength. Elmegreen et al. (2007) reported that \( f_{\text{UV,cor}} \) is \( \approx 50\%-60\% \) at \( z \approx 2-3 \) and \( \approx 30\% \) at \( z \approx 0 \) using a sample of 1003 starburst galaxies. Puech (2010) found \( f_{\text{clumpy}} \approx 20\% \) at \( z \approx 0.6 \) for 63 emission-line galaxies. Overzier et al. (2010) obtained \( f_{\text{UV,cor}} \approx 20\% \) for 30 Lyman break analogs (LBAs) at \( z \approx 0.2 \), which is a low-\( z \) UV-bright galaxy population (see also Guaita et al. 2015). Tadaki et al. (2014) examined clumpy structures for 100 Hα emitters (HAEs) at \( z \approx 2-2.5 \) and obtained \( f_{\text{UV,cor}} \approx 40\% \).

Wuyts et al. (2012) measured \( f_{\text{UV,cor}} \) to be \( \approx 70\%-80\% \) at \( z \approx 0.5-2.5 \) based on a sample of 649 star-forming galaxies. Murata et al. (2014) identified clumpy structures among 24,027 galaxies at \( z \approx 0-1 \) in COSMOS, suggesting a gradual decrease from \( f_{\text{clumpy}} \approx 20\% \) at \( z \approx 1 \) to \( \approx 10\% \) at \( z \approx 0 \). Recently, Guo et al. (2015) investigated clumpy structures of 3229 SFGs in the UDS and GOODS-S data for the evolution of \( f_{\text{UV,cor}} \) at \( z \approx 0-3 \). In an \( M_s \) bin of log \( M_s/M_\odot = 9-9.8 \), Guo et al.’s \( f_{\text{UV,cor}} \) show no evolution, \( \approx 60\% \) at \( z \approx 0 \). In contrast, \( f_{\text{UV,cor}} \) gradually decreases from \( \approx 60\% \) at \( z \approx 3 \) to \( \approx 10\%-30\% \) at \( z \approx 0 \) in the \( M_s \) bins of log \( M_s/M_\odot \). Guo et al.’s \( f_{\text{UV,cor}} \) and our measurements at \( z \approx 0-3 \).
than theirs at $z \approx 2$ by a factor of three. This discrepancy might result from the difference of clump identification methods.

These comparisons indicate that our $f_{\text{clumpy}}$ measurements at $z \approx 0$ to 3 are consistent with the results of the previous studies. The $f_{\text{clumpy}}$ agreements ensure the reliability of our clump structure analyses.

### 6.1.3. Comparisons of $f_{\text{clumpy}}$ between our LBGs and Previous Studies

We compare our $f_{\text{clumpy}}$ values for the LBGs with results of previous studies on UV-bright galaxies at $z \gtrsim 4$. In Figure 4, we plot $f_{\text{clumpy}}$ for UV-bright galaxies with a UV luminosity range of $L_{UV} \approx 0.3$–$1L_{UV}^*_{z=3}$ similar to ours (see Table 2). All of these UV-bright galaxies have been selected in the dropout technique (Steidel et al. 1999). Several of these studies aim to search for merger-like systems to derive the galaxy merger fractions. It is interesting to compare our “clumpy” galaxies with merger-like systems in these previous studies owing to the morphological similarity. Here we refer to all of these LBGs with irregular morphologies as “clumpy” galaxies.

Lotz et al. (2006) derived a clumpy fraction of $f_{\text{clumpy}} \approx 21\%$ for LBGs at $z \approx 4$ based on the $GM_{20}$ criterion (see the caption of Table 2). Ravindranath et al. (2006) obtained a roughly constant value of $f_{\text{clumpy}}^{UV} \approx 20\%$–$30\%$ for 1333 LBGs at $z \approx 3$–5 in the Sérsic profile fitting. Conselice & Arnold (2009) measured $f_{\text{clumpy}}^{UV}$ using the A index and obtained $f_{\text{clumpy}}^{UV} \approx 20\%$ at $z \approx 3$–5. Oesch et al. (2010) found two clumpy objects among 21 LBGs at $z \approx 7$, corresponding to $f_{\text{clumpy}}^{UV} \approx 10\%$, identified by visual inspection. Jiang et al. (2013) suggested $f_{\text{clumpy}}^{UV} \approx 40\%$ given by visual inspections for LAEs and LBGs at $z \approx 5$–7. Kawamata et al. (2015) found $f_{\text{clumpy}}^{UV} \approx 10\%$ at $z \approx 6$–7 and $\approx 50\%$ at $z \approx 8$, by visual inspection, for LBG samples selected in two HFF fields. These $f_{\text{clumpy}}^{UV}$ values are remarkably comparable to our results, albeit with relatively large error bars at $z \gtrsim 6$. The $f_{\text{clumpy}}^{UV}$ agreements with the results of the visual inspections encourage our automated method for faint sources at $z \gtrsim 6$.

On the other hand, we find that our $f_{\text{clumpy}}^{UV}$ values are smaller than those of LBGs at $z \approx 4$–8 in Curtis-Lake et al. (2014). As described in Section 6.3.2, $f_{\text{clumpy}}^{UV}$ depends on the UV luminosity. The sample galaxies of Curtis-Lake et al. (2014) would be slightly brighter than the range of $L_{UV} = 0.3$–$1L_{UV}^*_{z=3}$. 

![Figure 3. Redshift evolution of $f_{\text{clumpy}}^{UV}$ (top) and $f_{\text{clumpy}}^{opt}$ (bottom) for the photo-$z$ galaxies at $z \approx 0$–3. The left and right panels indicate $f_{\text{clumpy}}^{opt}$ for the SFGs and the QGs, respectively. The filled blue and red symbols denote our $f_{\text{clumpy}}^{opt}$ measurements for the SFGs and the QGs in each $M_*$ bin ($\log M_*/M_\odot = 9$–10: triangles; 10–11: circles; 11–12: squares). The error bars of $f_{\text{clumpy}}^{opt}$ are calculated via analytical error propagation from Poisson errors, $\sqrt{N}$, where $N$ is the number of sample galaxies or selected clumpy galaxies. The gray symbols show $f_{\text{clumpy}}^{opt}$ in the literature (asterisks: Elmegreen et al. 2007; open circle: Overzier et al. 2010; inverse triangle: Puech 2010; diamonds: Wuys et al. 2012; pentagon: Tadaki et al. 2014; triangles: Murata et al. 2014; gray filled inverse triangle, circles, and squares: galaxies with $\log M_*/M_\odot = 9$–9.8, 9.8–10.6, and 10.6–11.4, respectively, in Guo et al. 2015). The error bars are put by Poisson statistics from the galaxy number counts if the reference does not show uncertainties of $f_{\text{clumpy}}^{opt}$. Note that our SFGs and QGs are classified by the sSFR value, $\log \text{sSFR} = 0.1$ Gyr$^{-1}$. In this sSFR criterion, galaxies with a moderately high sSFR are included in our QG sample (see Section 6.1.1).]
Indeed, Curtis-Lake et al. (2014) obtained an \( r_c \) evolution, which also depends on \( L_{UV} \), different from ours (see Paper I). We thus attribute the \( f_{UV}^{clumpy} \) difference to the \( L_{UV} \) range.

6.1.4. Evolution of Clumpy Fractions at \( z \approx 0–8 \)

We present the redshift evolution of \( f_{UV}^{clumpy} \) at \( z \approx 0–8 \) in a compilation of the photo-\( z \) galaxy and LBG samples. Figure 4 shows \( f_{UV}^{clumpy} \) for SFGs and LBGs with \( L_{UV} = 0.3–1L_{z=3}^* \). We find that the \( f_{UV}^{clumpy} \) value is in good agreement between the SFGs at \( z \approx 3.5 \) and the LBGs at \( z \approx 4 \). This \( f_{UV}^{clumpy} \) agreement suggests that the difference of galaxy selections (i.e., photo-\( z \) or Lyman break) would minimally affect the \( f_{UV}^{clumpy} \) evolution. This argument is also supported by the evolution of galaxy sizes using the same photo-\( z \) and LBG samples as those of this study (Paper I).

We identify an evolutionary trend that \( f_{UV}^{clumpy} \) increases from \( z \approx 8 \) to \( \approx 1–3 \) and subsequently decreases from \( z \approx 1 \) to \( \approx 0 \). This \( f_{UV}^{clumpy} \) trend is similar to the Madau–Lilly plot of the cosmic SFRD evolution (e.g., Madau et al. 1996; Lilly et al. 1996). We fit the Madau–Lilly plot type formula,

\[
f_{UV,cor}^{clumpy}(z) = a \times \frac{(1 + z)^b}{1 + [(1 + z)/c]^d},
\]

where \( a, b, c, \) and \( d \) are free parameters (Madau & Dickinson 2014) to our \( f_{UV,cor}^{clumpy} \) evolution. The best-fit parameters are \( a = 0.035 \), \( b = 4.6 \), \( c = 2.2 \), and \( d = 6.7 \). As shown in Figure 4, the \( f_{UV,cor}^{clumpy} \) evolution is well described by the Madau–Lilly plot type formula. The best-fit function of \( f_{UV,cor}^{clumpy}(z) \) indicates the presence of an \( f_{UV,cor}^{clumpy} \) peak at \( z \approx 1–2 \). Figure 5 compares the best-fit \( f_{UV,cor}^{clumpy} \) function with the cosmic SFRD in Madau & Dickinson (2014). This comparison suggests the evolutionary similarity between \( f_{UV,cor}^{clumpy} \) and the cosmic SFRD albeit with a possible redshift difference of the peaks. Our self-
consistent analyses for clumpy structures at \( z \approx 0\) to 8 enable us to discover, for the first time, the evolutionary trend and the peak of \( f_{\text{clumpy}}^{UV} \).

For comparison, we plot \( f_{\text{clumpy}}^{UV} \) in previous studies on UV-bright galaxies at \( z \approx 1\) to 3, where the \( f_{\text{clumpy}}^{UV} \) peak is shown in our sample in Figure 4. Ravindranath et al. (2006) analyzed 153 starburst galaxies with \( L_{\text{UV}} \approx 0\) to 3 and obtained \( f_{\text{clumpy}}^{UV} \approx 60\% \) at \( z \approx 1\). The \( f_{\text{clumpy}}^{UV} \) value is in remarkably good agreement with our \( f_{\text{clumpy}}^{UV} \) measurements. Law et al. (2012a) selected clumpy objects among BX/BM galaxies and LBGs at \( z \approx 2\) to 3 using two selection criteria based on \( GM_{20} \) and A indices. We find that the A-based \( f_{\text{clumpy}}^{UV} \) is consistent with ours at \( z \approx 3\), but more quickly drops at \( z \approx 2\) than our \( f_{\text{clumpy}}^{UV} \). The \( GM_{20} \)-based \( f_{\text{clumpy}}^{UV} \) measurements show lower values of \( f_{\text{clumpy}}^{UV} \approx 20\% \) to \( 30\% \) at\( z \approx 2\) than ours. We do not reveal an exact cause for producing the \( f_{\text{clumpy}}^{UV} \) differences. The \( f_{\text{clumpy}}^{UV} \) difference may be caused by the combination of the \( L_{\text{UV}} \) range and clump detection methods. We also plot a morphological measurement for \( z \approx 2\) LAEs with \( M_{\text{UV}} \) and Ly\( \alpha \) equivalent widths similar to those of LBGs (Shibuya et al. 2014). We find that the LAE sample has \( f_{\text{clumpy}}^{UV} \approx 60\% \), which is consistent with our LBG results.

To enlarge the number of data points at \( z \approx 1\), we replot \( f_{\text{clumpy}}^{UV} \) of Guo et al.’s SFGs with \( M_{\text{UV}} \approx 9.8\) to 10.6 (see Figure 3). Guo et al.’s \( f_{\text{clumpy}}^{UV} \) has been measured in the \( M_{\text{UV}} \)-limited sample. Despite the difference of the galaxy selection methods, this \( f_{\text{clumpy}}^{UV} \) range roughly corresponds to \( L_{\text{UV}} \approx 0.3\) to 1.1 \( 10^{43} \) erg s\(^{-1}\) at \( z \approx 3\) according to the \( M_{\text{UV}}-M_{\text{UV}} \) relation (Paper I). As shown in Figure 4, the \( f_{\text{clumpy}}^{UV} \) in Guo et al. (2015) follows our \( f_{\text{clumpy}}^{UV} \) evolution at \( z \approx 0\) to 3. These previous studies of \( f_{\text{clumpy}}^{UV} \) support that the peak of \( f_{\text{clumpy}}^{UV} \) possibly exists at \( z \approx 1\) to 3.

6.1.5. Is the \( f_{\text{clumpy}}^{UV} \) Peak Real?

We examine whether the possible \( f_{\text{clumpy}}^{UV} \) peak at \( z \approx 1\) to 3 is real. Basically, high spatial resolution and high-sensitivity data are required to detect clumps in high-\( z \) galaxies. In the limited spatial resolution and sensitivity of \( HST \), a low detection completeness for clumps at \( z \approx 4 \) might produce an \( f_{\text{clumpy}}^{UV} \) peak at \( z \approx 1\). Here we discuss five potential systematics that may produce an \( f_{\text{clumpy}}^{UV} \) peak: the differences of (1) the spatial...
resolution, (2) clump search areas, (3) selection criteria of sample galaxies, (4) clump identification methods, and (5) the cosmological SB dimming effects between the SFGs at $z \lesssim 3$ and the LBGs at $z \gtrsim 4$.

1. Spatial resolution.—We check whether the difference in the spatial resolution changes $f_{\text{clumpy}}^{UV}$. In Section 4, we have used the co-added images to select clumpy LBGs. Here we measure $f_{\text{clumpy}}^{UV}$ for the LBGs at $z \simeq 4$ with the $I_{814}$ images whose PSF size is $\simeq 2$ times smaller than that of the co-added images. The $I_{814}$ band covers the rest-frame wavelengths slightly bluer than those of the co-added images. Even in the wavelength shift, we find a good agreement in the $f_{\text{clumpy}}^{UV}$ values between the $I_{814}$ and co-added images (i.e., $f_{\text{clumpy}}^{UV} = 0.146 \pm 0.012$ and $0.147 \pm 0.025$ for the $I_{814}$ and co-added images, respectively). This agreement indicates that the difference in the spatial resolution is unlikely to produce the $f_{\text{clumpy}}^{UV}$ peak.

2. Clump search areas.—We test whether $f_{\text{clumpy}}^{UV}$ is affected by the difference in the clump search areas. In Section 4, we have searched for clumps in areas defined by the segmentation maps. There is a possibility that clumps at outer galactic regions are not identified by small segmentation areas for high-$z$ compact sources. Here we enlarge the segmentation areas by a factor of $\simeq 2$ and measure $f_{\text{clumpy}}^{UV}$ for the LBGs at $z \simeq 4$. We find that $f_{\text{clumpy}}^{UV}$ changes within $\simeq \pm 5\%$ in the large clump search area. This test suggests that the difference in clump search areas does not significantly affect the $f_{\text{clumpy}}^{UV}$ values.

3. Selection criteria of sample galaxies.—We examine whether $f_{\text{clumpy}}^{UV}$ is changed by the different selection criteria of sample galaxies. In Section 3, the sample LBGs have been selected only by the $m_{UV}$ criterion to improve the statistics at $z \gtrsim 6$. Here we reselect LBGs in the selection criteria similar to those for the SFGs (i.e., the cuts of $R_{e,\text{major}}$, $H_{160}$ magnitude, and $q$) and measure $f_{\text{clumpy}}^{UV}$ at $z \simeq 4$. This sample selection significantly reduces the number of the LBGs at $z \simeq 4$. Nevertheless, we find that $f_{\text{clumpy}}^{UV}$ does not significantly change.

4. Clump identification methods.—We test whether the difference in the clump identification methods affects $f_{\text{clumpy}}^{UV}$. In Section 3, we have not used the $d_{cl}/r_e$ criterion to identify clumpy LBGs. Here we include the $d_{cl}/r_e$ criterion in the selection for clumpy LBGs at $z \simeq 4$ and measure $f_{\text{clumpy}}^{UV}$. We obtain $f_{\text{clumpy}}^{UV} = 0.2 \pm 0.1$, which agrees with the old $f_{\text{clumpy}}^{UV}$ value within a $1\sigma$ error. This agreement confirms that $f_{\text{clumpy}}^{UV}$ is not largely changed by the clump identification methods.

5. Cosmological SB dimming effects.—We investigate how the cosmological SB dimming effects affect $f_{\text{clumpy}}^{UV}$. In the previous sections, we have corrected $F_e$ for the $f_{\text{clumpy}}^{UV}$ measurements. The $F_e$ correction takes into account the cosmological SB dimming effects. However, one might expect that the evolutionary $f_{\text{clumpy}}^{UV}$ trends strongly depend on the $F_e$ values. Here we demonstrate the effect of the $F_e$ variation on $f_{\text{clumpy}}^{UV}$ (dashed lines in Figure 4; see the caption). We reproduce a broad peak of $f_{\text{clumpy}}^{UV}$ at $z \simeq 1–3$ even in the $F_e$ allowance. Moreover, we should note that typical clumps are reliably identified as less affected by the cosmological SB dimming effect than low SB structures.

These tests indicate that the $f_{\text{clumpy}}^{UV}$ peak would not be produced by the difficulties of clump identifications at high $z$. We thus conclude that the $f_{\text{clumpy}}^{UV}$ peak is real.

6.2. Radial SB Profiles of Clumpy Galaxies

We investigate structural properties of our clumpy host galaxies. To obtain the underlying components of clumpy galaxies, we construct the median stacked images of the clumpy galaxies. In general, clumps would be randomly distributed in a host galaxy. The median stacking analysis would allow us to examine the underlying galaxy components negligibly affected by the flux contributions of clumpy structures (e.g., Cassata et al. 2005; Ravindranath et al. 2006; Elmegreen et al. 2007).

Figure 6 presents the radial SB profiles of galaxies with UV clumps at $z \simeq 0–2$ in the median stacked images. Here we use the rest-frame optical images, which are less affected by the clumpy structures than the rest-frame UV ones (see $f_{\text{clumpy}}^{opt}$ in Section 6.1). The radial SB profiles of clumpy galaxies at $z \gtrsim 2–3$ are not shown in Figure 6. This is because the rest-frame optical wavelengths at $z \gtrsim 2–3$ are redshifted beyond the wavelength coverage of WFC3/IR.

The radial SB profiles are obtained in the following processes. First, we align the P.A. of individual clumpy galaxies in two-dimensional (2D) images. Next, we normalize the galaxy-light counts by the total magnitude of galaxies. We then stack the 2D images of clumpy galaxies in order to obtain the 2D median radial SB profiles. Finally, we extract one-dimensional (1D) radial SB profiles with a slice of 3 pixel width along the major axis to avoid the effect of the $q$ variety. The signal-to-noise ratios ($S/N$s) of the 1D radial SB profiles
Figure 6. Radial SB profiles of clumpy galaxies at $z = 0$–1 (left) and $z = 1$–2 (right) in the median stacked images at the rest-frame optical wavelength. The blue triangles, green circles, and red squares represent radial SB profiles in the bins of $\log M_*/M_\odot = 9$–10, 10–11, and 11–12, respectively. The error bars of each data point are smaller than the size of symbols. The colored curves indicate the best-fit Sérsic functions to each radial SB profile at $r = 3$–8 kpc, with the color coding the same as for the symbols. The gray lines denote the PSFs of the $J_{125}$ (left) and $H_{160}$ (right) images.

| Redshift | $\log M_*/M_\odot = 9$–10 | $\log M_*/M_\odot = 10$–11 | $\log M_*/M_\odot = 11$–12 |
|---------|----------------|----------------|----------------|
| 0–1     | 0.85 ± 0.13    | 1.16 ± 0.06    | 1.28 ± 0.11    |
| 1–2     | 1.03 ± 0.07    | 0.94 ± 0.03    | 1.24 ± 0.08    |

Note. Columns: (1) Redshift. (2)–(4) Best-fit Sérsic indices of the radial SB profiles for the photo-$z$ galaxies with $\log M_*/M_\odot = 9$–10, 10–11, and 11–12, respectively.

There are high (i.e., $S/N \gtrsim 30$ per pixel) even at an outer galactic region of $r \approx 8$ kpc in the low-$M_*$ and high-$z$ galaxy bins. Here we do not mask clumpy structures in the stacking. Even in no masking procedure, the median stacking analysis allows us to securely obtain the radial SB profiles of underlying galaxy components. The details of the stacking analysis are found in M. Kubo et al. (2016, in preparation). The number of stacked clumpy galaxies is 714, 300, and 36 (1015, 953, and 206) at $z = 0$–1 ($z = 1$–2) in the bins of $\log M_*/M_\odot = 9$–10, 10–11, and 11–12, respectively.

We fit the Sérsic function to the radial SB profiles at $r = 3$–8 kpc, where the PSF broadening effect would be negligible (e.g., Nelson et al. 2015). Table 3 summarizes the best-fit Sérsic indices. The best-fit $n$ values are $n \approx 1$ for the radial SB profiles in all the $M_*$ and $z$ bins. These low-$n$ values indicate that clumpy galaxies tend to have disk-like light profiles.

In our stacking analysis, we have not matched $r_e$ and magnitude distributions similar to those of the real galaxies. These $r_e$ values depend on the magnitudes following the size–luminosity relations from Paper I. The axis ratio randomly varies in a range of $0 \leq q \leq 1$. To characterize the typical morphology of galaxies, we fix the input Sérsic index $n_{in} = 1, 2, 3, or 4$ in each set of simulations. Next, we embed these artificial galaxies into the real images at random positions of the blank sky. Finally, we obtain stacked radial SB profiles and measure the Sérsic index $n_{out}$ for the artificial galaxies in the same manner as our analyses for the real galaxies. We do not find $n_{out} \approx 1$ for the artificial galaxy sets of $n_{in} = 2, 3, and 4$, but only for the one of $n_{in} = 1$. Thus, our test suggests that the $n \approx 1$ stacked radial SB profiles are truly made of galaxies with $n \approx 1$ radial SB profiles, and it supports our conclusion that the clumpy galaxies have a disk-like morphology.

In Paper I, the $n$ values were derived in the profile fitting for the entire galaxy regions, including the central bulge-like components. In general, the central components tend to have a large $n$ value of $n \gtrsim 2$ for galaxies at $z \approx 0$–2. For this reason, we obtained a slightly large value of $n \approx 1.5$ in Paper I. Here we remeasure the $n$ value including the central region for the radial SB profile fitting. We obtain the best-fit $n$ values of $n \approx 1$, similar to those found in this section.
6.3. Relations between Clumps and Physical Properties of Host Galaxies

We investigate relations between clumps and physical properties of the photo-z galaxies in Section 6.3.1 and the LBGs in Section 6.3.2.

6.3.1. Results for the Photo-z Galaxies

We first examine physical properties for clumpy photo-z galaxies. Here we evaluate three quantities related to star formation (SF), i.e., SFR, sSFR, and $\Sigma_{\text{SFR}}$, and a structural parameter, $n$. These quantities are derived from entire fluxes of host galaxies (Skelton et al. 2014; Harikane et al. 2015; Paper I). In Section 6.2, we have measured $n$ of the radial SB profiles in the stacked images. In this section, we examine $n$ on the individual basis complimentary to the median stacking analysis. To test whether clumps are related to these physical quantities of host galaxies, we employ two approaches: (i) to examine dependences of $f_{\text{clumpy}}^{UV}$ on physical quantities, and (ii) to quantify differences of number distributions between clumpy and nonclumpy galaxies. Approach (i) enables us to clearly identify $f_{\text{clumpy}}^{UV}$ trends with respect to physical quantities. Approach (ii) is sensitive to differences of two distributions because of comparisons in a wide dynamic range of physical quantities.

Approach (i).—Figure 7 represents dependences of $f_{\text{clumpy}}^{UV}$ on physical quantities (SFR, sSFR, $\Sigma_{\text{SFR}}$, and $n$ from left to right) for the photo-z galaxies. The top, middle, and bottom panels indicate the redshift bins of $z = 0–1$, 1–2, and 2–3, respectively. The cyan triangles, green circles, and red squares denote $f_{\text{clumpy}}^{UV}$ for galaxies with $\log M_*/M_\odot = 9–10$, 10–11, and 11–12, respectively. The colored lines indicate the best-fit linear function to $f_{\text{clumpy}}^{UV}$ in each $M_*$ bin, with the color coding the same as for the symbols. The gray symbols are $f_{\text{clumpy}}$ at $z = 0.6–0.8$ in Murata et al. (2014) (diamonds: $\log M_*/M_\odot > 9.5$; triangles: $\log M_*/M_\odot = 9.5–10$; circles: $\log M_*/M_\odot = 10–10.5$; squares: $\log M_*/M_\odot = 10.5–11$).

Figure 7. Dependences of $f_{\text{clumpy}}^{UV}$ on physical quantities (SFR, sSFR, $\Sigma_{\text{SFR}}$, and $n$ from left to right) for the photo-z galaxies. The top, middle, and bottom panels indicate the redshift bins of $z = 0–1$, 1–2, and 2–3, respectively. The cyan triangles, green circles, and red squares denote $f_{\text{clumpy}}^{UV}$ for galaxies with $\log M_*/M_\odot = 9–10$, 10–11, and 11–12, respectively. The colored lines indicate the best-fit linear function to $f_{\text{clumpy}}^{UV}$ in each $M_*$ bin, with the color coding the same as for the symbols. The gray symbols are $f_{\text{clumpy}}$ at $z = 0.6–0.8$ in Murata et al. (2014) (diamonds: $\log M_*/M_\odot > 9.5$; triangles: $\log M_*/M_\odot = 9.5–10$; circles: $\log M_*/M_\odot = 10–10.5$; squares: $\log M_*/M_\odot = 10.5–11$).
Figure 8. Number distributions of clumpy (filled red) and nonclumpy (open black) galaxies with respect to physical quantities (SFR, sSFR, $\Sigma_{\text{SFR}}$, and $n$ from left to right) for the photo-z galaxies with log $M_*/M_\odot = 9-10$. Each row, from top to bottom, denotes galaxies in a redshift bin of $z = 0-1, 2-3$, and $2-3$, respectively. The number in each panel represents $p$-values of K-S tests (see Section 6.3 for details).

Figure 9. Same as Figure 8, but for the photo-z galaxies with log $M_*/M_\odot = 10-11$. 

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with SFR and sSFR for SFGs at $z \approx 0$–1. As shown in Figure 7, the amplitudes of our $f_{\text{clumpy}}$ values are slightly higher than those of Murata et al. (2014). The difference of $f_{\text{clumpy}}$ amplitudes would be caused by clump identification methods. Nevertheless, we find that our $f_{\text{clumpy}}$ trends are comparable to Murata et al.’s measurements.

Figure 7. The amplitudes of our $f_{\text{clumpy}}$ values are slightly higher than those of Murata et al. (2014). The difference of $f_{\text{clumpy}}$ amplitudes would be caused by clump identification methods. Nevertheless, we find that our $f_{\text{clumpy}}$ trends are comparable to Murata et al.’s measurements.

Approach (ii).—Figures 8–10 compare the number distributions of clumpy and nonclumpy galaxies in the $M_*$ bins of $\log M_*/M_\odot = 9$–10, 10–11, and 11–12, respectively. We perform Kolmogorov–Smirnov (K-S) tests to quantify the significance level of differences between the number distributions of clumpy and nonclumpy galaxies. The K-S tests

Figure 10. Same as Figure 8, but for the photo-$z$ galaxies with $\log M_*/M_\odot = 11$–12.

Figure 11. Dependence of $f_{\text{UV,cor}}$ on the physical quantities $M_{\text{UV}}$ (left), $\Sigma_{\text{SFR}}$ (middle), and $\beta$ (right), for the LBGs at $z \approx 4$–7. The relations for $\Sigma_{\text{SFR}}$ and $\beta$ are derived in an $L_{\text{UV}}$ range of $0.3$–$1L_{\text{UV,5}}$. The blue squares, cyan circles, green triangles, and magenta inverse triangle denote the LBGs at $z \approx 4$, 5, 6, and 7, respectively. The gray lines indicate the best-fit linear functions of $f_{\text{UV,cor}}(x) = ax + b$, where $a$ and $b$ are free parameters. The data points are not shown for LBGs with $F_{\text{0.2}} < 0.2$ and/or $N_{\text{gal}} < 10$ in the bins of the physical quantities. The open pentagons present $f_{\text{UV,cor}}$ for $z \approx 4$ LBGs in Lotz et al. (2006).
determine probabilities (p-values) of accepting the null hypothesis that two samples are drawn from a statistically identical distribution. If the two distributions are statistically different, the p-values are significantly below \(\leq 5\%\). As shown in p-values in Figures 8–10, the K-S tests suggest that the two number distributions of clumpy and nonclumpy galaxies are statistically different in almost all \(M_\ast\) and \(z\) bins with respect to most physical properties (i.e., \(p \ll 5\%\)). These results of the K-S tests are compatible with the \(f_{\text{clumpy}}\) trends in approach (i).

However, we obtain a large p-value of \(\geq 5\%\) for galaxies in bins of \((\log M_\ast/M_\odot, z) = (9–10, 2–3), (11–12, 0–1),\) and \((11–12, 2–3)\). Such a high p-value might be attributed to the small sample size of high-\(z\) clumpy galaxies.

### 6.3.2. Results for the LBGs

We next examine physical properties for the clumpy LBGs. We have no measurements of \(M_\ast\) and \(n\) for the LBG sample. Instead of \(M_\ast\) and \(n\), we evaluate physical quantities of \(M_{\text{UV}}, \Sigma_{\text{SFR}},\) and \(\beta\) for the LBGs. Figure 11 shows dependences of \(f^{\text{clumpy}}\) on physical quantities, \(M_{\text{UV}}, \Sigma_{\text{SFR}},\) and UV slope \(\beta\). We perform the \(F_c\) corrections to \(f^{\text{clumpy}}\) for the LBG sample. This is because the detection completeness is sensitive strongly to \(M_{\text{UV}}\) (see Section 5) and weakly to \(\Sigma_{\text{SFR}}\) and \(\beta\) through weak correlations between \(M_{\text{UV}}\) and the two quantities of \(\Sigma_{\text{SFR}}\) and \(\beta\) (e.g., Bouwens et al. 2014; Paper I). We exclude high-SFR SD bins of \(\log \Sigma_{\text{SFR}} < 0 M_\odot\text{yr}^{-1}\text{kpc}^{-2}\) dominated by compact LBGs.

In Figure 11, we find a marginal trend that \(f^{\text{clumpy}}\) increases for LBGs with a bright \(M_{\text{UV}}\), a high \(\Sigma_{\text{SFR}},\) and a small \(\beta\) (i.e., blue UV slope). According to an empirical relation in Kennicutt (1998), \(M_{\text{UV}}\) is an indicator of SFR. The \(f^{\text{clumpy}}_{\text{MUV}}\) and \(f^{\text{clumpy}}_{\Sigma_{\text{SFR}}}\) trends for the LBGs are consistent with the correlations for the photo-\(z\) galaxies in Section 6.3.1. On the other hand, \(\beta\) is a coarse indicator of the stellar population and dust extinction of galaxies. The vigorous clumps would yield young stellar populations on entire galactic regions, producing a blue UV slope. The \(f^{\text{clumpy}}_{\beta}\) correlation could be another piece of evidence that clumps are related to the SF activity of host galaxies.

For comparison, we plot LBGs at \(z \approx 4\) in Lotz et al. (2006) in the panel of \(f^{\text{clumpy}}_{\text{MUV}}\) in Figure 11. The detection completeness has been corrected in Lotz et al. (2006). Our \(f^{\text{clumpy}}_{\text{MUV}}\) relation is comparable to that of Lotz et al. (2006).

We quantify the significance level of our \(f^{\text{clumpy}}_{\text{MUV}}\) relations. We are not able to apply approach (ii) in Section 6.3 to the LBG sample owing to the small sample size and the differential \(F_c\) values depending on \(M_{\text{UV}}, \Sigma_{\text{SFR}},\) and \(\beta\). Instead of approach (ii), we carry out Spearman rank correlation tests for the \(f^{\text{clumpy}}_{\text{MUV}}\) relations in Figure 11. In general, rank correlation tests do not adequately take into account fractional values (e.g., \(f_{\text{clumpy}}\) in the case of this study) and their error bars. We still expect that the test gives a rough estimate for significance levels of the correlations. We find that the significance levels of these \(f^{\text{clumpy}}_{\beta}\) trends are \(4.3\sigma, 4.9\sigma,\) and \(4.5\sigma\) with respect to \(M_{\text{UV}}, \Sigma_{\text{SFR}},\) and \(\beta\), respectively. The correlation tests suggest that the \(f^{\text{clumpy}}_{\beta}\) correlations are significant with these physical quantities for the LBGs at \(z \geq 4\). We have extended the correlation study up to \(z \lesssim 7\) and have found the relation between clumps and the SF activity of host galaxies at \(z \approx 0–7\).

### 6.4. Relations between Clump Colors and Galactocentric Distance

We examine relations between colors and \(d_{\text{cl}}/r_e\) for clumps. Figure 12 presents \(m_{\text{UV}} - m_{\text{opt}}\) colors as a function of \(d_{\text{cl}}/r_e\) for each clump, where \(m_{\text{UV}}\) and \(m_{\text{opt}}\) are the magnitudes of UV...
clumps at the rest-frame UV and optical wavelengths, respectively. Here we measure the $m_{\text{UV}} - m_{\text{opt}}$ colors in the double-detection mode of SEXTRACTOR after the PSF homogenizations. We obtain $m_{\text{UV}} - m_{\text{opt}}$ colors at $z \approx 1 - 2$, where both $m_{\text{UV}}$ and $m_{\text{opt}}$ magnitudes are measurable with the HST bands. As shown in Figure 12, we find that the $m_{\text{UV}} - m_{\text{opt}}$ values tend to be red at a small $d_{\text{cl}}/r_{\text{e}}$. This color trend is clearly shown for high-$M_*$ bins. To evaluate these trends, we perform Spearman rank correlation tests between $m_{\text{UV}} - m_{\text{opt}}$ and $d_{\text{cl}}/r_{\text{e}}$. The significance levels of these correlations are 5, 9, 7, 9, and 14 for the mass bins of $\log M_*/M_\odot = 9 - 10$, 10–11, and 11–12, respectively.

For comparison, we plot $z \approx 2$ clumpy HAEs with log $M_*/M_\odot \approx 10 - 11$ in Tadaki et al. (2014). We assume that the galaxy size of these HAEs is $r_{\text{e}} = 2$ kpc (see $r_{\text{e}}$ evolution in Paper I). We find that our clumpy galaxies have similar color--$d_{\text{cl}}/r_{\text{e}}$ correlations to those of these HAEs.

There is a possible source of systematics in which we obtain the clump color--$d_{\text{cl}}/r_{\text{e}}$ correlations. The background flux of host galaxies is not subtracted in the measurements of the clump magnitudes in Figure 12 and Tadaki et al. (2014). Evolved bright central structures (e.g., bulges) would make a similar color trend of host galaxies to those of clumps (e.g., van Dokkum et al. 2010; Patel et al. 2013; Morishita et al. 2015; Nelson et al. 2015). To show this effect, we compare the typical $m_{\text{UV}} - m_{\text{opt}}$ color gradients of host galaxies with those of the clump colors in Figure 12. The $m_{\text{UV}} - m_{\text{opt}}$ colors of host galaxies are derived from the radial SB profiles in the stacked images (Section 6.2). The $m_{\text{UV}} - m_{\text{opt}}$ uncertainties resulting from the galaxy color variations are typically $\pm 0.3$ mag (e.g., Guo et al. 2012). As indicated in Figure 12, the host galaxies show similar color gradients to those of clumps. Nevertheless, we still identify color--$d_{\text{cl}}/r_{\text{e}}$ correlations steeper than these galaxy color gradients for the massive bins of log $M_*/M_\odot = 11 - 12$ and marginally for log $M_*/M_\odot = 10 - 11$. These trends have already been reported in previous studies for massive galaxies (e.g., Förster Schreiber et al. 2011; Guo et al. 2012). In this study, we find, for the first time, the dependence of clump color correlations on $M_*$.

7. DISCUSSION

7.1. Implications for Clump Formation Mechanisms: Galaxy Mergers or VDI?

We investigate whether our results are consistent with the clump formation mechanisms of galaxy mergers (Section 7.1.1) or VDI (Section 7.1.2). As shown in the following subsections, our results suggest that VDI would be favorable as a clump formation mechanism. In Section 7.2, we discuss the possibility of the clump migration.

7.1.1. Galaxy Mergers?

We first examine the possibility that the galaxy merger is the major clump formation mechanism. In Section 6.1, we identify the $f_{\text{clumpy}}$ evolution at $z \approx 0 - 8$. $f_{\text{clumpy}}$ increases from $z \approx 8$ to $z \approx 3$ and decreases from $z \approx 1$ to $z \approx 0$. In the case of the ex situ clump origin, $f_{\text{clumpy}}$ should follow the evolution of the merger fraction. Observational studies have measured the galaxy major and minor merger fractions, $f_{\text{merger}}$ and $f_{\text{merger}}$, at $z \approx 0 - 3$, using galaxy close pairs that have a spatial scale of $\approx 20$ kpc different from the clump–clump separations (e.g., Le Fèvre et al. 2000; Bluck et al. 2009; Bundy et al. 2009; Williams et al. 2011; Man et al. 2012, 2014; López-Sanjuán et al. 2013). In Figure 5, we compare our $f_{\text{clumpy}}$ evolution with the merger fractions of Lotz et al. (2011) assuming that these $f_{\text{merger}}$ and $f_{\text{merger}}$ values continuously evolve beyond $z \approx 3$. As shown in Figure 5, the evolutionary trend of the major merger fraction is probably similar to our $f_{\text{clumpy}}$ evolution at $z \approx 0 - 1$, but it is inconsistent beyond $z \approx 3$. In contrast, the evolutionary trend of the minor merger fraction is comparable to our $f_{\text{clumpy}}$ evolution at $z \approx 3$, but it is incompatible at $z \approx 0 - 3$. These comparisons indicate that the merger fractions do not explain simultaneously both low-z and high-z trends of our $f_{\text{clumpy}}$ evolution.\(^{10}\)

Moreover, numerical simulations predict that the halo–halo major and minor merger rates strongly increase from $z \approx 0$ to $z \approx 6$, $\sigma(1 + z)^{2-3}$ (e.g., Genel et al. 2008, 2009; Fakhouri et al. 2010; Hopkins et al. 2010; Rodriguez-Gomez et al. 2015). Our decreasing $f_{\text{clumpy}}$ evolution beyond $z \approx 3$ is also incompatible with the theoretical predictions. Thus, our evolutionary $f_{\text{clumpy}}$ trend is inconsistent with the scenario that the clump formation is mainly driven by galaxy mergers.

7.1.2. VDI?

We next examine the possibility that the VDI is the major clump formation mechanism. The Sérsic index of clump halos is one of the key measurements for distinguishing the clump formation mechanisms. The VDI requires host galaxies to have disk-like underlying components. In Sections 6.2 and 6.3, we have obtained a low Sérsic index of $n = 1$ in the SB profiles of clumpy galaxies. These low-$n$ values support that clumpy galaxies tend to have disk-like structures.\(^ {11}\)

The $f_{\text{clumpy}}$ is another key measurement. As described below, our $f_{\text{clumpy}}$ evolution at $z \approx 0 - 8$ is consistent with the clump formation mechanism of VDI. The instability of galaxy disks could be sustained by the cold gas accretion as a result of continuous gas supply (e.g., Birnboim & Dekel 2003; Kereš et al. 2005, 2009, 2012; Dekel & Birnboim 2006; Dekel et al. 2009a, 2009b; Nelson et al. 2013). If clumps have the in situ origin, $f_{\text{clumpy}}$ is expected to evolve with the cold gas accretion rate. Kereš et al. (2005, 2009) calculated volume-averaged accretion rates of cold gas at $z \approx 0 - 7$ by performing cosmological hydrodynamics simulations. The simulations predict that the cold gas accretion rate shows an evolutionary trend similar to the Madau–Lilly plot with a broad peak at $z \approx 3$. As shown in Figure 4, we have indeed found that our $f_{\text{clumpy}}$ evolution at $z \approx 0 - 8$ is similar to such an evolutionary trend of the cold gas accretion rate. Our $f_{\text{clumpy}}$ peak is also remarkably consistent with the epoch of disk stabilization at $z \approx 1$ predicted by Cacciato et al. (2012). This evolutionary similarity suggests that a majority of clumps form through the VDI. The $f_{\text{clumpy}}$ measurements beyond $z \approx 3$ allow us to...\(^{10}\) We have compared $f_{\text{clumpy}}$ with the merger fractions, $f_{\text{merger}}$, based on $M_*$ ratios of merging galaxies (i.e., gas-poor mergers). The detailed comparisons between $f_{\text{clumpy}}$ and $f_{\text{merger}}$ require comprehensive censuses of both gas-poor and gas-rich mergers at high $z$ with merger ratios of $M_*$ and flux (see, e.g., Man et al. 2012, 2014).

\(^{11}\) The existence of galaxy disks at $z \gtrsim 3$ is also supported by numerical simulations (e.g., Romano-Díaz et al. 2011; Yajima et al. 2015) and studies on galaxy sizes (e.g., Paper I).
clearly identify the major clump formation mechanism over cosmic time. The results of our clumpy structure analyses at $z \simeq 0$–3 are also consistent with the in situ clump formation mechanism. The following arguments have been found in previous studies on clumpy galaxies at $z \lesssim 3$ (e.g., Guo et al. 2015). Our $z \simeq 0$–3 $f_{\text{clumpy}}^{\text{UV}}$ and $n$ results would be explained by the evolution of unstable gas-rich galaxy disks. According to observations for gas fractions and kinematics (e.g., Tacconi et al. 2010), $f_{\text{clumpy}}^{\text{UV}}$ is expected to decrease from $z \simeq 3$ to $z \simeq 0$ owing to the disk stabilization toward low $z$. In Figure 3, we have indeed found that our $f_{\text{clumpy}}^{\text{UV}}$ shows such a decreasing trend from $z \simeq 3$ to $z \simeq 0$. On the other hand, our $f_{\text{clumpy}}^{\text{UV}}$ correlates with the SF-related quantities of clumpy host galaxies (Section 6.3). These correlations could also be explained by the in situ clump formation. The in situ clump formation would enhance the global SF activity of clumpy host galaxies owing to the vigorous star (clump) formation in galaxy disks. This enhancement of the SF activity would naturally result in a correlation between $f_{\text{clumpy}}^{\text{UV}}$ and the SF-related quantities.

All of our $z \simeq 0$–3 results also suggest the picture that a majority of clumps form in VDI. Combined with the discussion in Section 7.1.1, the major clump formation mechanism at $z \simeq 0$–8 is likely to be the VDI rather than the galaxy mergers.

7.2. Clump Migration

We discuss the evolution of clumps in galactic regions. We find that the clump color tends to be blue at a large $d_{\text{cl}}/r_{\text{c}}$ and tends to become red toward galactic centers for the clumpy galaxies with $\log M/M_\odot \gtrsim 11$ (Figure 12 and Section 6.4). This result suggests that clumps at outer galactic regions would be young if we assume that the blue $m_{\text{UV}} - m_{\text{opt}}$ color implies young stellar ages and/or low dust extinction. Recently, numerical simulations predict that these young clumps may form around the central compact sources (i.e., blue and red nuggets) after the wet compaction phase (e.g., Dekel & Burkert 2014; Tacchella et al. 2015a, 2015b, 2015c; Zolotov et al. 2015). The color–$d_{\text{cl}}/r_{\text{c}}$ correlation would be explained by a scenario that such a young clump is evolved in the stellar population during the clump migration to the galactic centers (e.g., Dekel et al. 2009a; Krumholz & Dekel 2010; Förster Schreiber et al. 2011; Ceverino et al. 2012; Inoue & Saitoh 2012; Okamoto 2013; Mandelker et al. 2014, 2015). In contrast, we find that no strong color–$d_{\text{cl}}/r_{\text{c}}$ correlation is shown for the low-$M_*$ and the intermediate-$M_*$ clumpy galaxies with $\log M/M_\odot = 9$–11. The no correlation indicates that clumps may be destroyed by galaxy feedback effects before the clump migration in galaxies with $\log M/M_\odot \simeq 9$–11.

8. SUMMARY AND CONCLUSION

We present the redshift evolution of $f_{\text{clumpy}}^{\text{UV}}$ and investigate the properties of clumpy host galaxies using the $HST$ samples of $\sim 17,000$ galaxies at $z \simeq 0$–8. Our $HST$ samples consist of photo-$z$ galaxies at $z = 0$–6 from the 3D-$HST$+CANDELS catalog and LBGs at $z \simeq 4$–8 identified in CANDELS, HUDF 09/12, and HFF parallel fields. The large galaxy sample allows for the systematic search for clumpy galaxies over the wide redshift range of $z \simeq 0$–8. We identify clumpy galaxies with off-center clumps in a self-consistent clump detection algorithm for the $HST$ sample and measure $f_{\text{clumpy}}^{\text{UV}}$ at $z \simeq 0$–8.

We summarize our major findings below.

1. We identify an evolutional trend of $f_{\text{clumpy}}^{\text{UV}}$ over $z \simeq 0$–8 for the first time: $f_{\text{clumpy}}^{\text{UV}}$ increases from $z \simeq 8$ to $z \simeq 1$–3 and decreases from $z \simeq 1$ to $z \simeq 0$. This $f_{\text{clumpy}}^{\text{UV}}$ trend is similar to the Madau–Lilly plot of the cosmic SFRD evolution. We test whether the $f_{\text{clumpy}}^{\text{UV}}$ trend is real based on the tests.

2. We examine the underlying morphology of our clumpy galaxies. We obtain typical radial SB profiles by stacking the rest-frame optical images of our clumpy galaxies at $z \simeq 0$–2. Our median stacking analysis enables us to examine underlying components of clumpy host galaxies, negligibly affected by flux contributions of individual clumps. The best-fit Sérsic indices to these radial SB profiles show a low value of $n \simeq 1$. These low-$n$ values indicate that clumpy galaxies tend to have disk-like structures.

3. We investigate relations between $f_{\text{clumpy}}^{\text{UV}}$ and physical quantities of host galaxies. We find that $f_{\text{clumpy}}^{\text{UV}}$ tends to increase with increasing the SF-related quantities (i.e., SFR, sSFR, $\Sigma_{\text{SFR}}$) for the photo-$z$ galaxies at $z \simeq 0$–2. We also identify trends that $f_{\text{clumpy}}^{\text{UV}}$ increases for $z \simeq 4$–7 LBGs with a bright $M_{\text{UV}}$, a high $\Sigma_{\text{SFR}}$, and a blue UV slope. These relations suggest that the clump formation would be intimately related to the entire SF activity of host galaxies.

4. We find a trend that the clump $m_{\text{UV}} - m_{\text{opt}}$ colors are red at a small galactocentric distance $d_{\text{cl}}/r_{\text{c}}$ for massive galaxies with $\log M_*/M_\odot = 11$–12. The color–$d_{\text{cl}}/r_{\text{c}}$ correlations would be evidence that young clumps at galaxy disks migrate into the galactic centers. The clump color trends tend to be marginal for intermediate-$M_*$ and low-$M_*$ galaxies with $\log M_*/M_\odot = 9$–11. The clumps may be destroyed by galaxy feedback effects before the clump migration for these galaxies with $\log M_*/M_\odot = 9$–11.

In Figure 5, we find that $f_{\text{clumpy}}^{\text{UV}}$ does not show evolutionary trends similar to those of the galaxy major and minor merger fractions, but to the one of the cold gas accretion rate. All of these results are consistent with a picture that a majority of clumps form in the VDI and migrate into the galactic centers. The morphology of inner galactic regions remains unknown for compact sources with $r_c \lesssim 0''/2$ in the spatial resolution of PSF $\gtrsim 0''/1$–$0''/2$ in the FWHM of $HST$. According to the evolution of galaxy size–luminosity relations, galaxies at $z \gtrsim 3$ tend to be as small as $r_c \lesssim 1$ kpc, corresponding to $r_c \lesssim 0''/2$ (e.g., Paper I). The morphology of the inner regions for these compact galaxies will be revealed by future space missions and 30 m class telescopes that resolve galaxy structures with a physical scale of $\gtrsim 0.05$ kpc at $z \simeq 7$–15 (Holwerda et al. 2015; Skidmore et al. 2015).

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